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COMMENTARY
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The Critical Role of the Research Community in Space Weather Planning and Execution

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Key Points:
- The scientific research community has made important contributions to space weather that should be continued and encouraged
- Progress in space weather has been achieved largely through involvement of the research community in space weather planning/implementation
- The research community must continue to be supported and engaged in space weather going forward

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Abstract The explosion of interest in space weather in the last 25 years has been due to a confluence of efforts all over the globe, motivated by the recognition that events on the Sun and the consequent conditions in interplanetary space and Earth's magnetosphere, ionosphere, and thermosphere can have serious impacts on vital technological systems. The fundamental research conducted at universities, government laboratories, and in the private sector has led to tremendous improvements in the ability to forecast space weather events and predict their impacts on human technology and health. The mobilization of the research community that made this progress possible was the result of a series of actions taken by the National Science Foundation (NSF) to build a national program aimed at space weather. The path forward for space weather is to build on those successes through continued involvement of the research community and support for programs aimed at strengthening basic research and education in academia, the private sector, and government laboratories. Investments in space weather are most effective when applied at the intersection of research and applications. Thus, to achieve the goals set forth originally by the National Space Weather Program, the research community must be fully engaged in the planning, implementation, and execution of space weather activities, currently being coordinated by the Space Weather Operations, Research, and Mitigation Subcommittee under the National Science and Technology Council.

1. Introduction

The phenomenal growth in space weather as a scientific and technical discipline has inspired several retrospective examinations of the events, policies, and actions that have sustained the enterprise through the years (see, e.g., Bonadonna et al., 2017; Caldwell et al., 2017; Lanzerotti, 2017; Odenwald, 2015, Poppe & Jorden, 2006; Robinson & Behnke, 2001). While instructive and informative, these accounts do not highlight the important role played by the scientific research community in advancing space weather, particularly in the last 25 years. The fundamental research conducted at universities, government laboratories, and in the private sector has led to tremendous improvements in the ability to forecast space weather events and predict their impacts on human technology and health. The mobilization of the research community in the United States that made this progress possible was the result of a series of actions taken by the National Science Foundation (NSF) to build a national program aimed at space weather. Here we summarize those actions and then map a path forward for the national space weather endeavor that is based on continued involvement and leadership by the research community.

2. The Last 25 Years

Although the impacts from space weather on technological systems have been recognized for more than 150 years, space weather as a unique scientific discipline did not emerge until the 1990s. Cade and Chan-Park (2015) traces the history of the term "space weather" back to the 1950s, but it is fair to say that the nomenclature did not appear frequently in printed media until much later. The increased frequency of the term used in peer reviewed journal articles between 1994 and 2001 was documented by Robinson and Behnke (2001). A newer graph based on data from Google Scholar shows the number of times the term "space weather" has been used in the title of a peer-reviewed publication (Figure 1). In the 24 years preceding 1994, the term space weather did not appear in the title of any scientific publications. The increasing use of space weather in the title of publications within 5 years after the initiation of the U.S. National Space Weather Program (NSWP) in 1994 is indicative of the rising interest within the research community in the scientific challenges the endeavor presented.

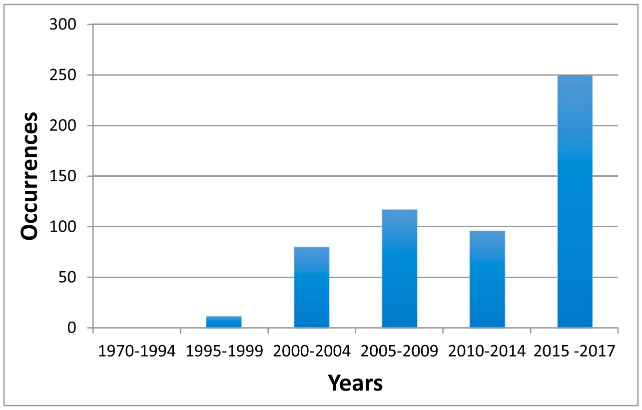

Figure 1. Number of occurrences of the term "Space Weather" according to Google Scholar.

So what happened after 1994 that inspired this blossoming interest? Quite simply, it was because in that year, at the urging of leading representatives of the research community from academia, government, and industry, NSF announced a targeted proposal competition aimed at improving the nation's capabilities to predict solar storms and their subsequent effects on Earth's space environment. Scientific research supported by NSF through that program was then, and still is, published under the broad heading of space weather.

The following activities undertaken by NSF after 1994 dramatically increased the involvement of the research community in achieving the goals and vision documented in the Office of the Federal Coordinator for Meteorology (1995):

1. NSF led and played a key role in the actions of the Committee for Space Weather, formed under the auspices of the Office of the Federal Coordinator for Meteorology (OFCM), from the beginning of the NSWP in 1994 to its maturity in 2014, when oversight was transferred to the White House Office of Science and Technology Policy (OSTP). During this time, the Committee for Space Weather oversaw the development of the Office of the Federal Coordinator for Meteorology (1995, 1997). and its subsequent update, the Office of the Federal Coordinator for Meteorology (2000). These efforts were based on numerous workshops, meetings, and working groups organized and hosted by NSF, all aimed at ensuring strong and continuing input from the research community.
2. The annual space weather proposal competition resulted in targeted space weather research grants to individual investigators in excess of $50M over 15 years. By the time the dedicated competition ended, space weather had solidified as a core focus of research activities in the science community. Basic research to develop and advance a systems level approach to geospace science and heliophysics continued to be supported by NSF through the CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions), GEM (Geospace Environment Modeling), and SHINE (Solar, Heliospheric, and INterplanetary Environment) programs, and at NASA by the Living With a Star Program. Many of the Department of Defense Multi-University Research Initiatives (MURI) also focused on space weather. In addition, research aimed at improving space weather forecasts has been successful in NSF-wide competitions such as PREEVENTS (Prediction of and Resilience against Extreme Events). All these programs contributed to maintaining an active and engaged research community dedicated to improving the nation's resilience to space weather events.
3. Recognizing the need to quantitatively assess the economic impacts of space weather, NSF supported a series of workshops focused on impacts to electric power systems, communication systems, and aviation. NSF also supported the annual Space Weather Enterprise Forum organized by NOAA and OFCM, an assembly that highlights the potential effects of space weather on federal and commercial technological assets. Additionally, NSF co-sponsored, along with NASA and NOAA, the annual Space Weather Week meetings, which later became the NOAA Space Weather Workshop, a multicommunity assembly aimed at continuing the close communication between researchers, space weather forecasters, and customers (Hildner et al., 2011; Robinson & Behnke, 2001).
4. NSF supported the Center for Integrated Space Weather Modeling (CISM), a Science and Technology Center involving 10 institutions led by Boston University, at $4M per year for 10 years. Among its many accomplishments over these 10 years, CISM helped advance the importance of a multidisciplinary approach to understanding the end-to-end space weather system (Quinn et al., 2009). CISM also enabled the successful transition of the Wang-Sheeley-Arge Enlil solar wind forecasting code to NOAA's Space Weather Prediction Center (Schultz, 2011).
5. NSF created a dedicated program called Faculty Development in Space Sciences (FDSS), which was aimed at establishing a greater foothold by space scientists in traditional academic departments. Space scientists hail from different academic departments, and only a few universities offer degrees specifically in the field of Space Physics. Space weather was highlighted in the proposal solicitation as an important area where new faculty was needed. In the selection of FDSS awards by NSF, high priority was given to universities making strong commitments to build and maintain critical mass in faculty expertise in space science, which is a prerequisite for strengthening space weather research.

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6. NSF originated the proposal to the American Geophysical Union that led to the creation of the Space Weather Journal (Robinson, 2003). NSF also provided initial funding for the journal, which has grown to be an important outlet for the broad range of scientific and technical articles reflecting the steadily increasing body of knowledge in space weather and establishing an important bridge between the research and operational communities. A search of the IEEE Xplore Digital Library shows more than 800 published articles in the Journal to date.
7. NSF supported, and still supports, a multifaceted array of space weather observations, including ground-based platforms, such as the Incoherent Scatter Radars, SuperDARN (Super Dual Auroral Radar Network), and SuperMAG, and space-based platforms, such as AMPERE (Active Magnetosphere and Planetary Electrodynamics Response Experiment), all of which represent valuable tools for understanding and observing space weather processes and phenomena (Coster et al., 2018; Lotko, 2017). Similarly, the tremendously successful NSF CubeSat program also paved the way toward improved space weather observational capabilities (Baker & Cleave, 2015; Moretto & Robinson, 2008; National Academies of Sciences, Engineering, and Medicine, 2016).
8. NSF demonstrated its commitment to transitioning research to operations by investing in the startup of the Community Coordinated Modeling Center (CCMC). Along with the U.S. Air Force, NASA, and NOAA, NSF played a critical role in the organization and management of the Center (Bellaire, 2004). NSF's initial and continuing investment of up to $500K per year was critical to getting the center started and continues to be an important component of CCMC support.

3. Looking Forward

The common theme of the activities described above is that each involved strong participation, partnership, and scientific leadership by the research community. Now, as we look toward the future, the way to continue the tremendous success space weather has enjoyed is to ensure the research community maintains a central role in the space weather enterprise. Here we suggest mechanisms that will take advantage of the vision and innovation resident in the science community.

Like many endeavors, the future lies in adequate education and training of the next generation of highly qualified personnel. Students supported by CISM were trained to view space weather as a system science that connected the solar atmosphere to Earth's atmosphere. The CCMC trains students in the knowledge and skills necessary for space weather forecasting. CubeSat projects provide students with the opportunity to participate in end-to-end space mission development and execution. Space weather model validation and testing also offers students excellent insight into space weather fundamentals, while simultaneously improving the accuracy and reliability of space weather specification and forecasting. Continued support for students at the undergraduate and graduate levels is essential to ensure the expertise is in place to confront future challenges.

To extend the progress made through the FDSS and other programs, faculty and curriculum development in academic departments should build on the current momentum in space weather. This will depend on the development of course curricula in the scientific and engineering disciplines needed for space weather that will lead to space weather degree programs at the undergraduate and graduate levels. Although originally designed to help jumpstart space weather programs at smaller universities, an expanded FDSS program should aim to grow faculty, degree programs, and student training in space weather at universities across the nation. These programs can build on existing short-course space weather schools, such as the Heliophysics Summer School (https://cpaess.ucar.edu/heliophysics/summer-school), the CISM Summer School (Lopez & Gross, 2008), and the Los Alamos Space Weather Summer School (http://www.lanl.gov/projects/national-security-education-center/space-earth-center/space-weather-school/index.php).

Progress in space weather has been, and will continue to be, dependent on advances in fundamental understanding of physical processes throughout the Sun-Earth system. Those breakthroughs will undoubtedly be achieved by research scientists from academia, the private sector, and government labs. Great progress has been made in recent years by the research community in such areas as forecasting solar storms, propagation of heliospheric disturbances, particle energization processes, geomagnetically induced currents, and ionospheric irregularities. Improvements have also been made in techniques for data assimilation, deep learning using large databases, coupling of global, multiscale (nested grid) magnetohydrodynamic models. These and other successful efforts were enabled by engaging scientists with knowledge of the fundamental physics, awareness of space weather customer needs, and the intellectual freedom to imagine beyond constraints of agency budgets and missions. As suggested by Stokes (1997), investment by federal agencies in use-inspired research enhances the pathways that lead both to new understanding and practical benefits. Such targeted research at universities, government laboratories, and in the private sector must remain strongly supported.

The science community can also play an important role in the application of research to improving space weather services and operational capabilities. Successful transitioning must be based on the development of new paradigms for applied technology that do not restrict or inhibit basic research but fully utilize it. To optimize research for space weather applications, an effective means to provide feedback from space weather customers and forecasters to the researchers is essential (Robinson, 2012). The Space Weather Journal, the Space Weather Workshop, and the CCMC are all designed to facilitate such an exchange. Establishment of heliophysics science centers that act as hubs for disciplinary expertise and information exchange will also help maintain a vigorous and engaged research community. At the same time, center activities are optimized when balanced with strong participation by scientists in the broader academic community and private sector worldwide.

Finally, it is important that researchers from academia, government laboratories, and the private sector be fully engaged in the development and implementation of current and future national space weather initiatives. The recommendations contained in the two reports released by OSTP, Office of Science and Technology Policy, National Science and Technology Council (2015a, 2015b) were developed with minimal input from the research community. Recently, NSF issued a request for information (Federal Register Doc. 2018-00031) soliciting input to help identify needed scientific priorities supporting the recommendations in the two plans. Ideally, to ensure a sound research component, input from the research community should have been well integrated into the entire plan throughout its development. Increased involvement and support of the research community is vital to sustaining an environment that nurtures the creativity and innovation needed to ensure greater fundamental understanding of the space weather system and, consequently, improved forecasts. One important step in the right direction would be to include the research agencies of NASA and NSF as co-chairs of the Space Weather Operations, Research, and Mitigation Subcommittee, which has been formed under the Office of Science and Technology Policy's National Science and Technology Council to oversee interagency space weather efforts going forward.

4. Conclusion

Government funding agencies play a critical role in supporting and encouraging fundamental research. Stokes (1997) showed that federal investment at the intersection of curiosity-driven and use-inspired research is most effective in leading to new discoveries and advancements. The success of this approach has recently been demonstrated by Ahmadpoor and Jones (2017), who showed that research driven by practical applications often produces the best science as well. The advances achieved by the space weather research community over the past 25 years is an excellent example of the merits of this approach to funding science. As predicted by Lou Lanzerotti in the first Office of the Federal Coordinator for Meteorology (1995), "While it is true that important applications will result from the National Space Weather Program, the science that will be accomplished will be first rate…Indeed, the initiative provides a context in which much of solar-terrestrial physics can and should be done."

Space weather is far from a solved problem. There is much research that needs to be done and many improvements to space weather forecasting yet to be realized. To achieve the goals set forth early on in the conception of the National Space Weather Program, the research community must be fully engaged in the planning, implementation, and execution of space weather activities now overseen by the Space Weather Operations, Research, and Mitigation Subcommittee.

Acknowledgments
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