National Aeronautics and Space Administration

Heliophysics Living With a Star Program

Enabling Science, Technology, and Exploration to Advance Society

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10-Year Vision Beyond 2015

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Our solar system is governed by the sun, a main-sequence star midway through its stellar life. The sun's influence is wielded through gravity, radiation, the solar wind, and magnetic fields as they interact with the masses, fields, and atmospheres of planetary bodies. Through the eyes of multiple spacecraft, we see our solar system as a "heliosphere," a single, interconnected system moving through interstellar space. On Earth, this interaction with our star is experienced through space weather's effects on radio and radar transmissions, electrical power grids, and spacecraft electronics, through modifications to the ozone layer, and through climate change. The LWS program emphasizes the science necessary to understand those aspects of the sun and Earth's space environment that affect life and society. The ultimate goal of LWS program is to provide a scientific understanding of the system, almost to the point of predictability, of the space weather conditions at Earth, interplanetary medium as well as the sun-climate connection.

The LWS program objectives are based upon these goals and are as follows:

1. Understand solar variability and its effects on the space and Earth environments with an ultimate goal of a reliable predictive capability of solar variability and response.
2. Obtain scientific knowledge relevant to mitigation or accommodation of undesirable effects of solar variability on humans and human technology on the ground and in space.
3. Understand how solar variability affects hardware performance and operations in space.

These objectives flow down from objective 1.4, "understand the sun and its interactions with Earth and the solar system, including space weather," in the 2014 NASA Strategic Plan, the 2014 Science Plan for NASA's Science Mission Directorate, and the Heliophysics Roadmap (Our Dynamic Space Environment: Heliophysics Science and Technology Roadmap for 2014-2033).

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LWS and the New Heliosphere

by Lika Guhathkurta

This report articulates a vision for NASA's Living With a Star (LWS) program spanning the decade 2015 through 2025. The vision is bold, and it must be, because the next decade could be unlike anything we've experienced in the Space Age.

Only a few years ago, the sun emerged from the deepest Solar Minimum in a hundred years. During the extreme quiet of 2007-2009, the solar wind became slow and weak; CMEs lost their punch; and cosmic rays hit a record high for the Space Age. We found ourselves living in a "New Heliosphere."

Normalcy was not restored by the 11-year swing of the solar cycle. Instead of a vigorous Solar Maximum, the 2010s brought us a "mini Solar Max," as peculiar in some ways as the extreme Solar Minimum that preceded it. There have been fewer intense flares, fewer strong geomagnetic storms, and fewer SEPs than any other Solar Max in modern times.

Given these events, there is no reason to think that the decade ahead will be "normal." Indeed, there is some evidence that the sun might plunge into a Minimum even deeper than the one in 2007-2009. If the sun's magnetic field weakens and the solar wind flags, researchers anticipate a significant surge of cosmic rays penetrating the solar system, eclipsing old records.

The questions this raises are very difficult to answer. For instance:

What effect will these cosmic rays have on the chemistry of Earth's upper atmosphere? Past experience may be of little help. During an extreme Solar Minimum, the upper atmosphere could collapse into a new state, prompted by a sharp drop in solar UV radiation. Its response to cosmic rays could be anyone's guess.

How will the new radiation environment alter Earth's ionosphere, where density gradients and scintillation can distort GPS signals and critical HF emergency communications? Forecasters have lots of experience with Solar Max, which puffs up the ionosphere and increases its ionization. But what about extreme Solar Minimum? The ionosphere of 2015-2025 could become very unfamiliar.

What can air travelers and astronauts expect? Even during "normal" times, cosmic rays penetrate Earth's atmosphere, creating a secondary spray of radiation that is absorbed by airplane passengers. The dose is probably not enough to harm occasional fliers. Pilots, on the other hand, are classified by the International Commission on Radiological Protection (ICRP) as "occupational radiation workers," and the impact on their health is the topic of ongoing studies. Deep-space astronauts have even more to worry about. Outside the protective cocoon of Earth's atmosphere and magnetic field, they will absorb an enhanced dose of primary cosmic rays with uncertain consequences for health. One study has shown that during the Apollo Era astronauts could travel nearly 900 days in deep space before reaching NASA safety limits; in the decade ahead, the "safe time" could be reduced to less than 300 days.

Our ten year plan for LWS addresses these questions and many others. As the sun thrusts us into territories of research so new that some of them don't even have names, we will have to bring together researchers from many disciplines to understand what is going on. Interdisciplinary research has been a strong suit of LWS since its inception. In fact, it is a cornerstone of our future plans.

We have identified seven "Strategic Science Areas" of special relevance to the New Heliosphere.

- SSA-0, Physics-based Understanding to Enable Forecasting of Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and inputs to Earth's atmosphere
- SSA-1, Physics-based Geomagnetic Forecasting Capability
- SSA-2, Physics-based Satellite Drag Forecasting Capability
- SSA-3, Physics-based Solar Energetic Particle Forecasting Capability
- SSA-4, Physics-based TEC Forecasting Capability
- SSA-5, Physics-based Scintillation Forecasting Capability
- SSA-6, Physics-based Radiation Environment Forecasting Capability

Using a variety of tools developed during the first 10 years of LWS (such as LWS Working Groups and TR&Ts), we will attack these interdisciplinary problems with the understanding that what we used to know may not apply in the years ahead. In all cases, our focus will be on developing fundamental science to serve the end user. What exactly do power grid operators want to know to help them prevent blackouts? That question will guide our work in SSA-1. Which forecasting tools do satellite operators need to safeguard their fleets against changes in atmospheric drag? That question will guide our work in SSA-2. Each of the strategic science areas focuses on delivering the key science needed by society to protect our technologies and our increasingly space-based infrastructures.

The heliosphere we study in the next ten years may not be much like the one we are used to. We must learn to adapt. LWS is ready.

Living With a Star Program Steering Committee Members:

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Tony Mannucci • JPL (Co-Chair)
Spiro Antiochus • GSFC
Amitava Bhattacharjee • Princeton
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Farzad Kamalabadi • U Illinois
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Executive Summary

NASA's Living With a Star program addresses societal needs for scientific understanding to enable prediction of the causes and effects of space weather events. Our society's heavy reliance on technologies affected by the space environment, such as GPS; the enormous population of airline customers; the interest in space tourism; and the developing plans for long duration human exploration missions are clear examples that demonstrate urgent needs for predictive space weather models and detailed understanding of space weather effects and risks.

Since its inception, the Living With a Star (LWS) program has provided pathways to innovate new approaches for conducting research, for building highly effective interdisciplinary teams, and ultimately developing the scientific understanding needed to transition research tools into the operational models that support the predictive needs of our increasingly space-reliant society. Future advances require a broad array of observations utilizing a full range of flight opportunities from a balanced portfolio as exclusive reliance on large missions presents a significant limitation. LWS must evolve to more rapidly prototype the science-based tools needed for our society's technological expansion and our development as a spacefaring world.

This report presents a vision for the LWS program for the next ten years, 2015-2025. The report builds on the strategy articulated in the 2013 Heliophysics Decadal Survey (DS). The DS vision is captured concisely by its title: "Solar and Space Physics: A Science for a Technological Society." The vision is further clarified by the first key goal developed by the DS: "Determine origins of sun's activity and predict variations in the space environment." The societal needs described in the DS Chapter 3 correspond exactly to the four main goals of the LWS Targeted Research and Technology (TR&T) program. Goals of the Decadal Survey are already being addressed by NASA's LWS program, which was designed to meet these challenges. Given the critical importance of LWS to achieving the Decadal's vision, it is essential that the LWS program be maintained and strengthened.

Goal 1	Deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars and throughout the solar system.
Goal 2	Develop a fuller understanding of how and to what degree variations in the Sun's radiative and particulate outputs will in conjunction with other forcing factors affect regional and global climate in the present century.
Goal 3	Deliver the understanding and modeling required for effective forecasting specification of magnetospheric radiation and plasma environments.
Goal 4	Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below.

LWS faces fundamental challenges in the coming decade that will require innovative approaches to obtaining necessary observations and developing needed research in the LWS program. LWS is facing the growing complexity of the field and the societal demands for improved services. The highest priority recommendation for new funding by the Heliophysics Decadal Survey is implementation of DRIVE (Diversify, Realize, Integrate, Venture, Educate) that represents an integrated approach to the management of crucial infrastructure investments and supporting program elements for spaceflight missions. It is critical for LWS that new DRIVE initiatives begin to address the challenges of developing transformative predictive capabilities in the coming decade.

The first decade of the LWS TR&T program was highly successful. The program significantly contributed to our improved understanding of the physical processes controlling space weather and it also provided high-quality community tools. A recent community survey showed that 75% of the respondents agreed that the Focused Science Team concept implemented by LWS TR&T "aided in the creation of interdisciplinary collaboration" and two-thirds of the responders agreed that the "FST team led to advancement of science beyond the individual proposals."

LWS is now in the position to leverage this past work for the development of predictive capabilities in key areas of LWS science. This leverage is critical in these times of challenging budgets to maximize the scientific return on our investments. In the second decade of LWS, it is imperative to establish a stronger link between the scientific community of LWS and user communities that can directly benefit from LWS strategic developments. Therefore, rather than concentrating on devising Focused Science Topics (FSTs) on separate areas of Heliophysics, the LWS Steering Committee has formulated long-term targeted areas of System Science deemed to most likely impact user communities in the future.

These goals require cross-disciplinary collaboration for predictive development, and are termed "Strategic Science Areas (SSA)":

- SSA-0, Physics-based forecasting of solar electromagnetic, energetic particle and plasma outputs driving the solar system's space environment and inputs to Earth's atmosphere
- SSA-1, Physics-based Geomagnetic Forecasting Capability
- SSA-2, Physics-based Satellite Drag Forecasting Capability
- SSA-3, Physics-based Solar Energetic Particle Forecasting Capability
- SSA-4, Physics-based TEC Forecasting Capability
- SSA-5, Physics-based Scintillation Forecasting Capability
- SSA-6, Physics-based Radiation Environment Forecasting Capability

The SSAs represent long-term goals of the LWS program that will be developed through FSTs, Strategic Capabilities, and Targeted Science and Technology (TST) Teams that will partner with members of existing space weather centers (e.g., the Community Coordinated Modeling Center (CCMC), NASA's Space Radiation Analysis Group (SRAG), and NOAA's Space Weather Prediction Center (SWPC). as well as with members of any new science centers initiated through the DS recommended DRIVE initiative. These partnerships will facilitate better interaction with user communities and the creation of deliverables that best serve user needs. Upon selection of future FSTs, SCs and TSTs, relevant modeling centers should identify liaisons to appropriate user communities.

While the LWS community currently has access to comprehensive observations of the heliophysical environment, there is a lack of a detailed plan for developing targeted products and observations in the future. The potential lack of continuity in acquiring needed observations poses a threat to LWS and to heliophysics science as a whole. No single mission will in the future provide all that is needed. However, data needs are acute for LWS and further advancement simply cannot take place without an expansion of the types of observations available for achieving predictive goals. This highlights the criticality of implementing new LWS-related DRIVE initiatives involving a combination of small satellite programs, science centers, and needed instrument and technology development that will enable the next generation of predictive needs for LWS science.

International collaboration offers another vital avenue for achieving the next generation observations critical for LWS predictive capabilities. The potential for new international synergies was highlighted in a recent 2014 report, "Advancing space weather science to protect society's technological infrastructure: a COSPAR/ILWS roadmap." The highest priority recommendations from the ILWS roadmap emphasize the research needs for observational, computational, and theoretical advances. The roadmap elaborates on the necessity for improved teaming to foster a coordinated collaborative research environment in the national and international community. Finally, the report found that there is a need to bridge the communities that exist at different funding agencies and research communities.

In addition to space-based assets, there exist numerous ground-based instruments and networks that obtain measurements concerning the state of the ionosphere, magnetosphere, and sun. An important part of the future strategy for developing a more flexible and affordable program will be making optimal use of ground-based facilities that fulfill critical needs of the LWS program.

The physical processes by which the dynamic sun impacts the environment of Earth are the same processes by which the sun impacts the environments of other solar system bodies and by which stellar variability impacts the environments of exoplanets. Therefore, the LWS Steering Committee finds a need for (1) a joint Heliophysics and Planetary Science program to investigate the effects of space weather throughout the solar system, especially at Venus, Earth, and Mars, which would be timely and potentially game-changing for our view of planetary systems with stars like our own; (2) a joint Heliophysics and Astrophysics program to investigate the effects of stellar variability on astrospheres and the exoplanets within them. The program would position us to test theories developed in light of the Voyager and IBEX discoveries concerning the heliosphere and take advantage of the unprecedented Kepler stellar observations to discover how dynamic stars affect the long-term habitability of planets. This larger view of our solar and other stellar systems ultimately informs us of the distant past and potential future of our home in space.

Model validation is also critical to LWS. The appropriate forums for model validation are needed to enable the LWS program to have continued success over the next decade. Two broad categories of validation should be developed:

1. Assessment of a model's abilities to reproduce space environment phenomena;
2. Assessment of the predictive capabilities of models for user-defined metrics.

Outcomes of validation activities must be broadly accessible. Prototyping facilities with community access and close proximity to models will be highly valuable for demonstrating operational potential of innovative forecasting techniques. Such facilities should provide:

1. Forums that bring together modelers, data providers and users of space environment prediction models to enhance communication, facilitate collaboration, and education between communities.
2. Forums for metric definition.
3. Web-based systems for the submission, analysis and public dissemination of community-wide validation projects.
4. On-line archives of model validation results and forecasts.
5. Access to observational data, model results, and metrics tools.
6. Databases of space weather impacts.

The LWS Steering Committee recognizes the importance of community tools focused on analysis and interpretation of large data sets that advance LWS objectives. The committee finds that these "big data" initiatives should be considered by the LWS community for future targeted development. A significant challenge is to innovatively use data in models throughout the Heliophysics enterprise. Traditional data assimilation methods from meteorology have been applied to models of the upper atmosphere, and these methods are under active research as a strategic capability. However, these methods will need to be adapted or completely re-invented to be applicable to many problems in heliophysics. Significant progress in a number of the SSAs described in this document will require such innovation.

The problem of forecasting collisions between operational satellites and the vast number of objects that have accumulated in low Earth orbit (LEO) over the past 60 years is related to many of the goals and challenges of the LWS program. LWS research that improves our understanding of the near-term (1-7 days) evolution of solar activity would contribute significantly to the problem of conjunction assessment. LWS can also contribute to the task of characterizing the density forecast uncertainty. Finally, LWS can contribute to long-term (decades to centuries) forecasting and remediation of the debris population itself.

The sun-climate theme within LWS TR&T has unique societal relevance. It also is a uniquely challenging interdisciplinary theme that extends well beyond the traditional heliophysics domain by involving many aspects of the geosciences. Despite the complex web of physical processes to be studied, LWS TR&T has proven to play an important role in the overall study of climate and climate change in particular because it stimulates the expertise close to the core of the LWS goals: understanding of solar and heliospheric activity, and the physical processes that couple that activity to the uppermost layers of the Earth's climate system.

Computational modeling, simulation, and data analysis have been among the most important drivers of scientific discovery during the last three decades. This progress has been enabled by remarkable leaps in computing technologies, producing parallel computers of great power and speed that have been brought to bear on increasingly sophisticated software and efficient algorithms. We anticipate a transition from the present-day terascale and petascale systems to the exascale in the near future, empowering the science community to further undertake challenges that can be potentially transformational.

From a societal perspective, the ultimate goal of space weather activities is to generate products or services (referred to here as "deliverables") that enable end-user action. Space weather is a natural hazard of global proportions, requiring effort to monitor the sun and near-Earth space, as well as local impacts on Earth, and perform research to develop the ability to predict space weather. Space weather involves global phenomena driven by large solar eruptions that impact large areas of Earth simultaneously, and at the same time it involves local disturbances that can vary significantly from place to place. Research that leads to actionable deliverables must remain a key element guiding the LWS TR&T program in the field of space weather. Establishing partnerships with the user community, commercial service providers, government agencies, and international groups is also key to the success of future LWS efforts.

A major challenge to achieving accurate space weather forecasts is bridging the gap between research and operational codes. To address this challenge, a viable national applied sciences program in the field of space physics and space weather to develop the space weather capabilities required today, as well as to remain competitive with, for example, European activities, would be beneficial.

On an international level, participation from countries around the globe is required to effectively monitor and to understand both the drivers of space weather as well as the impacts on Earth and throughout space. More and more countries are establishing their own procedures for mitigating the risks of space weather, warranting international coordination to ensure that consistent information is available across borders. It is essential that LWS continue to take leadership in forging international collaboration and coordination.

Thus we outline a decadal vision for the LWS program; whereby LWS will both broaden its applicability and sharpen its focus on delivering the key predictive capabilities to enable society's technological expansion, to enhance our utilization of space-based assets, and to advance human exploration as we develop as a space-faring world.

Chapter 1

Recommendations from the Decadal Survey

1a. LWS and the Decadal Survey Vision

The 2013 – 2023 Decadal Survey (DS) published by the National Research Council documented the accomplishments in Heliophysics science over the previous decade, developed a vision for the future of the field, and proposed a set of recommendations for achieving that vision. The DS consisted of a comprehensive canvassing of the US science community; consequently the vision developed by the DS represents the most accurate available consensus of the Heliophysics community. This vision is captured concisely by the DS title: "Solar and Space Physics: A Science for a Technological Society". The vision is further clarified by the first key goal developed by the DS: "Determine origins of Sun's activity and predict variations in the space environment."

The vision defined by the DS represents a revolutionary change in science. It shows the transformation of the classical science fields of solar and space physics into the emerging field of Heliophysics. Note that the previous Decadal, published in 2003, was entitled "The Sun to the Earth – and Beyond", which expresses the traditional science goal of simply increasing our knowledge. The new vision and goal state that increasing knowledge is no longer enough, we must also increase the direct benefits to life and society by increasing our capabilities to predict the space environment.

For the past decade, the NASA LWS program has been leading this transformation of the field of Heliophysics from science for knowledge to science for utility. Note that LWS explicitly calls for enabling prediction as a science goal. LWS was specifically created and structured to deliver the most relevant and directly applicable science to NASA and the Nation. The Program consists of two main elements:

1. LWS missions that obtain the measurements needed to further understanding.
2. LWS research has been competed through NASA Research Opportunities in Space and Earth Sciences as the Targeted Research and Technology program and is now called LWS Science. LWS Science includes:

- Focus Science Teams (FST) that attack those major cross-disciplinary science problems most important for improving understanding and prediction;
- Strategic Capabilities (SC) consisting of large-scale models that can test understanding and serve as prototypes for prediction schemes;
- Infrastructure Building (IB) programs designed to create a cross-disciplinary and unified Heliophysics science community.

Although not specifically discussed in the DS, each of these elements plays an essential role in achieving the vision and goals of the DS. The first "Guiding Principle" listed in the DS is that: "… the Sun, Earth, and heliosphere must be studied as a coupled system". This is exactly the motivation for the FST and SC programs within LWS. The FST brings together the cross-disciplinary teams required for attacking the science of the coupled system, while the SC develops the technologies required for modeling and predicting the coupled system. Furthermore, the IB programs develop the research community required for system science.

In its Chapter 3 "Addressing Societal Needs", the DS describes the various damaging effects of space weather and the need to predict them. The DS also emphasized the need to develop system-science models. The SC element has pioneered this effort and is continuing to support the development of increasingly sophisticated and robust system models. Through the Community Coordinated Modeling Center (CCMC), LWS is enabling the entire Heliophysics community to access these models for the purposes of model verification and validation, model coupling, and eventually forecasts.

It should be emphasized that the societal needs described in the DS Chapter 3, correspond exactly to the four main goals of the LWS Targeted Research and Analysis program (TR&T), now known as LWS Science:

- Deliver the understanding and modeling required for useful prediction of solar energetic particle (SEP) variability and GCR modulation at the Earth, Moon, Mars, and throughout the solar system.
- Deliver the understanding of how variations in solar radiation, particles and magnetic fields contribute to global and regional climate change.
- Deliver the understanding and modeling required for effective forecasting/specification of inner magnetospheric radiation and plasma.
- Deliver understanding and predictive models of upper atmospheric and ionospheric coupling above and below.

Note that these four goals capture fully and concisely the science needs for our technological society. We conclude that NASA has anticipated the vision and the goals of the DS and has designed the Living With a Star program to meet these challenges. The LWS program has already had a transformative effect on the field. The DS has reaffirmed that the goals and objectives of LWS are central to the future of Heliophysics.

Given the critical importance of LWS to achieving the DS vision, it is essential that the LWS program be maintained and strengthened. In the following Sections we describe the LWS needs to be enhanced in order to fully satisfy the challenges laid out by the DS.

1b. Implementation of DRIVE in LWS

The DRIVE initiative is the highest priority recommendation for new funding in the 2013 Heliophysics DS. DRIVE encourages re-investment in research and analysis (R&A), development of computing and hardware technology programs, and development of smaller programs such as CubeSats to achieve greater stability and flexibility in Heliophysics that will open new opportunities and create efficiencies for doing science.

Heliophysics faces fundamental challenges in the coming decade that require innovative new approaches to obtaining necessary observations and developing needed research in the LWS program. The following issues are fundamentally important to the health and vitality of the LWS program.

- Observations and measurements from the spacecraft and instruments that make up the Heliophysics System Observatory (HSO) provide critical input to existing models and developing models that will provide the basis for the future's predictive capabilities in the LWS program. Without the necessary observations and input for models, the necessary development of space weather models will be impossible. The question is how today's observations will continue to be supported in the future? How will we fulfill the need for new observations critical to predictive models?
- What are the necessary investments in technology development of hardware to keep pace with technology development in other sectors? Can we apply developments in computing, electronic architectures, new materials developments (etc.) to space technologies and, in so doing, achieve advancements in generating improved, more reliable and affordable space-based hardware necessary for future applications in LWS?
- What investments in computational model development are necessary to keep pace with advancements in distributed architectures and other strides in modern computing? Tomorrow's predictive models in LWS will need to take advantage of advances in computing. It is critical that future LWS programs experiment with new emerging computational systems and architectures to achieve the more efficient and effective models needed to improve LWS research predictive capabilities.
- Is the field of LWS researchers healthy and are there necessary opportunities for the next generation of scientists who will advance LWS goals?
- Is LWS capable of achieving more affordable missions by advancing international collaborations?
- Are partnerships with industry and academia sought out and supported where synergies exist?
- Do we understand the economic impacts of the space environment and space weather (all space weather, not just extreme events), and the economic losses incurred by a potential loss in capabilities, or a decreased rate of capability development?

Chapter 2

Solar Variability and Space Weather

The Living With a Star program addresses those impacts of the connected sun-Earth-heliosphere system that directly affect life and society. Studying space weather events is critical for understanding the implications for Earth, to predict and mitigate the hazards associated with exploration, and to understand the impact of the space environment for the habitability of other worlds. The Living With a Star program has spacecraft and instruments making critical measurements of solar phenomena such as solar flares and coronal mass ejections (CMEs) and to study the effects on planetary space environments. NASA and NOAA currently work together (with other government agencies through the National Space Weather) on satellite development, transitioning research to operations, data processing, and modeling that inform and improve space weather predictions. The importance of space weather research, mitigation, and impacts are currently being addressed with the development of a National Space Weather Strategy and National Space Weather Action Plan. Space weather affects the technologies of key industrial sectors. For those that have identified their risks from space weather, it represents a first step in a successful, broad, decades-long customer education campaign by the space weather community.

At the beginning of the 21st Century the primary challenges were to understand the physics of space weather phenomena, to identify the risks from space weather, and how to build applications for managing that risk. With the success of the National Space Weather Program and the emergence of the commercial sector ACSWA organization, these original challenges have seen progress toward resolution while new challenges have developed.

During the second and third decades of this century, challenges for the space weather enterprise start with the element of "institutional provincialism." The "not-invented-here" syndrome stems from both a legacy of competition for limited funding, which will persist for the foreseeable future, and a legitimate desire in each organization to maximize its own benefit for developing the capacity of the space weather domain. This syndrome occurs across all elements of the space weather enterprise including agencies, academia, and industry. Examples of enterprise collaborations do occur, for example with the hosting of models or the CME Scorecard comparisons by the NASA Community Coordinated Modeling Center (CCMC) and their respect for the intellectual property of the code developers. Separately, the commercial sector both competes and collaborates on proposals that are linked to improving the space weather enterprise.

However, major challenges still loom in the form of natural hazard and disaster recovery, for example, which can be worsened by untimely and severe space weather. We now know that hazards to our technology and our society clearly exist from space weather for communication outages and navigation position uncertainties; we saw this during the Gulf Coast Hurricane Katrina recovery from August 29 into early September 2005. If unmanaged, space weather hazards create additional stress during emergencies, compounding disasters. How to integrate this risk management into our technology infrastructure is a challenge we still face. In an era of climate change we may see an increased coupling of global natural disasters with severe space weather.

There have been numerous forums, including the 2013 DS that address the strengthening of the U.S. space weather enterprise. We know that government policies, funding, and requirements can degrade or strengthen global competitiveness of the U.S. space enterprise and its ability to sustain the nation's security. A "go-it-alone" approach tends to degrade security and is a byproduct of persistent funding limitations; it restricts our ability to compete globally. On the other hand, security improvement occurs with: i) data and model innovation; ii) using all assets of the national space weather enterprise, e.g., operational, research, and commercial satellites; iii) government purchases of commercial data and services that spur rapid advances and competitive innovation; and iv) long-term funding of the academic research base.

We face major societal challenges in this century, particularly from shortages of energy and fresh water. Solving those issues will be fundamental to ensuring the progress and security of our global society. A real challenge for the space weather enterprise is to make itself relevant to solving these fundamental challenges facing humanity this century. Making space-related assets useful for improving life on Earth, and understanding how to manage risks from space weather to those technology assets, is the start for making our enterprise relevant to society. Commercial space weather organizations are at the forefront for innovation, expansion, and integration of solutions as our enterprise responds to societal needs of managing the risks from space weather.

2a. Societal Impacts from Space Weather

As our society has emerged into the 21st Century and become more reliant on space-based systems, we have found that a variety of technologies are impacted by space weather. The affected technologies are found in all key industrial sectors. Examples of those impacted technologies, the source events for space weather effects, their symptoms, and the relevant NOAA space weather scale are listed in Table 1.

Classic examples of impacts from space weather on our technology that have led to game-changing innovations include the following events:

i. **March 13, 1989:** Hydro-Quebec transformer damage from ground-induced-current (GIC) that caused its power grid to go off line for 9 hours; this same storm caused GOES weather satellite communications to be interrupted with lost weather images, led to NASA's TDRS-1 communication satellite reporting over 250 anomalies, and induced unusually high pressure readings in a hydrogen fuel cell on the Space Shuttle Discovery; this storm spurred the current development of risk management efforts under the umbrellas of Federal Energy Regulatory Commission (FERC) and North American Electric

Table 1. Example technologies affected by space weather, space weather source, effects, and NOAA scale classification.

Technology	SpWx source	Effect	Scale
Aviation communication (commercial, business jet, and general aviation)	Solar flares & CMEs	Loss of high frequency radio signal for communications	R & G
Aviation health and safety (commercial and business jet)	SEPs	Increased radiation dose for human tissue and avionics	S
Aviation navigation (commercial, business jet, and general aviation)	Solar flares & CMEs	Loss of GPS position accuracy for plane en-route and loss of WAAS landing aid	R & G
Cell phones (connectivity)	Radio bursts	Interference with cell phone signals due to high energy solar radio bursts	–
Institutional facilities (hospitals, government, large data centers, banking, ERS)	CMEs	Power loss from electric grid outages	G
Oil & gas exploration (field ops)	CMEs	Drill bit misalignment using magnetic field; oil pipeline damage from GIC	G
Power grid (regional networks)	CMEs	Transformer loss from GIC surges	G
Radio communications (DoD, corporate fleet, Hams, ERS)	Solar flares, CMEs, & scintillation	Loss of HD/UHF/L-band radio signal for communications; D-region absorption	R & G
Satellite operations (LEO, MEO, GEO)	SEPs, solar flares & CMEs	LEO orbit error from drag; GEO spacecraft charging; SEUs and latch-up	S & G
Surveying (mega sites, roadways, field operations)	CMEs	Loss of GPS position accuracy	G
Transportation navigation (shipping, corporate fleet, ocean, rail)	Solar flares, CMEs, & scintillation	Loss of GPS position accuracy	R & G

Reliability Corporation (NERC) to warn the power industry of impending GIC surges, which are analogous to terrorism threats [NAP, 2008; 2012a];

ii. **March 23–24, 1991:** Loss of 200 satellites from the NORAD catalog due to atmospheric drag caused by large solar flares and geomagnetic storms; these events led directly to the USAF Space Command's initiative to improve operational thermospheric density uncertainty to much less than 10% with the creation of the High Accuracy Satellite Drag Model (HASDM) and the Jacchia-Bowman 2008 (JB2008) model [Bowman, et al., 2008a; 2008b; Tobiska, et al., 2008];

iii. **October 29-30, 2003:** The "Halloween" ionospheric storms of 2003 created the first recorded instance where the FAA's Wide Area Augmentation System (WAAS) might have transmitted hazardously misleading information to WAAS users. Although no accidents were reported, the highly localized ionospheric surges created by the storm revealed the WAAS algorithms to be inadequate in the case of the largest geomagnetic disturbances. The WAAS algorithms were subsequently revised at great expense to prevent future lapses;

iv. **September 7, 2005:** During a Hurricane Katrina recovery effort, an X17 solar flare caused HF radio communications between emergency responder helicopters and off-shore support ships to be lost for up to six hours; this communication failure led to the Space Environment Technologies (SET) and Space Environment Corporation (SEC) Communication Alert and Prediction System (CAPS) at the URL http://sol.spacenvironment.net/~ionops/index_ionops_caps.html for improving HF communication signal strength availability. CAPS was followed by the establishment of the Utah State University (USU) Space Weather Center (SWC) (http://spaceweather.usu.edu) with Utah's Federal ARRA funds, leading to its commercial spinoff, called Q-up for leveraging USU's Global Assimilation of Ionospheric Measurements (GAIM) ionosphere model for commercial applications;

v. **November 10, 2008:** NigComSat1, the commercial Nigerian communication satellite, failed due to >300 keV elevated energetic electron flux levels at GEO with a daily fluence of 2×1012 electrons cm^{-2} day-1; this event led to the establishment of Space Environment Technologies real-time GEO Alert and Prediction System (GAPS) for specifying the real-time and forecast surface and internal charging environment at GEO while utilizing data-driven statistical models from legacy studies; and

vi. **December 6, 2006:** A solar radio burst that was 10 times more intense than any previously recorded, temporarily disabled many GPS receivers on the sunlit side of the Earth, and affecting L-band GPS accuracies and cell phone reception. This led to the improvement of GPS sensors and resulted in Atmospheric & Space Technology Research Associates' CASES GPS receiver design that is more robust to such outages.

2b. Living With a Changing Star

The LWS program enters a new decade as the sun now exhibits behavior never observed before in the space age. The anomalous behavior observed over the last 5 years begs the question of what is in store. The changing state of the sun raises fundamental questions about the origin of solar transients and creates new opportunities to test our understanding of these transients in coronal conditions never before observed. Below we show how the anomalous behavior of the sun creates conditions throughout the interplanetary medium that differ from conditions ever observed in our solar system. The impacts of this new behavior have far reaching impacts for the solar wind, coronal mass ejections, solar flares, galactic cosmic rays, transient flows, co-rotating interactions regions, heliospheric boundaries and the host of interactions mediated by the magnetosphere, ionosphere, thermosphere, mesosphere, and atmosphere at Earth, at all planets and bodies including moons, comets, asteroids and dust. The complex interacting system that spans from the solar atmosphere through the solar system and out into the local interstellar medium is changing in ways never before observed. It is more critical than ever before to improve our understanding of the far ranging impacts of space weather hazards, radiation and interactions in geospace and planetary systems throughout our solar system. Connecting these diverse systems to astrophysical behavior observed at other stars and planets addresses new fundamental questions concerning astrophysical space weather and its impacts on habitability in these remarkable systems.

The deep solar minimum between cycles 23 and 24 and the activity in cycle 24 differed significantly from those of the prior cycle (Schwadron et al., 2011; McComas et al., 2013). In the solar minimum, the fast wind was slightly slower, it was significantly less dense and cooler, had lower mass and momentum fluxes (McComas et al., 2008), and had weaker heliospheric magnetic fields (Smith et al., 2008). During the rise of activity in cycle 24 the mass flux of solar wind remained low, (McComas et al., 2013b) and the magnetic flux of the heliosphere remained at significantly lower levels than observed at previous solar maxima in the space age (Smith et al., 2013). The current “mini” solar maximum of cycle 24 has shown only a small recovery in particle and magnetic fluxes. Therefore, the cycle 24 mini solar maximum continues to display the same trends as observed in the cycle 23-24 minimum. In fact, conditions during the cycle 23-24 minimum appear to be similar to conditions at the beginning of the 1800’s at the start of the Dalton Minimum (Goelzer et al., 2013). Taken together, these recent changes suggest that the next solar minimum may continue to show declining sunspot numbers, associated with declining values of magnetic flux and further reductions in solar wind particle flux.

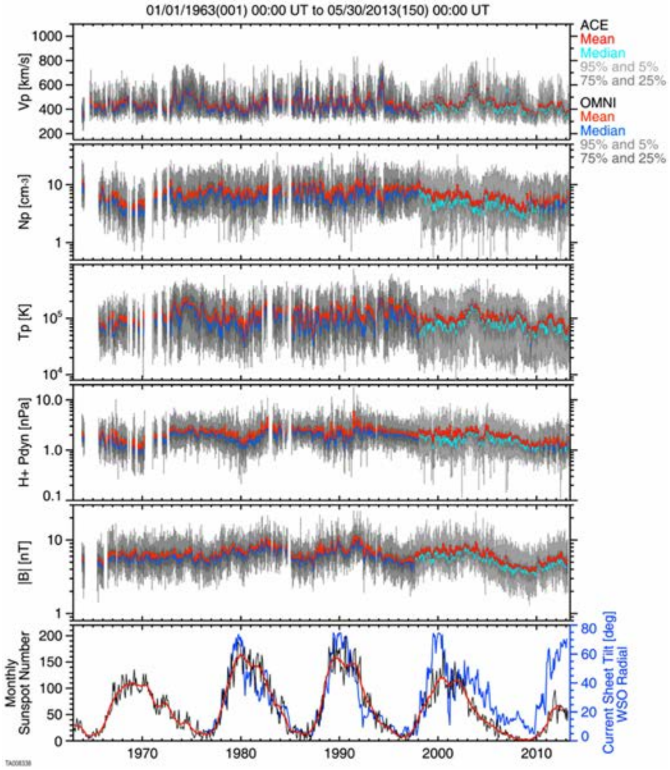


Figure 1. [From McComas et al., 2013] Solar wind parameters in the ecliptic plane at ~1 AU (a-e), taken largely from IMP-8, Wind, and ACE and inter-calibrated through OMNI-2. Means (red), medians (blue), 25%-75% ranges (dark grey), and 5%-95% ranges (light grey) are shown for complete solar rotations from 1974 through the first quarter of 2013. Panel f shows the monthly (black) and smooths (red) sunspot numbers and the current sheet tilt derived from the WSO radial model.

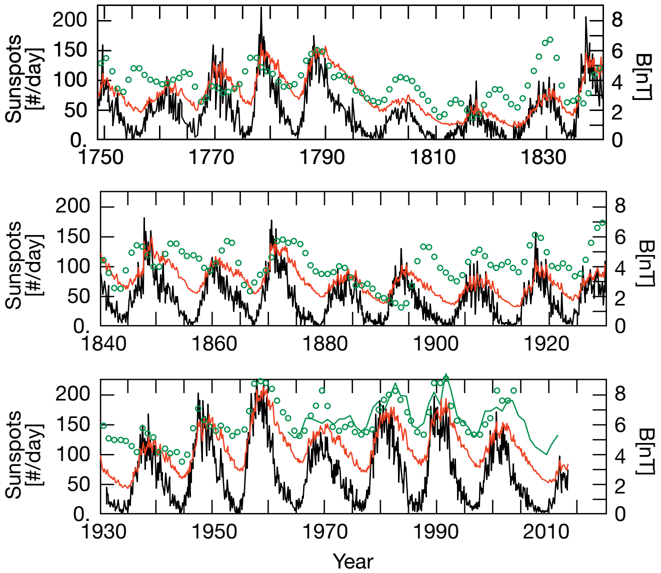


Figure 2. [From Goelzer et al., 2013] (black) Plot of monthly average sunspot number SSN from 1749 to the present. (red) Corresponding predicted Parker component of the HMF intensity at 1AU using theory and parameters in paper. (green circles) Yearly average value of |B| derived from Be10 data. (green curve) Measured yearly averages of |B| as determined by Smith et al. (2013) from the Omni2 data.

The anomalously weak heliospheric magnetic field and low solar wind flux during the last solar minimum have resulted in galactic cosmic rays (GCRs) achieving the highest flux levels observed in the space age (Mewaldt et al., 2010), and fluxes continue to be unusually elevated through the cycle 24 maximum. It is unknown if the recent anomalous deep solar minimum hints at larger changes in the near future, or if the unusual changes in GCR fluxes and conditions on the sun have an impact on Earth’s atmosphere. Given the fact that GCR radiation can damage living tissue, causing cellular mutagenesis, the changing state of the sun may have long-term implications for life on the planet. Figure 3 illustrates the critical growing record of the CRaTER dose rate throughout the LRO mission that quantifies the changing conditions and radiation hazards posed by GCRs and SEPs. Pronounced discrete SEP events punctuate the underlying trend of diminishing long-term GCR doses.

Does the recent anomalous deep solar minimum hint at larger changes in store? As GCR fluxes and the conditions of the sun change, we are forced to ask fundamental questions about the effects on our atmosphere, and the implications for life on the planet.

GCRs not only present a hazard to life through the breakdown of DNA, but also may help to stimulate evolution by increasing the rate of cell mutation [Todd, 1994]. In other words, the radiation environment of the Earth and planets, which is largely defined by the intensity and composition of GCRs in the solar system, may play a fundamental role in the formation and evolution of life. Similarly, as we begin our search for life elsewhere in the cosmos, particularly on planets surrounding other stars, we must also investigate the interstellar boundaries surrounding these stellar systems, and the effects these interstellar boundaries have on the cosmic rays within these systems. GCRs may also affect life in indirect ways through climate variability [Shaviv and Veizer, 2003], although this relationship remains highly controversial.

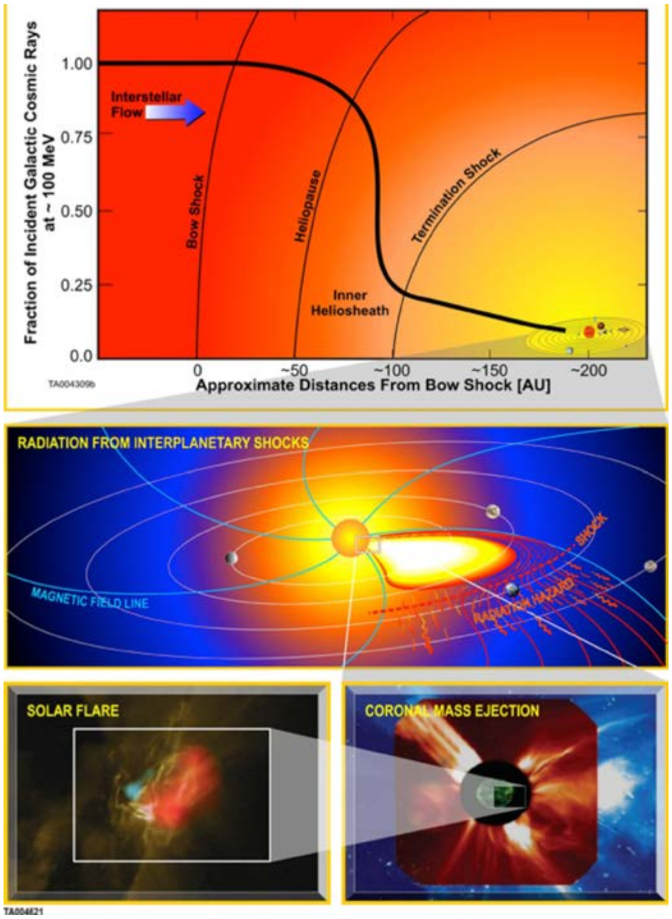


Figure 3. [From Schwadron et al., EMMREM special section, Space Weather, 2010] The hazards posed by particle radiation in space pose a serious challenge to human and robotic exploration missions to the Moon, Mars and beyond. The hazards include the following: (1) Galactic cosmic rays (GCRs), which are always present in the near Earth space environment and through- out the solar system, originate from beyond our heliosphere and produce chronic but not acute exposures. GCRs are very difficult to shield against beyond the Earth's protective atmosphere and magnetosphere. (2) Solar energetic particle (SEP) events (which we define to include ions; also solar particle events (SPEs)) are also dangerous to astronauts outside of Earth's protective layers (the atmosphere and magnetosphere). Current research in this area focuses on developing the ability to predict when and where SEP events will occur and finding ways to adequately shield against SEP-associated particle radiation. (3) There are unique radiation environments at each planet and their satellites. We have thoroughly characterized the locations of the radiation belts at Earth, which allows us to reduce the hazard they pose by rapidly transiting them. Human and robotic exploration of other planets and satellites requires that we adequately characterize planetary radiation environments and develop appropriate mitigation strategies and adequate shielding. Shielding is often considered the solution to space radiation hazards. Very high-energy radiation (e.g., >100 MeV), however, produces secondary penetrating particles such as neutrons and nuclear fragments in shielding material. Some types of shielding material may actually increase the radiation hazard. The radiation hazard is not sufficiently well characterized to determine if long missions outside of low-Earth orbit can be accomplished with acceptable risk.

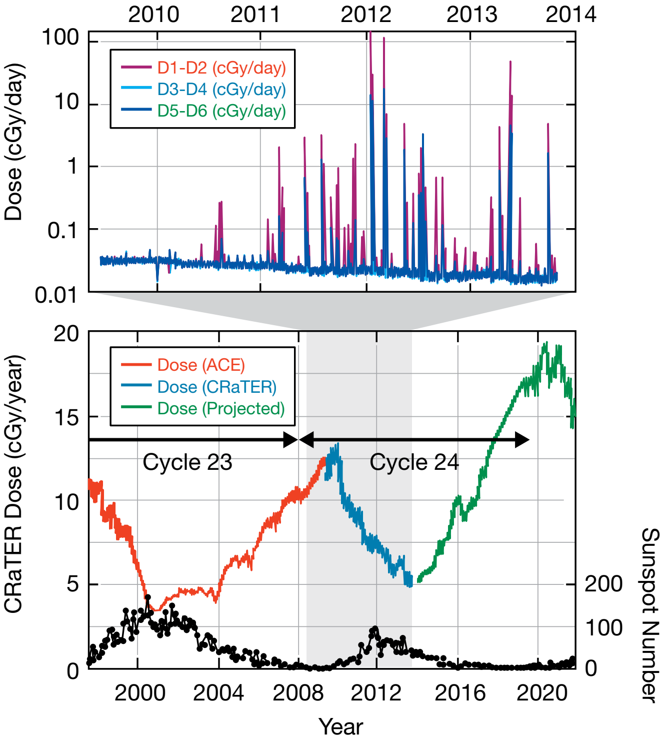


Figure 4. [Adapted from Schwadron et al., Space Weather, 12, 622, 2014] Dose rates over time quantify radiation hazards that damage tissue, and materials.

The sun evolves on all time scales from seconds through billions of years. The solar cycle has an approximately 11 year period in the transition from solar minimum to maximum and back to minimum. During solar maximum, the sun becomes magnetically violent with greater numbers of active regions and often associated sunspots with intense magnetic fields. As its powerful active magnetic fields reconfigure, the sun erupts mass and energy forming Coronal Mass Ejections (CMEs) and solar flares. By comparison, the solar minimum sun is magnetically quiet, generating fewer CMEs and less frequent flares. CMEs drag out magnetic flux from the sun, which leads to the temporary buildup of magnetic flux in the heliosphere during solar maximum when CMEs are more frequent [Owens and Crooker, 2006; Schwadron et al., 2010]. The more intense heliospheric magnetic fields near solar maximum inhibit GCRs from entering the heliosphere, although our understanding of the heliosheath and its shielding of GCRs remains uncertain.

While occurring since the dawn of the space age, the recent changes in the space environment are not at all surprising in the context of long-term trends deduced from sunspot records, chemical markers (Nitrate) in ice cores, ancient tree trunks (14C), and ice sheets or ocean sediments in the case of 10Be. For example, the Maunder Minimum was a prolonged solar minimum for the period roughly spanning 1645 to 1715 when sunspots became exceedingly rare. The Maunder Minimum coincided with the coldest part of the Little Ice Age, during which Europe and North America experienced very cold winters.

McCracken et al. [2007] studied the long-term changes in the cosmic ray intensity at Earth using an intercalibrated record (the ''pseudo-Climax neutron monitor record'') for the interval 1428–2005 (Figure 2). The residual cosmic ray modulation was low throughout the Gleissberg cycle 1540–1645, considerably higher for the next two Gleissberg Cycles, and highest of all since 1944. The cosmogenic data imply that solar activity was anomalously low throughout the whole interval 1428–1715. The amplitude of the solar activity during the Gleissberg cycle 1540–1645 was only ~50% of that during the following two Gleissberg cycles and ~25% of that in the post-1954 era. The weakening magnetic fields observed in the recent deep solar minimum appear a paltry reduction compared to very large reductions in interplanetary field strengths during the Spoerer and Maunder minima (Figure 5, bottom).

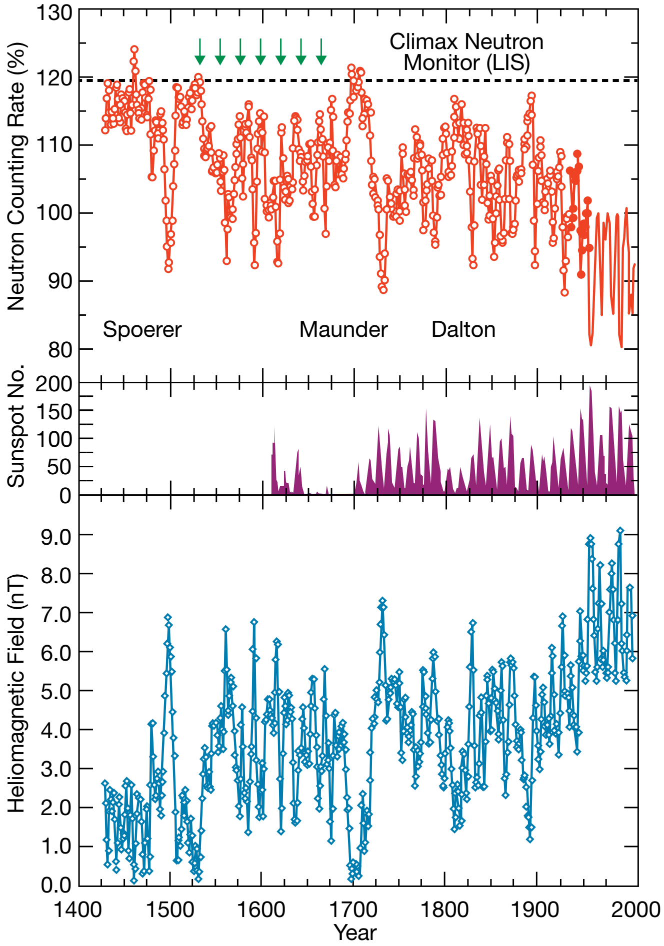


Figure 5. [From McCracken et al., 2007] The observed and pseudo-Climax neutron counting rate (derived from 10Be data) and the international sunspot number. The annual 10Be data (1428–1930) have been averaged prior to plotting; the other data are annual averages. The line CNM(LIS) is the estimated value of the pseudo-Climax counting rate in the absence of any solar modulation. The arrows between 1533 and 1686 are at 22-year intervals and demonstrate that the cosmic radiation was under solar control throughout this interval. The effects of the long-term change in the geomagnetic dipole, and the production of 10Be by solar cosmic rays, have been removed from these data.

2c. Space Weather – Swings Between Extremes

A Washington Post, July 18, 2013 article began “On a … September night in 1859, campers out in Colorado were roused from sleep by a ‘light so bright that one could easily read common print,’ … At the time, it was a dazzling display of nature. Yet if the same thing happened today, it would be an utter catastrophe.” The light was due to an aurora triggered by the so-called “Carrington Event,” when the sun hurled a huge CME, an ejection of plasma driving a massive shock wave, directly at the Earth. This “triggered an especially fierce geomagnetic storm that lit up the sky and frazzled communication wires around the world.” If a solar storm on the scale of Carrington Event occurred today, it could wreak havoc on power grids, pipelines and satellites, leaving possibly 20 to 40 million people in the Northeast without power—possibly for significant periods of time—as utilities tried to replace thousands of fried transformers stretching from Washington to Boston. That a similar event could happen again is no fantasy, reflecting instead a sober assessment by the insurance broker Lloyd’s of London. The much smaller geomagnetic storm of 1989 left 6 million people in Quebec without power for 9 hours. These are the impacts of Space Weather, an emerging science that embraces solar and space physics, electrical and software engineering, bioscience, economics and policy, materials science, computer science and simulations, health science, aerospace manufacturing, guidance systems, etc.

The importance of Space Weather on the Nation’s economy and security was captured in an April 2013 White House report “Space Weather Observing Systems: Current Capabilities and Requirements for the Next Decade.” The Report called for “a robust capability to monitor, model, and predict what is happening in the space environment.” The National Space Weather Strategy articulates six high-level goals for Federal research, development, deployment, operations, coordination, and engagement:

1. Establish benchmarks for space weather events;
2. Enhance response and recovery capabilities;
3. Improve protection and mitigation efforts;
4. Improve assessment, modeling, and prediction of impacts on critical infrastructure;
5. Improve space weather services through advancing understanding and forecasting; and
6. Increase international cooperation.

As discussed here and in the previous subsection, there really is no time during the solar cycle when the space environment is safe. Solar maximum is a period of abrupt explosive events. Coronal mass ejections impact and disrupt the magnetosphere and Solar Energetic Particle (SEP) events present radiation hazards to humans in space and to electronic equipment. During quiet periods near solar minimum, the weaker magnetic fields of the heliosphere allow much higher levels of GCR radiation, causing increased long-term radiation hazards for astronauts and raising the probability of single-event upsets for electronic equipment in space.

Solar minimum and maximum are opposite extremes of a great stellar rhythm. Solar activity never stops; it just changes form as the pendulum swings. To visualize this, Guhathakurta and Philips [2013] turn the solar cycle sideways (Figure 6). In the graphic, sunspot counts are plotted horizontally instead of vertically. Large sunspot numbers are on the right, small sunspot numbers are on the left. This rotated framework erases the concept of Solar Min and Solar Max, and replaces it with a terrestrial analog: La Niña and El Niño.

La Niña and El Niño are opposite extremes of a great Pacific oscillation. Every 2–7 years, when surface waters across the equatorial Pacific Ocean warm up (El Niño) and then cool down again (La Niña). Meteorologists struggle with a misunderstanding among some laypeople, who believe that El Niño brings wet, stormy weather, while La Niña brings a dry calm. In fact, each condition has its own distinct regional effects that are, like the extremes of the solar cycle, varied and complex. In southern California, for instance, El Niño years can bring heavy winter rainfall and floods; across the country, the very same El Niño pattern keeps New England warm and dry. In Ecuador and Peru, El Niño delivers good weather for farming. Fishermen hate it though, because their catch plummets at the same time that crop yields soar. On the other side of the Pacific, Australia experiences El Niño as a time of drought and wildfires—the exact opposite of the southern California imprint.

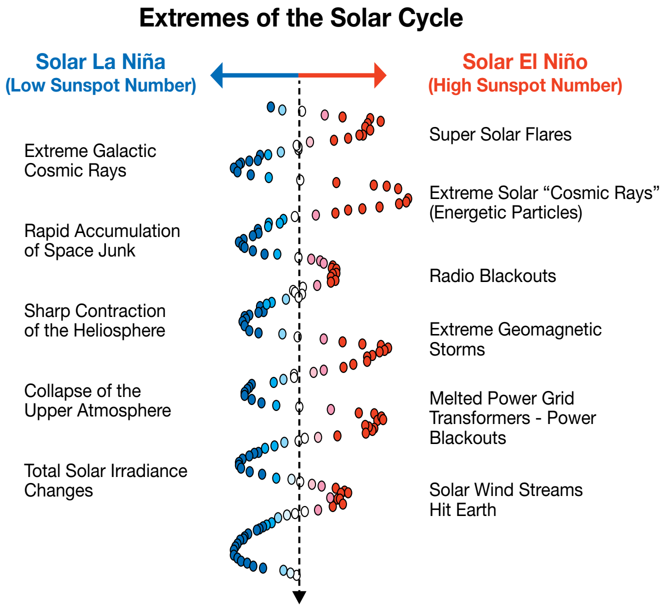


Figure 6. [From Guhathakurta and Phillips, 2013] Illustration shows smoothed monthly sunspot counts from the past six solar cycles plotted horizontally instead of vertically. High sunspot numbers are in red and on the right, low sunspot numbers are in blue and on the left. Associated with each high and low sunspot numbers are different space weather impacts experienced at Earth.

The solar cycle could be entering a phase with a stronger-than-usual "La Niña" character. Following a century-level solar minimum during 2008–2009, Solar Cycle 24 has risen up—but only enough to become the weakest cycle in more than 50 years. Total solar irradiance, which always experiences an uptick around Solar Max, increased only half as much as in the three previous cycles, while UV/EUV irradiances (key drivers of space weather) were up only 50%–70%. These low numbers are not indicators of "quiet," however. As the solar cycle turned sideways shows, solar variability always has the potential to have a major impact on Earth and humanity.

What will the sun do next? Is it possible that a grand minimum like a Maunder or Spoerer minimum is approaching? Large changes may not occur in the next decade, but history suggests that the interplanetary environment over the next 100 years will behave quite differently than it did over the past 50 years. What conditions will be encountered in the local galactic environment? How will changing cosmic ray fluxes and solar conditions affect Earth's atmosphere and life on the planet? These compelling questions, both basic and profound, remain and need to be answered.

Chapter 3

Assessment of the Existing Program

The first decade of the LWS TR&T program, now known as LWS Science, was highly successful. The program significantly contributed to our improved understanding of the physical processes controlling space weather and it also provided high-quality community tools through the Strategic Capabilities initiative.

The LWS community is extremely enthusiastic about LWS Science and its Focused Science Topic (FST) team concept for organizing research. A recent community survey conducted by the assessment committee led by Glenn Mason in 2012 showed that 75% of the respondents agreed that the "FST team concept aided creation of interdisciplinary collaboration" and two-third of the responders agreed that the "FST team led to advancement of science beyond the individual proposals." There were very few negative comments about the program.

Here we address progress made in achieving the Strategic Goals established for the LWS Program.

LWS Science Strategic Goals:

Strategic Goal 1	Deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars, and throughout the solar system.
Strategic Goal 2	Deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales.
Strategic Goal 3	Deliver the understanding and modeling required for effective forecasting/specification of magnetospheric radiation and plasma environments.
Strategic Goal 4	Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below.

Strategic Goal 1	Deliver the understanding and modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars, and throughout the solar system.

Progress on Understanding the Solar Wind

Developing robust models for how the heliospheric magnetic field and plasma connect to the sun's corona and photosphere is a central requirement for achieving this goal. For much of the heliosphere, this connection appears to be clearly established. It is now generally accepted that coronal holes are the sources of quasi-steady wind that exhibits a fairly constant velocity and plasma composition, and is generally fast (>500 km/s). However, the connection to the sun of the slow (<500 km/s) non-steady wind is far from understood and has long been a major problem in Heliophysics. The slow wind is especially important to LWS, because it is frequently found near the ecliptic plane and, therefore, is the wind that encompasses the Earth and other planets.

The past decade has seen great progress in understanding both the properties of the slow wind and its sources at the sun. The LWS Science program greatly contributed to this progress. Here is an incomplete list of contributions made by LWS Science supported projects:

1. Pseudostreamers are playing a critical role in the origins of the slow wind. In coronagraph images, pseudostreamers appear similar to the usual streamers that extend out to form the heliospheric current sheet, except that the field does not change sign across a pseudostreamer, and the field becomes open at lower radii than is usual for streamers. Substantial progress on understanding how pseudostreamers lead to the slow wind has been made in the 2009 FST on the slow wind.
2. Solar wind composition observations have led to a new theory for the source of the slow wind, the so-called S-Web model. In fact, this model was strongly influenced by a desire to understand the basic features and predictions of the Fisk model of large-scale reconfiguration of the coronal magnetic field through "interchange reconnection," and was developed directly as a result of the 2004 FST.
3. In addition to the work on the sources of the slow wind, there have been substantial advances on understanding the fundamental heating and acceleration of the quasi-steady fast wind as well. A consensus has developed among solar wind theorists that the basic process involves a non-linear cascade of Alfven wave energy flowing up from below, but the basic dissipation process is still under debate.
4. Numerical models for the quasi-steady solar wind have also made enormous progress in accuracy and sophistication during the past decade. Several 3D MHD models have been delivered to the CCMC and are now being used widely to calculate the 3D structure of the inner heliosphere. These models are especially important to missions such as STEREO and MESSENGER and all the MARS missions that are making observations far from the sun-Earth line.

Progress on Understanding the Coronal Mass Ejection – Interplanetary CME Connection

In the past decade there has been great progress in observing and modeling CMEs, shocks, and Solar Energetic Particles, or SEPs from solar eruptions. SOHO/STEREO/SDO observations of the initiation, propagation, and subsequent evolution of CMEs into interplanetary space have provided the means by which to compare theory and modeling advances. Uncertainties in forecasting CME Earth-arrival times have been significantly reduced by using STEREO observations more than 1 day in advance.

The success of simulations in reproducing many of these observations testifies to the maturity of scientific understanding of these space weather events. However, even though it is now possible to predict where on the sun a CME will originate, it is not yet possible to predict its timing, speed, energy, or momentum, nor is there a good scientific understanding of how a CME converts so much of its energy into particle radiation.

A number of LWS Science FST's have attacked various aspects of these specific problems. The combination of observations and modeling have led to significant improvements in predicting the arrival time of interplanetary shocks and CMEs at Earth, but the ability to predict other geoeffective properties (particularly, the direction and magnitude of Bz) remains a challenge. Validation for inner heliosphere models, SEP generation and transport mechanisms, as well as new strategies for observations are needed to take advantage of the novel space assets that will be available later this decade with the LWS Solar Orbiter and Solar Probe Plus missions.

Progress in Understanding Solar Energetic Particles

New observations of SEPs yielded a number of surprises. Solar-cycle 23 produced sixteen ground-level events in ground-based neutron monitors, which allowed us to establish that most large SEP events have a recent, preceding CME from the same solar active region. This indicates that the most intense events may involve the acceleration of particles in one or more flares that produce a seed population of energetic ions that can then reach very high energy through classical "diffusive shock acceleration" at the CME driven shock. The measured enrichments by ACE of 3He and Fe in many large SEP events are consistent with this picture. Continuing observations from STEREO, ACE and other platforms as well as upcoming Solar Orbiter and Solar Probe Plus missions will provide key measurements in the source regions of these events and their spatial extent and evolution so that the complex dynamics of SEP acceleration and transport to the geospace environment can be unraveled.

The most common SEP events are small "impulsive" events associated with coronal jets that are enriched in 3He and heavy ions up to $Z \approx 80$ by amounts that depend on mass:charge ratios. ACE and SOHO observations indicate substantially higher Fe charge states than ambient values, most likely because of electron stripping during acceleration in the low corona. 3He and Fe are also enriched in many large SEP events; this indicates that remnant suprathermal particles from previous impulsive flares are an important source of seed particles for CME-shock acceleration.

Several LWS FSTs were targeted to study the mechanisms responsible for these newly observed SEP features. One compared simulation results obtained from coupling two distinct SEP models with the MHD CME model outputs with SEP particle time-intensity profiles and energy spectra observed at ACE. The results were promising and reasonable for understanding the physics of shock acceleration in the inner heliosphere. Another compared the energy content of the SEPs with the energy content of the associated CMEs and found that the acceleration efficiency was could reach surprisingly high values of 10-20%. Another team studied the mixing of particles accelerated in flare loops with the population seed in interplanetary space and showed that the often observed enrichment of Fe in SEP onsets was most usually due to interplanetary transport effects. The widely varying intensity of SEPs associated with interplanetary shocks was found to often be related to the prior passage of CMEs, which had the effect of raising interplanetary turbulence levels and seed populations. While no teams focused on impulsive events by themselves, their frequent occurrence was used to trace active region sources of solar wind observed at 1 AU.

Progress in Understanding Shocks in the Corona and Interplanetary Medium

We outline here advances in understanding the source of solar energetic particles supported by the LWS FST team. It is interesting that in reviewing focus topics, the question of shocks in the interplanetary medium and corona have been studied with particular focus on the effects of the shocks for the acceleration of solar energetic particles, but not on the formation and evolution of the shocks themselves.

Understanding large SEP events is central to space weather and space climate. Large SEP events observed at Earth are accelerated near the sun and in the heliosphere by shocks associated with interplanetary CMEs, known as ICMEs. However, direct comparisons between observations, models, and theories have been scarce. The FSTs have culminated into studies of shock acceleration of energetic-particles, their propagation, and the evolution of CMEs in the heliosphere. One of the critical aspects developed in these studies is the importance of self-consistent wave generation upstream of CME-driven shocks, which is critical for preventing energetic particles from leaving the acceleration region near the shock. Indeed, the conditions of generating strong wave enhancements may be one of the most critical factors that differentiates large, prompt SEP events from lower energy, less dangerous events.

FSTs have added significant observational and theoretical support for the now widely accepted view that the largest SEP events are caused by CME-driven shocks. Observationally, the efficiency of particle acceleration by shocks is found to be highly variable. A 2004 statistical study showed that CMEs that erupt soon after a previous CME from the same active region are much more efficient in accelerating particles than those erupting into a pristine environment. Evidently, once a large eruption occurs, coronal and interplanetary properties play a key role, along with CME properties, in determining how intense the SEP event will be. This could be due to a stronger turbulence level or a larger population of seed particles at the second shock; other suggested explanations include differences in the open and closed field-line geometry, or a lowering of the Alfven velocity, leading to the formation of a stronger shock. Among the additional factors that likely affect acceleration and transport efficiency are shock geometry, global IMF structure, connection longitude, proton-amplified Alfven waves, and streaming limits.

Progress in Understanding Solar UV – X-Ray Radiation

Integral to achieving Strategic Goal 1 are the FSTs dedicated to understanding the variance and physical origins of the sun's UV and X-ray emission over a broad range of spatial and temporal scales. This includes understanding both localized UV and X-ray emissions during flares as well as global irradiance variations associated with active region magnetic fields.

Of direct relevance to Strategic Goal 1 is the 2006 team dedicated to the topic "Solar Origins of Irradiance Variations." The team made substantial progress toward the goal of understanding physical mechanisms that cause variations in solar UV, EUV, and soft X-ray emissions. They used models of varying degrees of sophistication to synthesize radiative output of the chromosphere, transition region, and corona over a variety of spatial scales. These theoretical investigations were carried out in conjunction with observational studies to advance our understanding of the nature of the heating, and its dependence on observable quantities (such as total unsigned magnetic flux at the solar photosphere). Collaboration between research groups produced new physics-based models of active regions and the global transition region and corona, and new semi-empirical models of the chromosphere and transition region. Significant scientific results published by the team include: (1) A determination of the relationship between solar spectral irradiance and total unsigned magnetic flux, and (2) A comparison of numerical simulations with imaging and spectral data that suggests coronal heating may be linked to highly impulsive, non-thermal sources (possibly concentrated close to the sun's visible surface). The latter results in particular can be considered a product of the LWS FST team concept. Collaborations between groups facilitated new scientific interactions between observers and different modeling groups. In this case, the team concept encouraged researchers to use distinctly different types of numerical models to address a single, focused scientific problem.

An example of how the LWS FST team concept facilitates successful collaboration between groups that may not have organically evolved is the 2007 team on "Exploring the Magnetic Connection Between the Photosphere and Corona." This FST team supported multiple efforts aimed at improving the capability to model the magnetic evolution and thermodynamic properties of solar corona necessary to characterize atmospheric emission. One such effort included the development of (1) radiative-magnetohydrodynamic simulations of solar active regions driven by the observed evolution of magnetic fields at the visible surface, and (2) inversion techniques to determine the electric field from observed changes in the photospheric vector magnetic field. A second effort within this FST team focused on the development of an idealized numerical model capable of characterizing the emergence and evolution of active-region magnetic fields over much longer time scales than is possible with an MHD code. Both of these projects required that streams of photospheric data be incorporated into a 3D dynamic model of the solar atmosphere at active region spatial scales. Again, in this case, the LWS FST team concept facilitated new collaborations that led to improved techniques for using data to drive physics-based models of the structure and evolution of the solar corona overlying active regions.

Strategic Goal 2	Deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales.

LWS Science Progress in Solar Spectral Irradiance

The LWS funded UV irradiance composites are daily-averaged spectra over the wavelength range 120-400 nm, 1 nm sampling, covering the time period from 8 Nov. 1978 to 1 Aug. 2005. This data set was created from SME, Nimbus-7 SBUV, NOAA-9 SBUV/2, NOAA-11 SBUV/2, UARS SUSIM, and UARS SOLSTICE measurements.

Three LWS FST teams studied the solar causes of irradiance variations. The achievements from the first team include: hot plasma from coronal nanoflares was discovered using X-ray observations from Hinode; new physics-based models of active regions and the global sun were constructed; new semi-empirical models of the chromosphere and transition region matched the observed non-LTE irradiance spectrum; the relationship between SSI and total unsigned magnetic flux, including a temporal delay component, was derived; discovery that TSI and probably SSI depend on sunspot type, not simply area; MDI magnetogram zero point and E/W asymmetry were calibrated; coronal loops were explained by storms of nanoflares; and integrated coronal and chromospheric models were developed.

The second FST team began in 2008 with the aim "to characterize the properties of the solar dynamo that determine the strength of the solar activity cycle and its terrestrial consequences (e.g., through irradiance changes and geomagnetic effects)." The team made progress in discriminating between and improve dynamo models, improving measurements of critical subsurface flows, clarifying the connections between dynamo operation and the properties of the active regions that give rise to terrestrial effects, and improving understanding of what aspect of dynamo action gives rise to eruptive regions.

The primary focus of the third FST team was "to explore the origins of, and decipher the evolution of solar magnetic activity over multiple time scales ranging from centuries to stellar and planetary evolutionary time scales" and "to produce accurate predictions for the sun's surface magnetic fields" that regulate the variations in the total solar irradiance.

Another important cross-disciplinary activity funded by the LWS program is to improve solar models and our understanding of spectral solar variability. For example, the Solar Radiation Physical Model (SRPM) has been developed over several years and provides the necessary physical basis for calculating high-resolution spectra and their variations directly from solar theory and analysis of solar images. Using ground-based images of the solar disk and a set of models with active- and quiet-sun features, the sources of the UV, visible, and IR spectral irradiance variations observed by SIM are being explored. Further studies are underway to investigate visible and infrared variations in the SSI, and to improve modeling of the MUV and FUV spectral regions, where large non-LTE effects play an important role in solar emissions. The extension and improvement of these studies over the full rise and decay of a solar cycle is needed for understanding the physics of the solar atmosphere in originating the observed SSI variations. This physical insight can guide much more reliable analyses of historical records and future expectations.

Progress on impacts of solar spectral irradiance variations

Impacts of solar spectral irradiance variations range from the effects of solar extreme ultraviolet (EUV) radiation on composition, ionization, and density in the thermosphere and ionosphere to effects of mid-UV radiation in the lower mesosphere and stratosphere. The LWS program supported a number of investigations of upper atmospheric responses to magnetospheric and solar variability, including EUV variability. This work led to improved first-principles thermosphere-ionosphere models that accurately calculate the response to solar EUV flux variations, magnetic activity level, and orientation of the interplanetary magnetic field. In addition, variations of thermospheric density and composition in response to changing concentrations of greenhouse gases were investigated.

Specific accomplishments included the development of more accurate and efficient methods for using solar spectral irradiance measurements or models to calculate dissociation rates and ionization throughout the upper atmosphere. These are necessary inputs for global time-dependent general circulation models (GCMs) of the thermosphere and ionosphere that are computationally economical. One modeling effort described the dynamical behavior of the upper mesosphere and lower thermosphere at the time of the major sudden stratospheric warming (SSW) of 2009. It found that the lunar and solar migrating semidiurnal tides, which modulate the ionospheric plasma, were significantly enhanced following the peak of the 2009 SSW. Inclusion of the lunar tide, in particular, was therefore found to dramatically improve the ability of GCMs to reproduce the observed ionospheric response to a SSW. Finally, long-term changes of thermospheric neutral density estimated using a combination of satellite drag measurements and upper atmospheric GCMs have been shown to be a consequence of secular changes in the concentration of greenhouse gases, thereby allowing better predictions of long-term density changes under solar maximum and minimum conditions.

Support was also provided for investigations of the stratospheric response to mid-UV variations and resulting effects on stratospheric circulation. One series of studies led to a better characterization of the observed solar cycle variation of minor species (especially ozone) and the expected response of ozone to different proposed models for the solar cycle change in UV spectral irradiance. Specific accomplishments included an improved estimation of the solar cycle change in ozone based on three independent long-term satellite data records. During the relatively strong solar cycles 21, 22, and 23 (~1975-2008), results show a positive (3-4%) response in the upper stratosphere, a negligible response in the tropical middle stratosphere, and a second positive (2-3%) response in the lower stratosphere from solar minimum to maximum. Solar cycle 24 has a greatly reduced maximum and may produce a correspondingly smaller ozone variation. Evidence for a positive solar cycle variation of the hydroxyl radical (OH) column amount in the stratosphere and mesosphere was also obtained from a combined analysis of ground-based and satellite measurements since 1997. Odd hydrogen radicals such as OH are important for ozone catalytic losses in the stratosphere and mesosphere. The amplitude of the variation (7 to 10% from solar minimum to maximum) is larger than expected based on current middle atmospheric chemistry models and presently accepted proxy-based reconstructions of 11-year solar UV variability.

A number of LWS-supported investigations have also addressed the extent to which direct solar UV forcing of the upper stratosphere can impact circulation in the lower stratosphere and troposphere. The importance of this ``top-down'' forcing is dependent on solar-induced changes in the propagation and absorption of planetary-scale Rossby waves that propagate from the troposphere into the stratosphere during winter-spring. Westward momentum deposited by these waves when they are absorbed slows the prevailing westerly zonal wind and induces a poleward meridional circulation (the Brewer-Dobson circulation; BDC). Reductions in the strength of the BDC near solar maxima result in less tropical upwelling that may be responsible for observed ozone and temperature increases in the tropical lower stratosphere from solar minimum to maximum. Interactions between these waves and the mean zonal flow can also potentially amplify an initial weak zonal wind perturbation in the subtropical upper stratosphere as it propagates poleward and downward.

One series of studies focused on how solar-induced changes in ozone and radiative heating in the upper stratosphere can alter the easterly and westerly phases of the quasi-biennial wind oscillation (QBO) in the equatorial lower stratosphere. Using a two-dimensional model with parameterized chemistry and a realistic semi-annual wind oscillation in the upper stratosphere, it was found that the duration of the westerly QBO phase at solar maximum is 3 months shorter than at solar minimum, which is qualitatively similar to some observational results. It was also found that a model simulation including imposed solar UV variations, the modeled QBO, and an imposed 11-year variation in planetary wave 1 amplitude produces a lower stratospheric ozone response of ~2.5% in the southern subtropics and an upper stratospheric ozone response of ~1% between 45 and 55 km, in good agreement with satellite observations. Another series of studies demonstrated the importance of zonally asymmetric ozone (ZAO) in modifying the shape of the Northern Hemisphere planetary waveguide during winter. In particular, ZAO was found to significantly alter the flux of planetary wave activity into the polar vortex compared to simulations that include only zonally symmetric ozone. This implies that GCMs should fully account for ZAO in order to accurately model wave-driven circulations (e.g., the BDC) that may be modulated by the 11-year solar cycle.

Finally, several LWS-funded investigations have examined the extent to which stratospheric top-down forcing could have a detectable impact on tropospheric circulation. In one study, the surface climate response to 11-year solar forcing in the Pacific sector during northern winter estimated using ~130 years of sea level pressure and sea surface temperature data was compared to simulations using an atmosphere-ocean GCM with a fully resolved stratosphere. The simulations differed only in the assumed solar cycle variation of stratospheric ozone. The model results were sensitive to the assumed ozone variation and the simulation that assumed a variation consistent with that estimated from satellite data produced the best agreement with the observationally estimated response. This result supports a role for top-down forcing of the tropospheric circulation response, at least during northern winter in the Pacific sector. However, other studies using shorter (~50 years) reanalysis meteorological data records have found a spatial pattern for the solar cycle tropospheric temperature response that is more consistent with a "bottom-up'' forcing from the small (<0.1%) 11-year change in total solar irradiance. Consequently, the relative importance of top-down and bottom-up forcing of relatively weak circulation changes in the troposphere is not yet established.

Progress on understanding energetic-particle variability

In 2001, the LWS program started supporting studies aimed at the physics of solar energetic particle (SEP) acceleration processes, as well as their transport and evolution from their source regions into and through geospace, and ultimately some making their way into Earth's upper atmosphere. In each year since 2001, through the current implementation of the program, LWS has typically made approximately five awards on average dealing with some aspect of SEPs, that in the end informs us about some aspect of their variability. Early in the program, awards tended to be strongly focused on a single aspect. Over time, the awards built on previous studies and advancements and tended to be more comprehensive in some way (whether through combining theory with observations, or considering multiple processes, etc.).

More recently, studies are even more integrative, for instance, studying not just the microphysics of the acceleration, but also recognizing the key role of suprathermal seed populations, as well as the means of particle transport from the source regions to their final destination and how that influences the resultant spectrum and intensity. In other words, studies have evolved to more and more consider the phenomenon as part of a coupled sun-heliosphere-Earth system. This has been facilitated by the formation of FST teams aimed at coordinating related efforts in order to make them more impactful than the mere accumulation of progress from uncoordinated, discipline-specific individual studies. This evolution is due to the combination of improved understanding of SEP mechanisms and their impacts, and to changes in the structure and emphasis of the NASA LWS research announcements and the review process that have both fostered and then awarded projects with broader scope and perspectives.

LWS investigations have made progress, simultaneously, in related areas needed to advance our understanding ideally to the point of predictability. First, we have made substantial progress in determining how the sudden release of magnetic energy powers both flares and CMEs and have discovered how these processes accelerate charged particles very efficiently and rapidly to high energies. Competing theories are being refined through the remarkable observational advancements made in the past decade. The sudden release of magnetic energy starts in very small regions where kinetic physics typically dominate, however, consequences of the magnetic energy release quickly evolve to extend over larger scale sizes well into the fluid domain. Numerical studies have shown how charged particles can tap the electric fields associated with these cross-scale evolving structures and be accelerated through a wide variety of ways, ranging from wave-particle interactions to shock acceleration mechanisms.

Progress on understanding galactic cosmic ray variability

Progress has also been made on understanding the modulation of galactic cosmic ray (GCR) variability due to controlling factors internal to the solar system and through the support of the LWS program. Theoretical studies and numerical simulations, both 2D and 3D, of cosmic ray transport through the heliosphere have explored and begun to quantify the various solar-related factors that control GCR variability. These include the large scale interplanetary magnetic field and its structure, the open magnetic flux in the heliosphere and its distribution, the strength of the magnetic field, as well as the effects of transient magnetic structures of solar origin (interplanetary coronal mass ejections and global merged interaction regions). Comparison of observations with simulation studies suggest that important elements of how particles propagate within the heliosphere are not fully accounted for in current theories. Such studies also point to a majority of GCR modulation occurring far from the sun, perhaps in the heliosheath, where magnetic structuring is most favorable to control GCR access.

Other studies have begun exploring the consequences of GCR intensities and energy spectral properties on astronomical time scales owing to differences between the early sun compared to its present state. Owing to differences in fundamental solar properties (rotation rate, etc.), studies have explored, using MHD models and models for GCR transport, how GCR intensities near Earth are sensitive to the latitude position of sunspots and their magnetic field strength, the strength of the large-scale solar magnetic field, and the solar wind ram pressure. There is growing consensus that GCR intensities at the early Earth were substantially lower than today (by up to two orders of magnitude), the result of a faster solar rotation rate and a tighter Parker spiral everywhere, but especially in the outer heliosphere.

Forces external to our solar system also operate on astronomical time scales to modulate the GCRs we see at Earth. MHD and GCR transport models have also shown how spatial structuring in the interstellar medium pressure can lead to dramatic dilations and contractions of the heliosphere as the solar system moves in its orbit through the galaxy and traverses regions of higher and lower interstellar material. Studies suggest that these variations, too, could produce order of magnitude changes in the GCR intensity at Earth, both higher and lower than at present, and occurring on time scales of millions of years.

Progress on understanding impacts of energetic particles on climate

Solar particles, galactic cosmic rays, and geomagnetically trapped particles are included in the definition of energetic precipitating particles (EPP), which can influence climate. It is believed that there are three primary mechanisms whereby EPPs could cause climatic changes:

1) ***Lower energy EPPs, such as auroral electrons, produce nitrogen oxides (NOx) in the polar thermosphere***
   This NOx can be transported (predominantly during winter) through the mesosphere and into the stratosphere, leading to the destruction of high-latitude stratospheric ozone on time scales of weeks to months. The magnitude of this lower-energy EPP-caused change on stratospheric ozone varies dramatically from one year to another and is currently being studied. Members of the LWS FST team on Thermospheric Density and Composition have addressed auroral particle precipitation issues including the seasonal dependence of the energy input, the lower latitude variation of the input, and the Joule heating of the input. Some

work by other LWS investigators has led to a better computation of the electron impact ionization for auroral electrons. This work on the thermosphere and the ionization by auroral electrons will likely lead to a better understanding of NOx formation from these lower energy particles in the future. LWS investigators have included auroral electrons in a global general circulation model (GCM), which had a domain from the Earth's surface to the thermosphere. Also, there has been a good effort in analysis of measurements from at least five satellites (UARS, SCISAT-1, Envisat, POAM II and III) regarding this issue. Certain years (e.g., 2004, 2006, and 2009) have shown some descent of NOx from the lower thermosphere to the upper stratosphere. Only 2004, however, showed significant ozone depletion from this NOx source.

2) ***Medium-energy and higher-energy EPPs, such as solar protons, medium-energy and high-energy electrons, and galactic cosmic rays (GCRs), produce hydrogen oxides (HOx) and nitrogen oxides (NOx) at polar latitude.***
This can lead to a change in atmospheric ozone. The polar mesospheric and stratospheric HOx-caused ozone loss is rather short-lived (days) due to the relatively short lifetime (hours) of the HOx constituents, whereas the NOx-caused ozone loss is on a longer time scale of weeks to months. Ozone increases in the lower stratosphere may result from the interference of NOx constituents with chlorine- and bromine-containing gases. Ozone increases in the troposphere may result from the reaction of enhanced levels of NOx constituents with volatile organic compounds (VOCs), i.e. smog-type reactions. The impact of solar protons on the middle atmosphere (stratosphere and mesosphere) is relatively well understood and quantified. In contrast, the effects of medium-energy and high-energy electrons and GCRs on the atmosphere still need to be reliably computed and validated. LWS investigators also quantified the impact of solar proton events (SPEs) on the middle atmosphere over short (days) to long (years) time scales with a GCM. These GCM results were compared with satellite measurements, whenever possible. Significant polar mesospheric ozone depletion >30% over a few days resulted from large SPEs (~15-20 in the past fifty years), which occurred sporadically near solar maximum. Although polar stratospheric ozone depletions >10% were computed to last for up to 5 months past the few largest SPEs in the past fifty years, the calculated annually averaged temperature and total ozone change were not found to be statistically significant. Using a NASA satellite (EOS Aura), a group of European scientists found that precipitating medium energy electrons enhanced the polar mesospheric hydroxyl radical, OH, in the sub-auroral region (55o -65o geomagnetic latitude). There did not appear to be a measurable ozone response over the same geographic region. Research by LWS investigators has led to a better computation of the electron impact ionization for medium and high-energy electrons.

3) ***The highest-energy EPPs, primarily galactic cosmic rays (GCRs), produce ionization in the atmosphere that may impact cloud cover***
These cloud-cover changes may result either from modified aerosol nucleation rates or an impact on precipitation through changes in the near-cloud electrification. The magnitude of this highest-energy EPP-caused change on clouds is controversial and needs further investigation. LWS investigators in an ongoing study have found a relatively large sensitivity of cloud forcing to nucleation processes. This research suggests that a GCR-caused variation in ionization and, therefore, nucleation rate, may have significant consequences for the cloud cover over solar cycle time-scales. Future work is needed to quantify the GCR/cloud cover link.

The LWS Science program has sponsored several Coordinated Data Analysis Workshops (CDAWs), which have brought together researchers in somewhat different disciplines to investigate particular topics of heliophysical importance. Among those of interest to the climate community include the "Solar Energetic Particles: Solar and Geospace Connections CDAW," held in 2002, and the "CDAW on Ground Level Enhancement (GLE) Events," held in 2009. In particular, the CDAW in 2009 brought together climate and extremely high-energy solar proton flux investigators. As a result of this CDAW, the highest-energy solar protons (300-20,000 MeV), not normally included in model computations, were incorporated into global model calculations for the largest GLE in solar cycle 23.

Strategic Goal 3	Deliver the understanding and modeling required for effective forecasting/specification of magnetospheric radiation and plasma environments.

Global dynamics, controlled by changes in the north-south component of the interplanetary magnetic field (IMF)

The global dynamics of the magnetosphere is dominantly controlled by the north-south component of the interplanetary magnetic field (IMF), which is variable in space and time, and drives global circulation in the magnetosphere. Changes in the IMF and solar wind dynamic pressure produce storms and substorms, auroral brightenings, and local as well as global convection patterns in the magnetosphere and the ionosphere. Sophisticated global imaging, supported by global simulations, have identified heretofore invisible plasma populations of the magnetosphere, the drastic changes in the configuration of the plasmasphere and the ionospheric density enhancements under the influence of powerful storms. These and other observational features have been the subject of FSTs in 2005, 2006, 2007, and 2009. The LWS Strategic Capability (SC) has led to global magnetosphere models that couple several physical domains including the global and inner magnetosphere, the radiation belts, the plasmasphere, and ionospheric electrodynamics. Some of these models have demonstrated the capability to model the strongest storms. In particular, it has been demonstrated that the magnetospheric ring current is substantially enhanced during storms, altering the magnetic field at the Earth's surface significantly. Global images as well as numerical simulations exhibit strong asymmetries during the main phase of storms, suggestive of strong coupling to the ionosphere.

Wave-particle interactions in the radiation belts

Wave-particle interactions have been established as the principal drivers of particle energy gain and loss in the radiation belts, which have been the subject of two FST investigations in 2010 and 2012. Greater understanding of the theory of plasma micro-instabilities, simulations, and spacecraft observations demonstrate that the local acceleration of radiation belt electrons due to wave-particle interactions can dominate due to diffusive radial transport. Time-dependent models of the radiation belts and the ring current show that storm-time particle dynamics are the result of a balance between acceleration and loss of relativistic particles mediated by wave-particle interactions due to plasma instabilities.

Role of ionosphere-magnetosphere coupling on ionospheric outflows

There have been major advancements in the understanding of conditions leading to the flux of ionospheric plasma to high altitudes and into the magnetosphere. Solar wind density and dynamic pressure increases lead to enhanced ionospheric outflows, which also correlate well with electromagnetic energy flux into the ionosphere. Intense ionospheric ion outflows occur due to a combination of local heating by waves and external forcing. It has been demonstrated that ionospheric outflow has dramatic consequences on the dynamic evolution of the magnetosphere. Outflows merge with plasmas of solar wind origin in the plasma sheet, creating a multi-species plasma that alters the dynamics of magnetic reconnection. Multi-fluid global simulations confirmed the major role ionospheric outflow plays in the creation of sawtooth intervals.

Major new understanding of collisionless magnetic reconnection in the context of the Earth's magnetospheric plasma environment

In situ probing by multiple satellites and sophisticated computer simulations have elucidated collisionless mechanisms and triggers of fast reconnection (mediated by the Hall current and electron pressure tensor in a generalized Ohm's law), particle energization and production of fast and bursty bulk flows. These studies have pointed to the necessity of integrating kinetic effects in global MHD codes, which has been the subject of a LWS 2008 FST.

Strategic Goal 4	Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation, and to coupling above and below.

Ionosphere:

1) Modeling the longitudinal variation in the post-sunset far-ultraviolet OI airglow using the SAMI2 model

Recent global-scale observations of the low-latitude airglow bands associated with the equatorial ionospheric anomaly (EIA) have revealed a longitudinal variation in the brightness and latitude of the peak airglow emission. The simulation showed that changes at all local time periods make a significant contribution to the total change in the airglow, with the most significant being close to local noon and during the late afternoon.

2) Storm time signatures of the ionospheric zonal ion drift at middle latitudes and its relationship with particle precipitation

Using a quantitative identification of convection and particle boundaries at high latitudes, the relative extent of auroral convection and auroral precipitation was examined during superstorm events. During superstorms the convection reversal boundary normally located near 75 magnetic latitude moves to magnetic latitudes near 60. The edge of the diffuse auroral precipitation that normally terminates near 60 magnetic latitude moves to magnetic latitudes near 40. This limited study shows that during the main phase of the superstorm ion drifts driven by the magnetosphere penetrate to latitudes as low as the dip equator on the dusk side but extend only a few degrees equatorward of the auroral zone on the dawn side. Evidence for ion drifts driven by a disturbance dynamo may be found during the storm recovery phase when the interplanetary magnetic field is less strongly southward or turns northward, but the previously established flows below the auroral region remain.

3) Atomic and molecular ion dynamics during equatorial spread F

The first simulation study of atomic and molecular ion dynamics during equatorial spread F (ESF) was carried out with LWS Science support. The simulation results are based on the SAMI3/ESF 3D code. The key findings are the following: (1) a 'super fountain' effect can occur in the initial stage of ESF with upward ion velocities ~1 km/s, (2) plasma depletions can be enhanced by the 'drainage' of H+ ions along the geomagnetic field, and (3) molecular ions (e.g., NO+) can be 'lifted' to high altitudes (~400 km). Satellite observations support these results.

4) Ion and electron temperature evolution during equatorial spread F

The first simulation study of ion (O+ and H+) and electron temperature evolution during equatorial spread F (ESF) was presented. The simulation results are based on the SAMI3/ESF 3D code. It is found that the ions and electrons undergo both cooling and heating during bubble evolution. The main cause of cooling is adiabatic, associated with the increase of the flux tube volume as the plasma bubble rises. Ion heating is primarily caused by the compression of ions as they stream down the converging magnetic field. The electrons are heated by collisional coupling with the ions. Additionally, it is found that the electrons are heated at high altitudes (>1200 km) because of thermal conduction, and that hydrogen ions can be heated at relatively low altitudes (~300 km) because of ion-neutral frictional heating. The simulation results are consistent with observations from the ROCSAT and Hinotori satellites.

5) Formation of a plasma depletion shell in the equatorial ionosphere

An accurate description of the irregularity region defined by a plasma bubble is critically important in understanding the dynamics of the region and its effects on radio scintillation. LWS supported-research describes a plasma depletion region as a ''depletion shell'' and shows how two-dimensional optical images from space can be used to define the shape of the depletion shell. A simple model calculation demonstrates that the space-based optical observation can detect the plasma-depleted magnetic flux tubes only near the F-peak height. The backward C-shape in bubble images from optical observations is the trace of the plasma depletion shell near the F-peak height. The westward tilt of bubbles at the magnetic equator can also be explained by this shell structure. The *in situ* measurement of the ion velocity at night in the topside shows the decrease of the eastward plasma drift with an increase of latitude. The formation of the plasma depletion shell is consistent with the latitudinal/altitudinal shear in the zonal plasma flow.

6) Neutral wind effect in producing a storm time ionospheric additional layer in the equatorial ionization anomaly region

A new type of the additional layer is predicted to occur in the low-latitude F region ionosphere during evening hours of a major magnetic storm. By using the coupled TIEGCM and SUPIM runs during the major magnetic storm of 29–30 October 2003, researchers presented a new type of additional layer which occurs at the equatorial ionization anomaly (EIA) by a new physical mechanism. This mechanism requires that storm time meridional neutral wind surges travel from high to low latitudes and cross into the opposite hemisphere. The wind surges modify the field-aligned plasma velocities in the EIA regions significantly after uplift of the ionospheric layer by a penetration electric field and interact with the downward field-aligned plasma velocities of the enhanced equatorial fountain. The combined storm effects of the enhanced plasma fountain and the neutral wind surges result in plasma convergence in altitude and form the additional layers underneath the EIA crests.

7) The effect of electric fields on the ionospheric F-layer

The generation and re-distribution of plasma in the ionosphere during major storms are dramatic phenomena with large deleterious impacts on critical communication and navigation systems. The changes in the ionosphere are induced by the imposition of electric fields from the magnetosphere, modified by the changed ionospheric conductivity. Research demonstrates different phenomena occurring during ionospheric F-region storms that in principle might be caused by electric fields and identifies challenges that must be faced when considering the physical processes at work. The transport of plasma across many degrees of latitude at sub-auroral latitudes, the origin of patches of so called "storm enhanced density" at high mid-latitudes, and the very high reported heights of the F2 peak at low latitudes have been considered. The role that electric fields might play in changing locally the net production of ionization as well as transporting it was examined. Analysis suggests that the local change in ionization production should be considered as a more important process for producing plasma density enhancements than transport from a more remote source of enhanced density.

Thermosphere:

1) Thermospheric global average density trends, 1967-2007

Emmert et al. (2008a) used orbit data on ~5000 near-Earth space objects to investigate long-term trends in thermospheric total mass density, which has been predicted to decrease with time due to increasing CO2 concentrations. They refined and extended to 2007 previous density trend estimates, and investigated solar cycle-dependent bias in empirical density models previously used to filter out solar irradiance effects. They found that the bias is caused in part by the solar cycle dependence of the long-term trends, and they developed a new representation of solar cycle, seasonal, and geomagnetic activity effects. At 400 km, they estimated an overall trend of –2.68 ± 0.49% per decade and trends of ~–5% and –2% per decade at solar minimum and maximum, respectively, in fair quantitative agreement with theoretical predictions. The global average density trends also depend on the phase of the year, with the strongest trends around October and weak trends in January.

2) Seasonal variation of thermospheric density and composition

Qian et al. (2008) investigated the causes of seasonal variations in thermospheric neutral density and composition, which exhibit maximum densities near the equinoxes, a primary minimum during northern hemisphere summer, and a secondary minimum during southern hemisphere summer. These patterns of variation are described by thermospheric empirical models; however, the mechanisms are not well understood. The annual insolation variation due to the sun-Earth distance can cause an annual variation; large-scale inter-hemispheric circulation can cause a global semiannual variation; and geomagnetic activity can also have a small contribution to the semiannual amplitude. However, simulations by the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) indicate that these seasonal effects do not fully account for the observed annual/semiannual amplitude, primarily due to the lack of a minimum during northern hemisphere summer. A candidate for causing this variation is change in composition, driven by eddy mixing in the mesopause region. Other observations and model studies suggest that eddy diffusion in the mesopause region has a strong seasonal variation, with eddy diffusion larger during solstices than equinoxes, and stronger turbulence in summer than in winter. Qian et al. determined a seasonal variation of eddy diffusion that is compatible with this description. Simulations showed that when this function is imposed at the lower boundary of the TIE-GCM, neutral density variation consistent with satellite drag data, and O/N2 consistent with measurements by TIMED/GUVI, is obtained. These model-data comparisons and analyses indicate that transmission of turbulent mixing from the lower atmosphere may contribute to seasonal variation in the thermosphere, particularly the asymmetry between solstices that cannot be explained by other mechanisms.

3) The thermospheric semiannual density response to solar EUV heating

Bowman et al. (2008) characterized the thermospheric semiannual density response to solar heating during the last 35 years. Historical radar observational data were processed with special orbit perturbations on 28 satellites with perigee heights ranging from 200 to 1100 km. Approximately 225,000 very accurate average daily density values at perigee were obtained for all satellites using orbit energy dissipation rates. The semiannual variation was found to be extremely variable from year-to-year. The magnitude of the maximum yearly difference, from the July minimum to the October maximum, was used to characterize the yearly semiannual variability. It was found that this maximum difference can vary by as much as 100% from one year to the next. A high correlation was found between this maximum difference and solar EUV data. The semiannual variation for each year was characterized based on analyses of annual and semiannual cycles, using Fourier analysis, and equations were developed to characterize this yearly variability. The use of new solar indices in the EUV and FUV wavelengths was shown to very accurately describe the semiannual July minimum phase shifting and the variations in the observed yearly semiannual amplitude.

4) ***Analysis of thermospheric response to magnetospheric inputs***

Deng et al. (2008) investigated the influence of the high-latitude energy inputs and heating distributions on the global thermosphere by coupling a new empirical model of the Poynting flux with the NCAR-TIEGCM. First, in order to show the contribution of the electric field variability to the energy input and thermospheric temperature, model results were compared for simulations where Joule heating is calculated with the average electric field (called "simple Joule heating") and where Joule heating is adjusted according to the Poynting flux from the empirical model. In the northern (summer) hemisphere, the Poynting flux has a peak in the dayside cusp, which is missing in the altitude-integrated simple Joule heating. The hemispheric integral of the Poynting flux is approximately 30% larger than the integral of simple Joule heating, and the polar average (poleward of 400) temperature calculated with the Poynting flux increases by 85-95 K, which is more than 50% of the temperature increase caused by the polar energy inputs. Second, three different methods to distribute the Poynting flux in altitude were investigated. Different heating distributions cause a difference in the polar average of heating per unit mass as high as 40% at 160 km altitude. Consequently, the difference of the polar average temperature among these three cases is close to 30-50 K. These results suggest that not only the total amount of energy input, but the way that the energy is distributed in altitude is significant to the impact of the magnetosphere on the thermosphere and ionosphere.

5) ***Effects of high-latitude ionospheric electric field variability on global thermospheric Joule heating and mechanical energy transfer rate***

Matsuo and Richmond (2008) investigated the effects of high-latitude ionospheric electric field variability on Joule heating and the mechanical energy transfer rate to the thermosphere by incorporating realistic spatial and temporal characteristics of electric field variability derived from observations into the forcing of the NCAR Thermosphere Ionosphere Electrodynamic General Circulation Model (TIEGCM). They first examined the characteristics of subgrid-scale variability from a spectral analysis of Dynamics Explorer-2 (DE-2) plasma drift measurements. The analysis revealed that the subgrid-scale electric field varies with magnetic latitude, magnetic local time, interplanetary magnetic field (IMF), and season in a manner distinct from that of the resolved-scale electric field and of the climatological electric field. The subgrid-scale electric field varies strongly with season, and its magnitude averaged over the polar region does not depend on the interplanetary magnetic field (IMF). On the other hand, the resolved-scale electric field depends less on season but more on the IMF. Matsuo and Richmond characterized the spatial-temporal structure of resolved-scale electric fields from various electromagnetic observations taken during the storm period of January 10-11, 1997, using a space-time covariance model derived from the DE-2 observations. Using this characterization in the model showed that the amount of Joule heating and mechanical energy transfer rate in the thermosphere is significantly altered by taking into account the electric field variability and its space-time structure. Additional electromagnetic energy due to the electric field variability dissipates in the ionosphere almost exclusively as Joule heating if the variability has no spatial and temporal correlation. However, the spatially and temporally correlated electric field variability has seasonally dependent effects on the mechanical energy transfer rate.

6) ***Analysis of High-Latitude Force Balances***

The analysis of forces in model simulations gives insight into the physical mechanisms causing various phenomena. To understand better the dynamics of the high-latitude lower thermosphere in response to magnetospheric inputs, Young-Sil Kwak, Art Richmond, and Ray Roble analyzed the forces acting on the air as a function of altitude for different interplanetary magnetic field (IMF) orientations, using the TIE-GCM. They found that the balance among pressure-gradient, ion-drag, and centrifugal accelerations between 105 km and 200 km altitude varies significantly with IMF, and that the wind and density structures are closely coupled at high latitudes. Results are published in Kwak and Richmond [2007] and Kwak et al. [2007].

7) ***High latitude thermospheric density cell structure first discovered by Crowley et al (1989)***

Researchers showed for the first time that there is a strong relationship between the sign of the IMF BY component and the orientation of the cell structure with local time. Specifically, the cell pattern rotates to earlier local times as the BY changes from negative to positive. They also showed that the same rotation applies to the composition of the high latitude thermosphere. The TIMEGCM global first-principles model has been pushed to extremes of storm behavior by simulations of some of the largest storms of the past 10 years. We have used the high latitude electrodynamic inputs provided by AMIE for all of these runs, representing the most extensive use of AMIE to drive first principles models. The model simulations are generally improved substantially by using the AMIE fields to drive the model.

8) ***Analysis of density variations measured during geomagnetic storms***

The GRACE team validated thermospheric density estimates from the GRACE accelerometers. GRACE densities are in excellent agreement with densities from the limb remote-sensing data from the GUVI instrument on TIMED (provided by Bob Meier). Seven one-month intervals including some major storm periods have been simulated using the TIMEGCM, with high latitude inputs specified by the AMIE technique. The model reproduces many of the large-scale features measured by the satellites, including major density enhancements during storms, enabling explanation of these features. The effects of in-track winds have been shown to be generally on the order of <5%, and therefore, negligible.

Coupling With The Magnetosphere and Plasmasphere:

1) ***Regulation of solar wind–magnetosphere coupling by ionospheric outflows***

The ionosphere is a persistent source of outflowing plasma and essentially the only source of singly ionized oxygen in geospace. The presence of O+ in the magnetosphere-ionosphere convection cycle, among other effects, has the capacity to undermine the dayside-nightside balance of reconnection. This imbalance cannot persist. Either the nightside merging line must migrate earthward to enable a higher inflow of magnetic flux, or dayside merging must decrease on average. Which state ensues depends on the flux, velocity and location of the ionospheric outflow. How does it happen? First, exhaust flows from nightside reconnection, enriched with O+, enhance the ring current. The intensified, asymmetric ring current then inflates the flankside magnetosphere relative to the nose region. The dayside boundary is effectively blunted. The bow shock is forced to move away from the magnetopause, causing more of the upstream magnetic flux to be diverted around the magnetopause rather than piling-up and reconnecting in the subsolar region. Electromagnetic power flowing from the solar wind dynamo into geospace is reduced as dayside and nightside reconnection synchronize at a lower average rate. Convection and, thus, the cross-polar cap potential are also reduced, as is the flux of outflowing ionospheric ions, access of solar wind plasma to the inner magnetosphere, and the amplitude of magnetopause surface waves.

2) ***Magnetosphere sawtooth oscillations induced by ionospheric outflow***
The 2-5 hour planetary-scale oscillation of the geospace system known as the sawtooth mode was discovered in geostationary satellite data 20 years ago, yet its origins remain unknown. A breakthrough in understanding the phenomenon is emerging from multi-fluid simulations of the solar wind-magnetosphere-ionosphere (SW-M-I) interaction, which show that ionospheric O+ outflows can induce sawtooth oscillations for steady SW driving.

3) ***Confirmation of role and impact of enhanced SED ionization at F-region heights on cusp field lines in enhancing heavy ion injection into magnetotail***
Combined incoherent-scatter radar and TEC measurements were used to statistically quantify the role and impact of storm-enhanced density ionization at F-region heights in enhancing heavy ion injection into magnetotail on cusp field lines; upflow fluxes up to 1014 O+ ions/m2-s are observed in the cusp region, which are comparable to F-region convective fluxes in afternoon subauroral polarization streams that are swept westward to feed the region during storms.

4) ***Determination of the principal drivers of ionospheric outflows including the role of Alfvén waves***
Correlation studies based on FAST satellite data have provided new knowledge of the role of Alfvén waves, dc Poynting flux, electron precipitation and low-frequency turbulence in driving ionospheric outflows.

5) ***Development of "scaling law" representations of ionospheric outflows in terms of causal drivers, including electromagnetic power and electron precipitation characteristics***
Two first-principles models developed as part of the project provide two possible pathways for interpreting correlation as causation. A first principles fluid-kinetic model (DyFK) was used to demonstrate the efficacy of transverse ion-cyclotron heating followed by mirror-force lifting in producing observed outflow fluxes in the cusp-cleft region given observed, F-region convective fluxes into the cusp and in auroral outflow regions. This first-principles model was used to derive simple analytical scaling relations between O+ outflow flux, magnetic field-aligned dc Poynting flux flowing into the ionosphere, electron precipitating energy flux and ion-cyclotron wave intensities. A new ambipolar pickup mechanism was also developed and sample calculations based on a generalized "Jeans escape" to yield the scaling law between outflow flux and DC Poynting flux.

6) ***Determined how the plasmasheet distribution and composition change during a storm and for different solar wind drivers***
Determined changes in the state of the plasmasheet including ion composition over the course of a storm and how these changes influence the ring current and the boundary conditions used to drive ring current models

Coupling With the Lower Atmosphere

1) ***Analysis of Wave-Wave Interaction in the Whole Atmosphere Model (WAM) simulation of the January 2009 sudden stratospheric warming***
The recent simulation of the whole atmosphere response to the January 2009 sudden stratospheric warming (SSW) revealed an increase in the amplitude of the terdiurnal, westward propagating wave number 3 (TW3), apparently at the expense of the semidiurnal, westward propagating wave number two (SW2). The migrating SW2 and TW3 are major drivers of the E-region dynamo winds. The simulations were performed using the WDAS analysis system, which includes a whole atmosphere model (WAM) together with a modified version of the NCEP Gridpoint Statistical Interpolation (GSI) data analysis system. At the SSW peak time, TW3 attained a comparable magnitude to that of SW2, which is likely to have significant impact on the E-region dynamo and electrodynamics. The forecast experiments indicate the amplitudes of the main tidal modes can be forecast several days ahead indicating a possibility for a prediction of the electrodynamic and ionospheric response.

2) ***Studying the lunar tides and their impact on the ionosphere using WACCM/WACCMX/GIP***
Observations have shown lunar tides could be important for ionosphere variability, and can display large short-term variability (e.g., during stratospheric sudden warmings, SSW). Recently the M2 semi-diurnal lunar tide has been implemented in WACCM/WACCM-X model. The climatology and the latitudinal and seasonal variation of the M2 lunar tides are well reproduced in both the surface pressure and in the mesosphere and lower thermosphere. Ensemble WACCM simulations with the M2 tide included have clearly established an increase in its amplitude following SSW. Wind fields from a WACCM-X simulation of SSW including the M2 tide have been used to drive the Global Ionosphere and Plasmasphere (GIP) model to study the impact of lunar (as well as solar thermal) tides on the ionosphere electrodynamics. The simulated changes are consistent with observations.

3) ***Study of whole atmosphere teleconnections using SABER and WACCM***
Analysis of SABER temperature anomalies from the stratosphere to the lower thermosphere (15-110km) reveals a clear correlation pattern over the whole atmosphere during Northern Hemisphere winter. This pattern is robust and

does not depend on the occurrence of stratospheric sudden warmings (SSW), major or minor. This pattern, and its independence from SSW, is reproduced well in WACCM simulations. Analysis of WACCM simulations also indicates that these patterns are closely tied to anomalies in the circulation driven by planetary waves and gravity waves. The results are consistent with previous observational and modeling studies, and further show that the temperature responses near the summer mesopause to winter stratosphere changes vary on intra-seasonal and inter-annual scales.

Strategic Capabilities

The NASA LWS program and the NSF Geospace section jointly initiated a very ambitious program to develop physics-based global space weather models for science community use. Three strategic goals have been identified:

1. The need for a comprehensive, coupled, quantitative three-dimensional model for the outer magnetosphere, inner magnetosphere (plasmasphere, ring current, and radiation belts), and the ionosphere, including polar regions; and
2. The need for a three-dimensional time-dependent model of the solar corona and the ambient solar wind; and
3. The need for a predictive model for radiation exposure anywhere on the surface or in the atmosphere of Earth, on the Moon, on Mars, and in interplanetary space between Earth and Mars.

These goals were fully accomplished. Two LWS Science SC supported solar-heliosphere model suites (CORHEL/MAS/WSA/ENLIL and AWSOM) have been transitioned to CCMC and are routinely used by the research community. Two global magnetosphere model suites have been supported by LWS Science SC (OpenGGCM/CTIP and SWMF/BATS-R-US/RCM) and were used for several thousand runs by the community. In addition, SWMF is running real time at CCMC. The Earth-Mars radiation environment model (EMMREM) is also available at CCMC for community use and runs in real-time for PREDICCS (Predictions of radiation from REleASE, EMMREM, and Data Incorporating CRaTER, COSTEP, and other SEP measurement). PREDICCS is an on-line system to predict and forecast the radiation environment throughout interplanetary space (http://prediccs.sr.unh.edu).

Additional model developments (solar active region model, whole atmosphere model and solar irradiance model) were also supported by the LWS Science SC program. These models are still under development and are not yet available at the CCMC.

The above brief summaries clearly demonstrate the significant progress that LWS Science has made in our understanding of space weather and improving the capability to address impacts, such as predicting geomagnetic storms. The research clearly couples the traditionally separate subdisciplines in heliophysics, such as solar, heliospheric, and geospace physics to provide a connected system advancement. Additionally, the research demonstrates how results could enable operational capabilities.

Chapter 4

LWS Program Elements

The LWS program has built a remarkable foundation of strategic capabilities and focused science topics (FSTs). LWS is now in the position to leverage this past work for the development of predictive capabilities in key areas of LWS science. This leverage is critical in these times of challenging budgets to maximize the scientific "return on our investments."

As such, rather than concentrating on devising FSTs on separate science areas of Heliophysics, the LWS SC has formulated long-term targeted areas of System Science, requiring cross-disciplinary collaboration, for predictive development, termed "Strategic Science Areas (SSA)":

- ***SSA-0, Physics-based Forecasting of Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and Inputs to Earth's Atmosphere:*** The goal is a physics-based understanding that will enable forecast capabilities for the variability of solar magnetism, with a particular focus on a better understanding of the processes that drive the formation, interaction, and emergence of magnetic flux systems within the solar interior and their implications for the space environment and responses of Earth's atmosphere. Success measures will include the development and application of observationally constrained modeling efforts across the LWS discipline that lead to insights into, and therefore improved forecast capability for, solar-forced electromagnetic, energetic particle, and plasma drivers of the space environment and the Earth's atmospheric inputs across temporal scales from years to centuries.
- ***SSA-1, Physics-based Geomagnetic Forecasting Capability:*** The goal is to develop scientific capabilities that enable 1-3 day (long lead-time) and 15-30 min (short lead-time) predictions of pending extreme GIC events;
- ***SSA-2, Physics-based Satellite Drag Forecasting Capability:*** The goal is to enable specification of the global neutral density in the thermosphere and its variations over time by providing the capability to predict the densities that satellites in low Earth orbit will encounter with a lead-time of at least one hour as well as longer-term predictions. There should be quantifiable levels of uncertainty that are specified for different data conditions and levels of redundancy in data/models;
- ***SSA-3, Physics-based Solar Energetic Particle Forecasting Capability:*** The goal is develop scientific capabilities that enable probabilistic prediction of the intensity of SEP events, and increased time periods for all-clear forecasts with higher confidence level;
- ***SSA-4, Physics-based TEC Forecasting Capability:*** The goal is to derive a model, or coupled set of models, that enable specification of the global ion density in the topside ionosphere and plasmasphere and its variations over time under varying geomagnetic conditions. The model or coupled models should have the capability to predict the TEC observations globally, with a lead time of at least one hour (based on availability of real-time solar wind/IMF measurements), as well as longer-term predictions for up to three days based on solar wind forecasts;
- ***SSA-5, Physics-based Scintillation Forecasting Capability:*** The goal is the capability to predict scintillation occurrence utilizing limited sources of available data and ascertain how radio signals are degraded by ionospheric irregularities. Achieving this will require elucidation of the complete set of physical mechanisms responsible for producing ionospheric irregularities, the most important sources of free energy, and the causal chains that both generate and suppress irregularities leading to scintillations. We will develop the methods for maintaining signal lock when scintillations occur. The resulting "clean" radio signals would themselves be incisive diagnostics of ionospheric irregularities. We will fold radio signal information back into irregularity analysis and modeling.
- ***SSA-6, Physics-based Radiation Environment Forecasting Capability:*** The goal is science-based predictive capability for the radiation environment and its effective dose as well as dose rates based on GCR, SEP, cutoff rigidity, atmospheric density, and gamma-ray/X-ray inputs. Other success measures will include the development and application of new observational methods, both in situ and remote, that lead to new data sets for assimilation into models on global and regional scales, and new insights into the spatial/temporal scales of radiation storm variations that are affected by space weather.

An imperative in the development of SSA goals is making a stronger link between the LWS scientific community and user communities that can directly benefit from LWS strategic developments. The SSAs represent long-term goals of the LWS program that will be developed through Focused Science Topics, Strategic Capabilities and Targeted Science Teams. The FSTs/TSTs listed here were considered as opportune areas that both provide leverage for achieving the long-term goals of the SSAs and are uniquely positioned for rapid near-term progress.

Future FST, SC and TST teams should partner with members of key space weather centers (e.g., CCMC, NASA/SRAG, and NOAA/SWPC) to facilitate increased interaction with user communities and the creation of deliverables that best serve user needs. Upon selection of future FSTs, SCs and TSTs, relevant modeling centers should identify liaisons to appropriate user communities.

SSA-0, Physics-based Understanding to Enable Forecasting of Solar Electromagnetic, Energetic Particle, and Plasma Outputs Driving the Solar System Environment and Inputs to Earth's Atmosphere

Basic Science Components

Characterizing the properties of the solar convective interior remains a significant challenge and is needed in order to understand the response of the space environment and Earth's atmosphere. The properties of the solar interior are required as constraints for investigations of the solar magnetism that lie at the heart of our interaction with the sun. Largely masked from direct observation, the flows and feedbacks between the solar magnetic field and large-scale flows within the solar interior drive the persistent modulation of our star's electromagnetic, energetic particle, and plasma and includes eruptive output that in turn drives variability throughout the space environment and the upper terrestrial atmosphere.

The "unusual" temporal extension and depth of the 2009 solar minimum in addition to the episodic, but relatively subdued output of Solar Cycle 24, have underlined deficiencies in established theories. These conceptual roadblocks have placed a premium on observational investigations of solar interior structure and understanding large-scale evolutionary patterns visible in the historical data such as the "Torsional Oscillation" and even the "given" patterns of differential rotation, as well as meridional circulation.

At a time when solar activity may be in a significant, but gradual long-term decline, it is imperative for our community to develop stronger feedbacks between observation, remote sensing techniques, and modeling efforts of the solar interior to place stronger constraints on the latter. Enabling development of robust data-assimilation methodologies for forecasting the evolution of the system is needed. Such, well-constrained models can then be used to inform modeling and forecast activities of global solar activity across the international community.

We are seeking studies that will provide a science-based understanding and forecast capability for the variability of solar magnetism. We are especially encouraging studies that will focus on a better understanding of the physical processes that drive the formation, interaction, and emergence of magnetic flux systems in the convective solar interior across the timescales relevant to the variability of space climate.

Success measures will include the development and application of observationally constrained modeling efforts across the LWS discipline that lead to insights into, and therefore improved forecast capability for, solar drivers of the heliospheric system.

Models

- Observationally testable models of large-scale flows in the solar interior that relate to, and push advances in, observational techniques.
- Models of helioseismic signatures in and around the complex interfaces likely in the convective interior.
- Models of magnetic flux production in a rotating convective plasma with observationally testable outputs.
- Models of magnetic flux system interaction including the formation of complex active regions.
- Models of instabilities at the radiative–convective interface, tachocline, their detectability and their potential impacts on magnetic flux emergence and observational tests.

Observations

Interpretation of available datasets from the Solar Dynamics Observatory (SDO), Solar-Terrestrial Relations Observatory (STEREO), Hinode, Global Oscillation Network Group (GONG), Synoptic Optical Long-term Investigations of the Sun (SOLIS), and other space- and ground-based assets including long-term proxies of solar variability (e.g., Be10, and other proxies).

Products

- Outputs capable of reproducing the large scale flow patterns of solar activity and their variability over wide-ranging timescales (up to centuries).
- Models of the decadal, annual and monthly solar magnetic activity to be used as drivers for electromagnetic, energetic particle, plasma and eruptive models of the solar system environment.
- Records and proxies of radiative and energetic particle inputs into the terrestrial system.

Potential User Base

- NASA, DHS, DoD, DoE, FEMA, IPCC

Metrics and Assessment

- All statistical analyses need to also address the uncertainty in the estimates of magnetic variability and flow characteristics.
- Capability to estimate onset and magnitude of global flux emergence events: start time, end time and maximum amplitude of the event.

Types of Investigation

- Consolidation and conservation of historical synoptic observational records;
- Development of methods to discriminate between the presence of subsurface magnetic fields and thermal structures in the convective interior;
- Determination of the cellular, or multi-cellular, structure of the plasma flow fields at all depths and latitudes at and below the visible surface of the sun;
- Analyses revealing how the evolution of the flow field and magnetic environment of the solar poles can affect the dynamo and the solar activity cycle;
- Analysis across the spectrum of ground- and space-based platforms to exploit ancillary observations of the corona, solar wind, and heliospheric environment and help constrain the global evolution of the magnetized system;
- Development of methods to constrain and inform forecast models of solar activity on year to multi-decadal scales;
- Development of accurate historical records including proxies such as Be10 for solar activity.

Implementation Specifics

The groups that will carry out the investigations will have experience on space-based solar physics data sets, analyzed (possibly jointly) with ground-based data, and modeling of key phenomena in the solar interior. As the primary goal of the studies is enabling improved predictive capability of magnetic variability, both empirical and first-principles modeling of key physical phenomena are appropriate approaches. The types of appropriate investigations (see also above "Types of Investigations") include theoretical modeling analyses of key physical processes, data analyses and comprehensive statistical analyses will improve our capability to predict the timescales and range of variability in solar activity across the timescales relevant to space weather and space climate investigations.

SSA-1: Characterization and prediction of geomagnetically induced current (GIC) events.

Basic Science Components

Externally driven geomagnetic field fluctuations, or dB/dt, induce a geoelectric field on the surface of the Earth. The geoelectric field that is strongly dependent on, for example, local ground conductivity conditions drives geomagnetically induced currents (GIC) that can flow in power grids, pipelines and railway systems. Large dB/dt can also hamper geophysical exploration surveys.

One of the key and insufficiently understood issues of the GIC topic is how large regional dB/dt or GIC events can get during storm conditions. While moderate events can also have an impact, for example, via premature aging of transformers, in particular GIC during extreme storms conditions are of major current interest. Quantification of extreme GIC characteristics is the fundamental quantity that will feed into engineering analyses that will ultimately determine how vulnerable, for example, power grids are to space weather events. The question is very timely as FERC is in the process of generating standards that will eventually require power transmission system operators to carry out vulnerability assessments. These assessments cannot be carried out satisfactorily without the “extreme boundary conditions” provided by the space physics community.

Equally important is to have an enhanced capacity to predict the extreme events. We are seeking studies that will improve our capability to provide 1-3 day (long lead-time) and 15-30 min (short lead-time) predictions of pending extreme GIC events. Ultimately, new prediction systems need to be tailored for the needs of individual power grid operators, and consequently studies should address local or regional aspect of GIC.

We are seeking studies that will improve the characterization and prediction of extreme GIC events. We are especially encouraging studies that will quantify statistical occurrence and spatiotemporal characteristics of extreme GIC events and improve our capability to predict extreme GIC events. These activities also include possible studies of the theoretical maximum GIC that will provide a robust, upper boundary that can be used in further engineering analysis. Further, it is important that studies will address the local or regional aspect of dB/dt and GIC.

Predictive Goal

We are seeking studies that will improve our capability to provide 1-3 day (long lead-time) and 15-30 min (short lead-time) predictions of pending extreme GIC events.

Models

- Long lead-time predictions: i) models for coronal mass ejection (CME) eruption/generation, ii) models for transient propagation in the heliosphere. Models should target capturing both transient plasma and magnetic field evolution.
- Short lead-time predictions: i) models for magnetosphere, ii) models for ionosphere and upper atmosphere, iii) models for geomagnetic induction. Ultimately a systems approach coupling these different domains will be required.
- Statistical models quantifying occurrence, spatial distribution and temporal evolution of extreme GIC events.

Observations

- Coronal mass ejections in the outer corona. New capability to observe magnetic field structure of CMEs of major interest.
- Solar wind plasma and magnetic field conditions at 1 AU.
- Electric current systems in the magnetosphere and ionosphere.
- Ground magnetic field perturbations.

Products

- Extreme GIC event scenarios providing information about occurrence, spatial distribution and temporal evolution of GIC.
- 1-3 day lead-time GIC predictions.
- 15-30 min lead-time GIC predictions.

Potential Users of Products

- NERC, FERC, DHS, DoE, FEMA, high-voltage power transmission industry.

Metrics and Assessment

- All statistical analyses need to also address the uncertainty in the estimates.
- Capability to capture GIC events: start time, end time and maximum amplitude of the event. Prediction time windows will vary from days to minutes.
- Capability to capture events can be recorded in contingency tables that can be characterized using metrics such as probability of detection and probability of false detection.

Types of Investigations

- Statistical extreme value studies of GIC amplitudes, spatial distribution and temporal evolution.
- Studies of electric current dynamics in the solar wind-magnetosphere-ionosphere system.
- Studies of maximum theoretical rate of change of magnetosphere-ionosphere electric current system.
- Studies of CME magnetic field evolution during propagation from solar corona to 1 AU and interaction with the magnetosphere.
- Studies of CME sheath (e.g., turbulent magnetic field fluctuations) evolution during propagation from solar corona to 1 AU and interaction with the magnetosphere.

Implementation Specifics

The groups that will carry out the investigations will have experience on solar and space physics data sets, analyzed possibly jointly with ground-based data, and modeling of key space physical phenomena such as CME evolution in the interplanetary medium, solar wind-magnetosphere-ionosphere system and geomagnetic induction. As the primary goal of the studies is improved predictive capability, both empirical and first-principles modeling of key space physical phenomena are appropriate approaches. To address the extreme event analyses aspects of GIC phenomenon also groups with experience on statistical analyses of experimental data are encouraged to propose.

The types of appropriate investigations (see also above "Types of investigations") include theoretical modeling analyses of key solar and space physical processes, data analyses and comprehensive statistical analyses of extreme GIC that will improve our capability to predict extreme GIC events and quantify statistical occurrence and spatiotemporal characteristics of extreme GIC events.

SSA-2: The neutral upper atmosphere and its modulation in the coupled magnetosphere, ionosphere, and atmosphere system.

Basic Science Components

With an increasing number of satellites in low Earth orbit, as well as an increasing amount of debris, there is a growing risk of collisions and damage to scientific research satellites and manned NASA missions. There is a need to be able to closely monitor the orbits of every object, in order to alert operators to the risk of collisions, as well as for national security concerns.

Low-altitude satellites move within the upper boundaries of the atmosphere, the thermosphere and exosphere. They may have their orbits perturbed by changes in the neutral atomic density, resulting from variable solar and auroral activity. After large geomagnetic storms, these perturbations make it difficult to track and predict the locations of satellites to avoid space debris. A long-standing goal of LWS science is to produce improved predictions of the thermosphere neutral density that will enable more accurate satellite drag and orbit calculations. A number of scientific problems need to be solved in order to achieve a fuller understanding of the variability in the thermosphere leading to the capability for prediction on hours to days timescales. The topics to be investigated include:

- The lower thermosphere coupling with adjacent regions above and below.
- The rapid, global response of the thermosphere to sudden enhancements in polar, auroral heating.
- Modes of propagation of these disturbances, from high latitudes to the equator.
- Variability in the cooling rates, particularly after large heating events, due to the effects of nitric oxide.
- Mechanisms of nitric oxide production and how it affects regional densities.
- Thermosphere response to variable solar radiation on short to longer timescales related to X-ray flares up to active region evolution and solar rotation.
- Thermosphere response to variable solar particle fluxes on short to longer timescales related to SPEs up to high-speed streams and geomagnetic storms.
- Variations in the geocorona, at higher altitudes beyond the exospheric boundary.
- Changes in the composition of the neutrals in the thermosphere.
- Changes in satellite drag coefficients due to physical processes.

Predictive Goal

The goal is to derive a model, or coupled set of models, to specify the global neutral density in the thermosphere and its variations over time. This capability should be able to predict the densities that satellites in low Earth orbit will encounter with a lead-time of at least one hour as well as longer-term predictions out to three days and preferably to seven days. There should be quantifiable levels of uncertainty that are specified for different data conditions and levels of redundancy in data/models. Specification of the densities of different atomic species would be desired but not required.

Models

The types of models that could contribute to this solution could include:

- Theory or models for propagation modes, variable cooling rates due to nitric oxide production, atmospheric effects, winds, and tides.
- Numerical or empirical models, separate or in combination, having good temporal and spatial structure, including the rapid temporal changes following sudden and intense auroral heating, and the subsequent cooling.
- Improved understanding and/or models of composition above the thermosphere.

Observations

Observations that could be used in this project may include, but are not limited to:

- Solar wind velocity and interplanetary magnetic field (IMF).
- Neutral density or neutral wind measurements from CHAMP, GRACE, and future SWARM or CubeSats.
- Indices or spectra of solar radiation, solar particles, and/or the state of the geomagnetic field.
- Electric and magnetic fields in ionosphere.
- Remotely sensed observations of the upper atmosphere and geocorona.

Products

The expected product is a model or a system of thermosphere neutral density and composition specification and prediction from the current epoch, through 1 hour to at least 3 days.

Potential Users of Products

Potential users of these capabilities might include U.S. Air Force satellite and debris tracking systems, NASA conjunction risk management, and private-sector forecasters who aid commercial space operators.

Metrics and Assessment

Metrics should be based on specified or predicted neutral densities compared to those measured by CHAMP and GRACE or other high precision density sensors such as SWARM. The USAF HASDM database also provides global, time-resolved mass densities of high accuracy that can be used to assess the validity of a thermospheric density prediction capability. A successful project will make neutral mass density and composition predictions that are demonstrably better than the baseline existing models such as JB2008 or NRLMSISE-00.

Types of Investigations

The expected types of investigations could include observation-based studies and empirical modeling, numerical/

physics-based models, or a combination of all three, such as numerical models linked with empirical components and/or data assimilation.

Team Makeup and Responsibilities

The team may contain expertise in fields such as (but not limited to) numerical modeling, data analysis and empirical modeling, assimilation techniques, solar irradiance and particle observations, and theory. The final product likely will need to combine components from each area of expertise. The Principle Investigator (PI) will need to coordinate the development of models, discussions with potential users, and metrics and assessments evaluations.

Implementation Specifics

Investigations that use first-principle, numerical models are needed to understand the coupling between different atmospheric regions. Input of energy in the auroral regions could be derived from magnetospheric models, or obtain these values from empirical models. Numerical models may meet the objectives for obtaining a predictive capability.

Investigations that use data analysis or empirical modeling, will be needed to serve as a benchmark or validation of the numerical models. Such models may also meet the objective for obtaining a predictive capability. Assimilation techniques may be useful. Optical observations of the upper atmosphere and geocorona may be useful.

An investigation of solar radiation, at multiple wavelengths, and solar energetic particles and their influence on the upper atmosphere and thermosphere will be required. These energy sources are the primary external driver of the thermosphere temperature variations, upon which the more rapid auroral influences are superimposed. This group will need to determine how to use solar observations and indices. A long-term (three days or more) predictive capability to predict the effect of solar flares is highly desired, including the effects of sunspot regions on the far side of the sun. It is possible that this group will also require optical observations of the upper atmosphere and geocorona, in addition to measurements of neutral densities in the thermosphere.

An investigation into orbital dynamics could help to reach the goal of an improved capability to predict satellite positions. This group would need to understand the processes that may influence satellite drag coefficients, and how to derive better values of the drag from realistic satellite geometries.

All investigations will specify the objective deliverables and delivery dates, along with a specification of the expected quantities to be predicted. A validation plan is to be included, including the measurements and metrics to be used, and the benchmark, existing capability for comparison.

SSA-3, Physics-based Solar Energetic Particle Forecasting Capability.

Target Description

Solar Energetic Particle (SEP) events increase radiation hazards throughout the solar system and adversely impact our space- and ground-based assets. These events are associated with fast CMEs in the low corona, typically originating from complex active regions. The prompt response can arrive at Earth in less than an hour from the onset of eruption, followed by the less intense, but longer lasting event associated with the CME shock propagating through the heliosphere.

The prediction of these events and their connectivity to Earth or space assets is a multi-faceted problem.

- Potentially dangerous active regions must be observed and tracked and the probability of major eruptions needs to be quantified.
- Physical mechanism(s) accelerating the particles should be characterized and modeled within the context of the low solar corona and out into the solar wind.
- Field line connectivity from the acceleration region(s) to arbitrary points in the heliosphere must be simulated and the uncertainly must be quantified.
- The transport and acceleration of the particles along these field lines must be modeled and observed.

Basic Science Components

CMEs/flares, SEP acceleration and propagation, background solar wind, coronal and heliospheric magnetic field structure.

Predictive Goal

Probabilistic prediction of intensity of SEP events, increased time periods for all-clear forecasts with higher confidence levels.

Models

Models of the background corona and solar wind that provide connectivity to Earth and other points in the heliosphere; models of eruption/shock propagation in the corona and heliosphere; models of SEP acceleration and propagation from CMEs, flares, and shocks; models providing empirical and/or physics-based predictions of flares/CMEs.

Observations

Observational characterization of SEPs during large events, especially those factors that can distinguish between competing models; observational characterization of the corona (white-light, EUV and X-ray emission, radio) during large SEP events.

Products

Predictions of onset, intensity and duration of SEP times, improvement in all-clear forecasts.

Potential Users of Products

NOAA/SWPC, NASA SRAG, airlines, satellite operators, companies engaged in private human spaceflight, private launch service companies.

Metrics and Assignments

False alarm rates, rate of missed events, SEP intensity predictions, uncertainty quantification.

Types of Investigations

Studies of acceleration and propagation of SEPs in realistic fields, CME/flare eruption studies linked to SEP production, studies of the connectivity of SEPs from the Sun to points in the heliosphere, studies of flare/CME prediction from solar observations (e.g., magnetograms, EUV and X-ray observations, previous flare productivity).

Implementation Plan

Achieving the goals of this SST requires both scientific and modeling progress. Steps along this path include two Focused Science Topics (FSTs) that would address necessary scientific progress in the areas of forecasting of eruptions and the connectivity of SEP producing regions to points in the heliosphere. Another likely requirement would be a Strategic Capability (SC) to link together models of CME evolution/propagation, SEP particle acceleration and transport, and realistic models of the corona and solar wind to produce predictions of SEP intensity and duration for real events. These investigations are briefly described below.

Focused Science Topic: Forecasting Eruptions. A key difficulty is predicting the likelihood of a major eruption from active region(s) on the sun, at least 24 hours prior to the event. NOAA/SWPC currently relies on qualitative assessments of sunspot groups to produce a forecast. Statistical methods that characterize the magnetogram properties exist that could potentially improve these forecasts. While there is significant theoretical/modeling work on the eruptive properties of solar magnetic fields, it appears we are still many years away from an entirely first principles approach for predicting eruptions. A focused science team to improve predictions of eruptions would combine experts in statistical methods, solar data analysts for relevant observations, and theorists/modelers to improve upon or produce new methods for flare/CME forecasting. An important deliverable for the team would be the production of a prototype code/method for forecasting large events (e.g., M/X class flares and/or >1000 km/s CMEs), and a demonstration of its validity against a database of past events. This would be compared against known methods (e.g., present NOAA/SWPC forecasts). These comparisons should go beyond individual case studies and demonstrate improved predictive capability by rigorous statistical quantification, including the limits of predictability for the method(s). Users of these results could include NOAA/SWPC, NASA/SRAG, and possibly private space launch service companies.

Focused Science Topic: Predict connectivity of SEPs to points in the inner heliosphere, tested by location, timing, and longitudinal separation of SEPs. Even with a forecast of a SEP-producing event on the Sun, an essential question is whether/when those particles will connect to points of interest in the heliosphere, such as at Earth. This information is crucial for forecasting the onset of prompt events, increasing the time period of all-clear forecasts, quantifying uncertainty and providing higher confidence levels. An important result form the STEREO mission is the recognition that many SEP events extend over much larger ranges of longitude than previously estimated. For example, small 3He-rich events have also been found to sometimes extend over much broader longitudinal extend than expected. The surprising longitudinal extent of these events shows that basic features of SEP acceleration and transport are not included in the standard picture. This FST would combine theoretical studies, numerical modeling, and remote observations as well as in-situ measurements in order to identify the mechanism(s) that result in SEP events with extremely large breadth in longitude. The solicitation would bring together theorists, modelers, and data analysts of SEP events to understand and model the longitudinal (and latitudinal) spread of events. The team would develop metrics and skill scores to quantify the relative accuracy of available methods for predicting connectivity of SEPs. Another key deliverable for the team would be the quantification of uncertainty in the longitudinal extent of SEPs, as demonstrated by the prediction of SEP detection from known source regions in past and/or future events. Users of these results could include modelers of SEP acceleration/propagation, NASA/SRAG, and NOAA/SWPC.

Strategic Capability: A model or combined set of models for forecasting the intensity and duration of SEPs for points in the heliosphere, tested against real events. Models for CME eruption, evolution, and propagation, as well as theory/models for SEP propagation and transport presently exist in isolation. While there are still many issues to be addressed in these areas, achieving the goals of the SST requires linking together these capabilities and assessing how well they can meaningfully predict SEP properties. The primary activity of this Strategic Capability would be to combine the results of the two FSTs with a unified model of CME propagation, SEP acceleration and transport within the context of realistic models of the corona and inner heliosphere. The primary deliverable of the SC would be a model capable of predicting SEP intensity and duration at points in the heliosphere for any given day. Validation of model against past events, including uncertainties and false alarm rates would be crucial. Users of these model results could include NOAA/SWPC, NASA/SRAG, airlines, satellite operators, companies engaged in private human spaceflight, and private space launch service companies.

SSA-4, Physics-based TEC Forecasting Capability: Target Description.

A compelling and long-standing scientific challenge is forecasting ionospheric total electron content using physics-based models of the coupled neutral atmosphere, ionosphere, and plasmasphere. While globally distributed GPS-based observations of total electron content (TEC) have been a significant advance for the Space Weather community, the challenge of forecasting global TEC has not been realized due to limitations in our understanding and modeling the full vertical extent of the ionosphere and plasmasphere.

Basic Science Components

In order to move toward physics-based TEC forecasts with quantified uncertainty, improved global models of the ionospheric topside and plasmasphere electron density are needed, to augment more mature models of the bottom side ionosphere. Models of the topside ionosphere, which can be responsible for more than half of the TEC encountered by GPS signals traversing from satellites to ground, must include reliable quantification of proton sources and sinks, which depend in turn on H, O, and O+ densities, with additional accuracy gained by inclusion of He and He+ concentrations.

A number of scientific problems need to be solved in order to achieve the necessary understanding of the ionosphere and plasmasphere. Particular topics to be investigated include:

- The densities and composition of ion and neutral species as a function of altitude, and how they vary during geomagnetic storms.
- The neutral wind and temperature fields and how they vary.
- Electrodynamics due to dynamo and magnetospheric electric fields mapped to high altitude (above ~300 km).
- Plasmaspheric erosion and recovery during and following storm periods.

Predictive Goal

The goal is to derive a model, or coupled set of models, that is able to specify the global ion density in the ionosphere and plasmasphere and its variations over time under varying geomagnetic conditions. The model should be able to predict the TEC observations globally, with a lead-time of at least one hour (based on availability of real-time solar wind/IMF measurements), as well as longer-term predictions for up to three days based on solar wind forecasts.

Models

An important need is to elucidate photochemistry and dynamics governing ion-neutral interactions in the topside ionosphere and exosphere, particularly during geomagnetic storms, to the point of being able to represent these interactions in numerical models. In the plasmasphere, the primary goal is representing erosion during storm periods and refilling processes during recovery. Quantification of how upper atmospheric state parameters respond to drivers, from the solar wind to the thermosphere, must be incorporated into physics-based assimilative models to improve TEC forecasting capabilities.

Also required is inverse theory technique development that fuses diverse observations, taking measurement physics into account, to better estimate underlying atmospheric state parameters that are not observed directly. Data fusion techniques for both ground- and space-based observations, combined with existing techniques to estimate fundamental state parameters from these observations, must be further developed for use in forecasts.

Observations

Besides observations of TEC derived from Global Navigation Satellite Systems (GNSS), DORIS and other active radio sources, including ground and space-borne receivers, observations that are useful to this objective may include, but are not limited to:

- UV and optical airglow emission data acquired from satellite and ground-based photometer networks, of the ionosphere and plasmasphere.
- Solar radiation EUV to X-ray fluxes.
- [O]/[N2] abundance ratio data, derived from satellite.
- Ground-based radar measurements of plasma and neutral parameters.
- Neutral wind and airglow emission measurements to resolve chemical and dynamical influences on storm-time responses, from ground and space-based platforms.
- Observations of infrared emissions (e.g., from NASA's SABER instrument) to constrain energy deposition into the topside during storms.
- Observations from ground-based ionosonde networks, in particular true-height profiles, are important for bottom side contributions to TEC.
- Observations of electric fields and plasma convection at high and low latitudes.
- Magnetospheric energetic neutral atom fluxes, which are the product of exospheric and plasmaspheric chemistry.

We expect that the upper atmosphere missions ICON and GOLD, selected for launch in 2017, will significantly advance scientific knowledge and modeling capabilities leading to reliable TEC forecasts.

Products

The expected product is a global predictive model of ionospheric total electron content, with prediction lead times ranging from 1 hour to 3 days. The model will be coupled to solar wind, magnetosphere and lower atmosphere models to capture driving forces.

Potential Users of Products

Total electron content variations affect many commercial and government systems. Users include: single frequency navigation and positioning (e.g. precision architecture, surveying, aircraft navigation) and radar.

Metrics and Assignments

A primary measure of success rests on numerical model capabilities to reproduce real-time behavior of key plasma and neutral species in the bottom side and topside ionosphere and plasmasphere. Successful forecasts will rely on parameter estimation techniques and accurate representations of physical processes that drive TEC variations. A secondary measure of success is the accuracy of models in reproducing historical climatologies of key species. Specifically, models should be able to reproduce morphologies associated with observed storm-time and day-to-day variability of TEC, including extreme variability as caused by coupling to the solar wind and magnetosphere.

Two types of metrics are encouraged:

- Metrics that provide insight into the underlying physical processes are particularly encouraged for future development. For example, [O]/[N2] abundance ratio metrics.
- Metrics should characterize the current state-of-the-art regarding application of existing models to forecasts of quantities of interest to applications. These metrics would be application (user) dependent.

Types of Investigations

Observation-based studies and empirical modeling; numerical, physics-based model development; and assimilative and data-fusion techniques.

Research Teams and Responsibilities

Investigations that advance this topic should include expertise in these fields (not all inclusive):

- Numerical modeling
- Data analysis and empirical modeling
- Data assimilation techniques
- Solar and solar wind observations and modeling
- Magnetospheric observations and modeling
- User needs
- Metrics

Metrics should assess progress towards the predictive goal, and measure improved prediction as models are refined and improved.

Upper atmosphere scientists need not have all expertise that is required for a forecast capability. However, those responding to investigations addressing this SSA must be aware of and use existing tools (e.g., at CCMC) in other domains to inform their forecast capability. The TEC team's primary responsibility is to advance science and modeling toward a predictive capability assuming that other forecasts (solar wind and magnetosphere) are available and reasonably accurate. Understanding sensitivity to upstream forecast error is encouraged.

Investigators responding to this SST will coordinate model development with observations, coordinate with the user community, and provide metrics and assessments.

Implementation Plan

Several existing Focused Science Topics (FST) with the Living With a Star program, which are relevant to TEC prediction, have been solicited by the program or are currently in progress. These include:

- Thermospheric wind dynamics during geomagnetic storms and their influence on the coupled magnetosphere-ionosphere-thermosphere system
- Determine the Behavior of the Plasmasphere and its Influence on the Ionosphere and Magnetosphere
- Plasma-Neutral Gas Coupling
- Global Distribution, Sources and Effects of Large Density Gradients
- Storm effects on global electrodynamics and middle and low latitude ionosphere
- Response of thermospheric density and composition to solar and high latitude forcing
- Lower-upper atmosphere coupling for determining pre-conditioning and background conditions
- Sources and effects of large electron density gradients

Strategic capabilities exist or are in progress that are relevant to predicting TEC, including the development of a comprehensive Magnetosphere-Ionosphere Model, and an Integrated Model of the Atmosphere-Ionosphere system. These strategic capabilities have not been developed into a forecasting capability at this time. Investigations that advance these or other models towards predictive capability are needed. Advancing towards predictive capability requires identifying:

1. Missing physics in the models that have a large impact on TEC forecasts.
2. Spatial or temporal resolution limits that do not capture phenomena accurately enough for TEC prediction.
3. Observations needed to derive boundary conditions for the modeled domains.

Future investigations that address these issues are required. In addition, investigations that bring the prior FST outcomes towards predictive capability are required.

SSA-5: Ionospheric Irregularities and Scintillation

Understanding and mitigating the effects of ionospheric irregularities on radio communication and navigation.

Basic Science Components

Radio scintillations rank among the most obvious and hazardous manifestations of space weather. Radio scintillations occur when radio ray paths transect regions of ionospheric irregularities caused by plasma instabilities and plasma turbulence. Plasma instabilities are widespread and occur at low, middle, and high latitude in the E and F regions of the ionosphere. In the auroral zone, scintillations are strongest during geomagnetically active periods but occur at all times in auroral bands. At low latitudes scintillations are associated with equatorial spread F events triggered by such large-scale instabilities as Rayleigh-Taylor, which occur in active and quiet periods. While irregularities have definite climatologies, forecasting them has proven to be challenging, both because the most important ionospheric drivers can be difficult to measure and/or predict and because the ionospheric response to the drivers is often complicated and not obviously deterministic.

Predictive Goals

One goal of this FST will be to elucidate completely the physical mechanisms responsible for producing ionospheric irregularities, the most important sources of free energy, and the causal chains that both generate and suppress irregularities leading to scintillations. Another goal is to develop strategies for predicting scintillation occurrence utilizing limited sources of available data. A third goal is to ascertain more completely how radio signals are degraded by ionospheric irregularities and to use this insight to develop methods for maintaining signal lock when scintillations occur. The resulting “clean” radio signals would themselves be incisive diagnostics of ionospheric irregularities, and a final goal of this topic is the explorations of means of folding radio signal information back into irregularity analysis and modeling.

Models

Mitigating ionospheric scintillations requires an improved theoretical understanding of the plasma instabilities underlying them. It is unclear, for example, whether the main sources of free energy and physical processes at work have been correctly identified in all cases, and both the seasonal and day-to-day variability of irregularities are not well accounted for by existing theory as a result. Reliable forecast models remain elusive, and forecasts incorporating assimilated data will remain ineffective so long as their theoretical foundations are incomplete. Managing scintillations also requires an improved understanding and modeling of radio wave propagation and scintillation and the different ways that signals are degraded by different classes of irregularities. This information will be essential for developing strategies for minimizing the effects of scintillations on operational communications and navigation systems.

Observations

Observations include experimental studies of plasma waves and instabilities aimed at establishing their gross morphology, revealing causal relationships to background driving parameters and geophysical conditions, and fully specifying their climatology. Observations from TIMED, C/NOFS, and FORMOSAT-3/COSMIC will be leveraged to elucidate the salient processes responsible for scintillations and advance understanding. The DORIS radio measurement system of satellite-to-ground links is available from several non-NASA satellites. Furthermore, ground-based networks of GPS receivers provide a valuable diagnostic tool for investigating scintillation effects and enable innovative observation schemes such as diffraction tomography. Ground-based radar observations are also valuable.

Products

Products including analytical and empirical models will reproduce unfolding irregularity climatologies through numerical modeling and simulation, and provide the onset times, growth times, scale sizes, propagation characteristics, and general morphologies of irregularities consistent with individual observations, and predict the day-to-day variability in irregularity occurrence with an accuracy surpassing forecasts based on climatology and persistence alone. Products include the development of increasingly robust radio signal decoding schemes able to maintain data integrity and signal lock when scintillations occur.

Potential Users of Products

Consequences of scintillations include signal fading, distortion, data loss and, in the case of navigation systems like GPS, loss of signal tracking. As society becomes more dependent on GPS navigation in time-critical applications such as aircraft approach, the impact of ionospheric scintillations will become increasingly intolerable. Instabilities at middle latitudes have the greatest direct impact on North American residents but are the least well-understood and most difficult to forecast. Other than commercial aviation, user sectors potentially benefiting from developments resulting from this SST include transportation engineering and traffic management systems, precision agriculture, emergency response, autonomous vehicles, marine navigation, environmental sensing, and critical resource and infrastructure monitoring. Furthermore, all sectors relying on HF communication including defense and communication service providers in remote areas would benefit from the developments resulting from this SST.

Metrics and Assessment

Establishing quantitative benchmarks (skill scores) for success in these areas should be considered part of the SST. Metrics should be developed based on specific impact domain requirements. Assessment should go beyond case studies and model runs and should establish rigorous statistical quantification of limits of predictability and demonstrate improved prediction capability resulting from the proposed innovations.

Types of Investigations

The research would involve theoretical analysis, numerical modeling and simulation, measurement and signal processing, and algorithm design, development, and testing.

Implementation Specifics

Solicitations should include FST and SC investigations that lead to improved understanding and predictive capability of scintillations, guided by clearly defined requirements articulated through interaction with the user community.

SSA-6, Physics-based Radiation Environment Forecasting Capability

Predict the dynamic radiation environment from GEO to the troposphere and its variability due to GCR and SEP coupling with the Earth's magnetosphere-ionosphere-atmosphere system.

Target Description

The radiation environment between the thermosphere and troposphere is variable, changing dynamically due to Galactic Cosmic Ray (GCR) and Solar Energetic Particle (SEP) heavy ion, neutron, proton, beta particle, gamma-ray and X-ray inputs. In addition, and of particular relevance to human tissue as well as avionics radiation dose and dose rate risks, secondary and tertiary particles from high energy neutron and ion impacts can vary with changes of target atoms and molecules, such as in the tropospheric air mass. The GCR background is typically variable only on the timescale of days, with a long-term trend, which changes slowly, modulated by the effects of the solar Interplanetary Magnetic Field (IMF) that varies with the approximate 11-year solar cycle. The SEP environment, however, can be highly time variable, with impulsive order of magnitude changes that can occur in the matter of seconds to minutes in association with solar eruptive events. Together, the GCRs and SEPs couple with the Earth's Magnetosphere-Ionosphere-Thermosphere (M-I-T) system, modifying the ionizing radiation environment throughout these different regions across a wide range of timescales.

Recent observations and modeling developments have permitted substantial progress in understanding the drivers and responses of the radiation environment. For example, global radiation climatology specification from the Civil Aerospace Medical Institute (CAMI) model, the Nowcast of Atmospheric Ionizing Radiation System (NAIRAS), the Automated Radiation Measurements for Aviation Safety (ARMAS) aviation altitude dose rate measurements, the upcoming Rad-X high-altitude balloon flights, the energetic particle measurements throughout Earth's radiation belts on the NASA LWS Van Allen Probes mission, and even the boundary condition specification of the radiation environment measured by the NASA LRO/CRaTER instrument at the Moon and by the NASA ACE mission at L1, have been successfully developed over the past several years. However, the variability and forecasting potential of the coupled systems behind this radiation environment are not yet well quantified. First principles and empirically based models, combined with new data streams are needed to permit substantial progress toward predictability.

Basic Science Components

GCR and SEP fluxes, cutoff rigidities, magnetosphere-ionosphere-atmosphere coupling as it affects high-energy particle precipitation, radiation environment at all altitudes, validating dose and dose rate measurements.

Predictive Goals

Improve specification and prediction of the radiation environment from geosynchronous orbit, through the radiation belts and thermosphere, into the troposphere, particularly for high radiation disturbed periods such as during solar proton events.

Models

First principles, empirical, and data assimilative models for basic science component areas are needed for improving predictive capabilities of the radiation environment at aircraft, LEO spacecraft, and GEO spacecraft altitudes; the coupling of existing models with a data assimilative approach for current epoch specification and near term prediction would represent a major advance in the community.

Observations

Primary and secondary particle fluxes from GCRs and SEPs, possibly including more neutron monitor observations at a variety of magnetic latitudes as well as heavy ions in deep space, energy spectra and particle LET at altitudes from the Earth surface out to the system boundaries in deep space, and calibrated dose/dose rate measurements at all altitudes for model validation.

Products

New primary and secondary particle along with dose and dose rate data sets; improved specifications and a new prediction capability, especially using data assimilation, for the radiation environment's effective dose and dose rates based on GCR, SEP, cutoff rigidity, atmosphere density, and gamma-ray/X-ray inputs; a capability that may alert operational users of the impacts of extreme radiation conditions in their environment.

Potential Users of Products

Commercial aviation crew, frequent flyers, and pregnant mothers; high altitude private and military jet crew and passengers; space tourists and astronauts; aircraft, LEO and GEO satellite avionics systems.

Metrics and Assignments

Validation and verification, including metrics, of new specification and prediction capabilities that can be compared with current state-of-art practices; PI-defined accountability for providing the investigation's results to defined users, to the scientific community, and to the public at large.

Types of Investigations

Substantial progress on this Strategic Science Topic is possible with the following types of investigations that can be supported:

- New observations and characterization of primary and secondary particle GCR, SEP radiation sources (heavy ions, neutrons, protons, beta particles, gamma-rays, and X-rays) using in situ and/or remotely sensed measurements from ground, sub-orbital, and satellite assets.
- New methods for characterizing specific environmental domain radiation fields using data assimilative techniques in existing coupled modeling systems.
- Analyses of radiation environment background variability due to galactic, solar, magnetospheric, and atmospheric inputs that lead to fundamentally new insights.
- Analyses that elucidate radiation environment dynamics during energetic particle storms and that can lead to improved physical explanations as the basis for predictions.
- Development and/or use of first-principles and empirical modeling systems, with data assimilation, to more accurately characterize the current state of the weather of the radiation environment and lay a foundation for its prediction.
- Theoretical and modeling studies that describe the role of space weather drivers causing radiation environment variability and that demonstrate a capability for prediction at all time scales.
- Innovative use of existing and new data sets that improve our understanding of radiation environment variability.
- New methods for quickly identifying the potential effects on humans and technology from extreme radiation events and that could be integrated into predictive systems.

Implementation Plan

An improved specification of the weather of the radiation environment dose and dose rate, along with the prediction of its variability, can be accomplished by investigations that have the following components:

- a plan for identifying existing modeling and data production systems with their strengths and weaknesses;
- a characterization of the existing state-of-art for predicting the radiation dose and effective dose rate in a specific environmental domain;
- a methodology for substantially improving radiation dose and effective dose rate predictability for that environmental domain;
- a demonstrated collaborative relationship with a user-community in the environmental domain; the user community should be able to provide feedback during the investigation and should potentially benefit from improved predictability;
- a path for team accountability that provides the investigation's results to defined users, that engages the relevant scientific community, and that informs the public-at-large; and
- a validation and verification plan that includes metrics from the investigation compared with current state-of-art practices.

Strategic Capability: provide improved specification and prediction of the radiation environment from geosynchronous orbit, through the radiation belts and thermosphere, into the troposphere, particularly for disturbed periods with high radiation conditions such as during solar proton events.

Chapter 5

Future Opportunities and Challenges

5a. Observational Requirements and Data Sources

Figure 7 shows physical regimes (top), observations (middle) and models at the CCMC utilizing LWS observations. Emphasis is placed on the need for white light observations, rotational tomography, Thomson scattering tomography, UV, EUV X-ray observations, longitudinally distributed in situ observations of solar wind including ion composition, the interplanetary magnetic field and Solar Energetic Particles (SEPs). Table 2 highlights select models at the CCMC that depend on these observations.

Global Magnetic Field: The global solar magnetic field extends out into the heliosphere to become the interplanetary magnetic field (IMF). It defines the structure of the corona and heliosphere, including the position of the heliospheric current sheet and the regions of fast and slow solar wind. Therefore, the solar magnetic field is the key observational input to LWS models of the corona and solar wind. Models typically require global maps of the radial magnetic field at the solar surface. The most widely available full-disk measurements are of the line-of-sight field in photosphere. These are used to build-up so-called "synoptic maps" over the course of the solar rotation. Such maps are presently available from the Helioseismic and Magnetic Imager (HMI) instrument aboard SDO and a number of ground-based observatories, notably NSO's SOLIS (Synoptic Optical Long-term Investigations of the Sun) and GONG (Global Oscillation Network Group) observatories, the Wilcox Solar Observatory (WSO), and the Mount Wilson observatory (MWO). The measurements from the older observatories (WSO and MWO) provide an important baseline for comparison of measurements, as quantitative disagreements between the different observatory magnetographs are yet to be resolved. It is imperative that multiple sources for these observations be maintained until a full understanding of the quantitative differences is obtained. Funding for all of the ground-based telescopes is precarious.

Solar and heliospheric modeling could make quantitative leaps in improvement with new measurements. Two well-known problems arise from the use of the "synoptic" maps commonly provided by observatories. First, the maps contain data that is as much as 27 days old. Second, the line-of-sight (LOS) field at the sun's poles is poorly observed, and the polar fields in these maps are filled with a variety of interpolation/extrapolation techniques. Unfortunately, these observational gaps can strongly influence the solution for the global magnetic field. In particular, poorly or unobserved active regions at the limbs (as viewed from Earth) as well as inaccurate polar field estimates can introduce unacceptable errors in the field on the Earth-facing side of the sun. Obtaining photospheric magnetograms off of the sun-Earth line off of the east limb (portion

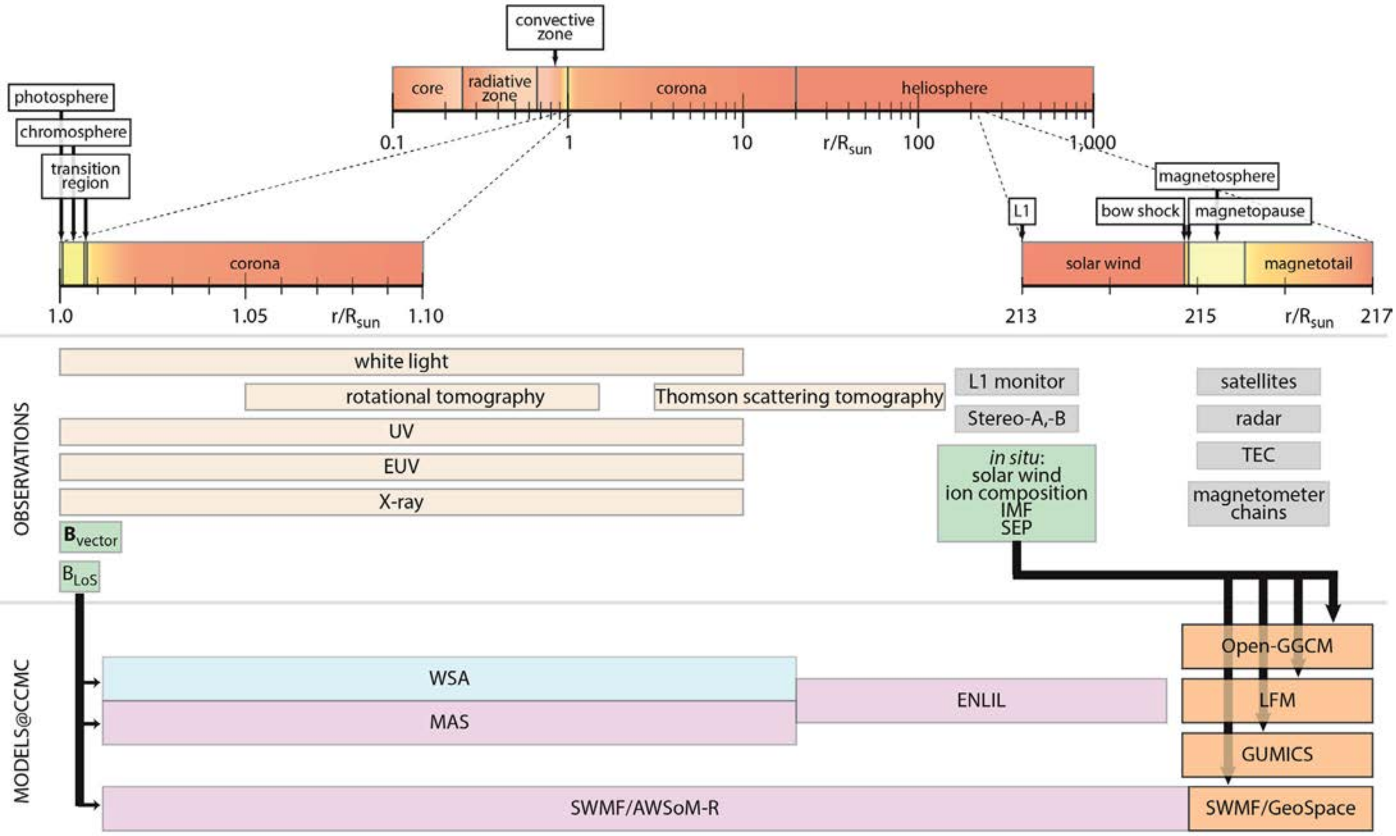


Figure 7. Physical regimes (top), observations (middle) and models at the CCMC utilizing these observations.

Model	Description	Developer
CTIP	Ionosphere + Thermosphere	NOAA SWPC
GITM	Ionosphere + Thermosphere	Michigan
SAMI	Ionosphere	NRL
TIEGCM	Ionosphere + Thermosphere	NCAR HAO
USU-GAIM	Ionosphere	USU
LFM	Magnetosphere	Darthmouth (NRL)
OpenGGCM	Magnetosphere	UNH (UCLA)
SWMF	Corona + Heliosphere + Magnetosphere	Michigan
ENLIL	Heliosphere	George Mason (NOAA SWPC)
MAS	Corona	PSI
EMMREM	SEPs and GCRs	UNH (BU)
PREDICCS	Nowcasting SEPs and Radiation Interaction	UNH (BU)

of the sun with the oldest observations as viewed from Earth), to complement presently available observations would yield significant improvements. Observations of the polar fields for several years would allow strong constraints to be placed on flux transport models, which predict the evolution of the field. Solar Orbiter observations may partially fulfill this goal in a late stage of the mission.

Pre-Eruptive Magnetic Fields: Vector magnetograms offer the possibility to investigate the energization of the solar magnetic field, a crucial aspect of solar eruptions. HMI and SOLIS provide full disk vector magnetograms; however the transverse magnetic field is difficult to measure reliably outside of strong field regions. Therefore, thus far the data has been primarily used to study active region magnetic fields. The Hinode SOT-SP provides high-resolution vector magnetograms for a relatively small field of view. Many difficult technical issues arise in using vector magnetograms in models. One issue is that the measurements do not specify the direction of the transverse field. Ambiguity resolution techniques can be time-consuming and/or inaccurate when very complex fields are present. An important difficulty with the use of photospheric vector magnetograms is the non-force free nature of the field where the line formation occurs. This could be alleviated with measurements in the chromosphere. These are possible but are more difficult to obtain and interpret.

Accurate measurements of the solar field at chromospheric heights will allow the shear/twist of the solar field to be incorporated into model boundary conditions. This is crucial for characterizing the free magnetic energy stored in the field. Measurement of the vector field at two heights (photosphere and chromosphere) can provide significant improvements to ambiguity resolution algorithms. Measurements of the magnetic field at coronal heights can provide important constraints on both the global field and pre-eruptive fields. These measurements are difficult but are becoming feasible, as demonstrated by the Coronal Multi-channel Polarimeter (COMP). Future instrumentation may allow such measurements to be routinely utilized.

Magnetosphere and Ionosphere: Present observational data sources include upstream monitors (e.g., ACE, Wind, and GOES), which provide one-hour nowcasts of the space environment. Models of coronal mass ejections (CMEs) are currently in the testing phase. The challenge for these models is the accurate determination of CME arrival times and uncertainties. It is also critical in this case to accurately simulate Bz, which can drive magnetospheric storms and substorms. In the future, it will be necessary to develop tested and accurate models of ionospheric electrodynamics. Significant development is needed for accurate data assimilation models that include conductivities in the ionosphere.

Significant needs exist for measuring electrodynamic and particle inputs that originate in the magnetosphere, including electric fields and quantities that characterize how energy and ionization is deposited into the high latitude ionosphere, from magnetospheric electric currents, convection and particle precipitation. Electric fields and different forms of input energy profoundly influence upper atmosphere parameters including neutral mass density and plasma density, which lead to important space weather impacts. The upper atmosphere itself is strongly under-observed and requires multiple observations both to improve models and to characterize space weather.

The profound upper atmosphere changes that occur during geomagnetic storms are due to several factors that act simultaneously and affect each other: 1) momentum input from the solar wind creates large-scale changes to high latitude ionospheric plasma convection, reconfiguring the boundary between quiescent middle latitudes and the strongly-convecting higher latitudes; 2) ionospheric electric fields of magnetospheric origin cause global-scale changes to plasma transport processes and plasma structure, 3) frictional heating between convecting ions and neutrals, and heating from magnetospheric particle precipitation and currents, create large-scale changes to the thermosphere composition, density and circulation (winds). Ionization from precipitating particles changes plasma density and the conductivity at high latitudes, which in turn influences where heating is deposited. Thermosphere circulation changes also have electrodynamic impact via the neutral wind dynamo mechanism. These processes affect the plasma density and the neutral composition, mass density, temperature and circulation.

Solar Energetic Particles and Galactic Cosmic Rays: The EMMREM and PREDICCS models are currently the main models at the CCMC that utilize SEP and GCR observations to determine SEP and GCR event risks. The main data sources for the models include ACE, STEREO, GOES, and LRO/CRaTER.

Recent results from EMMREM and PREDICCS are shown in Figures 8 and 9. Figure 7 shows the probability of SEP events as a function of dose in cycle 24. The results show that while solar energetic particle events in cycle 24 present some hazard, the accumulated doses for astronauts behind 10 g/cm^2 shielding are well below current dose limits. Galactic cosmic radiation presents a more significant challenge: the time to 3% Risk of Exposure Induced Death (REID) in interplanetary space was less than 400 days for a 30 year old male and less than 300 days for a 30 year old female in the last cycle 23-24 minimum (Figure 8). The time to 3% REID is estimated to be ~20% lower in the coming cycle 24-25 minimum. If the heliospheric magnetic field continues to weaken over time, as is likely, then allowable mission durations will decrease correspondingly.

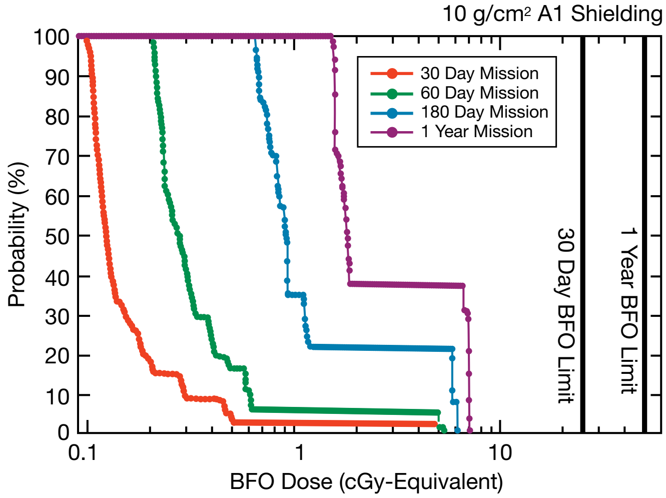


Figure 8. [From Schwadron et al., Space Weather, 12, 622, 2014] Probability (%) versus integrated BFO dose for 30 day to 1 year missions. We use the PREDICCS database [Schwadron, 2012, http://prediccs.sr.unh.edu] to build up statistics for the probability of SEP events of varying integrated dose behind spacecraft shielding (10 g/cm^2). The database currently provides doses for the period from July 2011 through April 2014. The PREDICCS doses are derived from proton spectra and use dose in 10 g/cm^2 water as a proxy for the Blood Forming Organ (BFO) dose.

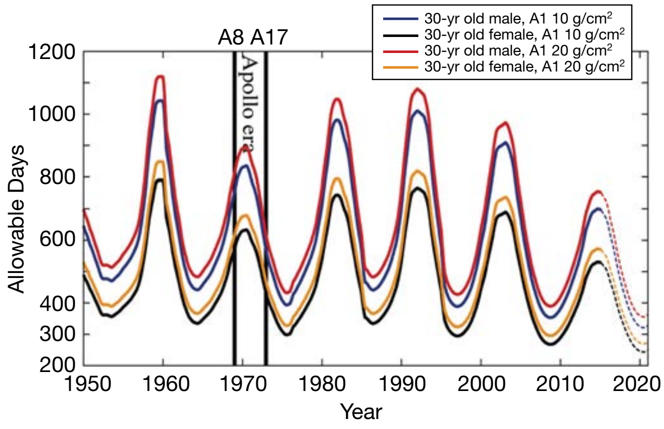


Figure 9. [From Schwadron et al., Space Weather, 12, 622, 2014] Days in interplanetary space before a 30-year old astronaut reaches their career radiation limit for 3% Risk of Exposure Induced Death (REID) at the 95% confidence level. Shown are maximum days before 3% REID limits are reached assuming different amounts of Al shielding (10 g/cm^2 and 20 g/cm^2). Black lines indicate times spanned by the Apollo missions from Apollo 8 (A8) to Apollo 17 (A17).

The fact that solar cycles are weakening suggests that solar maximum may be an optimal time to launch humans on long duration missions in deep space. Such a strategy relies heavily on the developing capabilities in Heliophysics to accurately describe the changes in the space environment and predict solar energetic particle events.

In the area of SEP prediction, there are a number of emerging areas needing further development and testing. Statistical approaches such as Baysian methods show particular promise for developing predictions based on existing now-casting models. Such statistical methods could be implemented as an addition to the PREDICCS system.

The large longitudinal spread of SEP events also facilitates data assimilation methods for making predictions at widely distributed observers (see Figure 10). Recent work suggests that a longitudinally distributed set of SEP observations inside of 1 AU would provide for significant improvements in predicting SEP events. The use of cubesats for these distributed HSO input data may be a prime area for development in the near future.

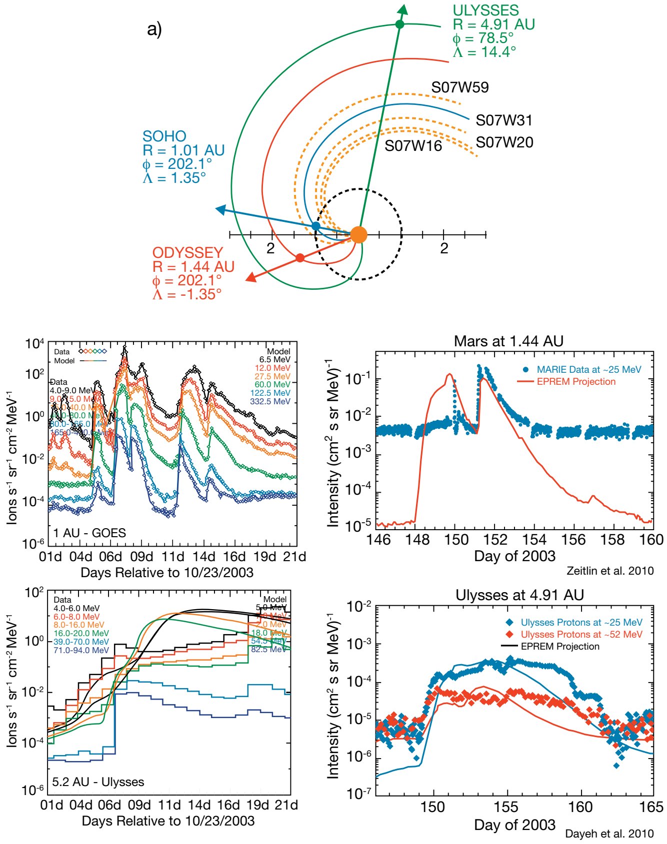


Figure 10. Due to the broad longitudinal extent of SEP events, observations near 1 AU can be used with SEP models to accurately describe SEP fluxes and doses at widely distributed observers in the inner heliosphere (Schwadron et al., 2010; Dayeh et al., 2010; Zeitlin et al., 2010). Shown here are SEP time profiles and onsets that were successfully predicted at Mars (Odyssey) and Ulysses located at 1.44 AU and 4.91 AU, respectively. 1 AU measurements from ACE, SOHO, and GOES were assimilated by the EMMREM model to perform these simulations. Modeled curves are solid, and observations are shown by points, or histograms. The top left panel shows magnetic field lines connected to Earth (blue), Odyssey (red) and Ulysses (green) during the Halloween storms in 2003.

Solar Flare Prediction: LWS capabilities for predicting solar flares is advancing rapidly, highlighting our growing reliance on advanced solar observations. We may ask the following specific questions concerning the predictability of solar flares:

- How well can we tell that an active region will produce a large solar flare tomorrow?
  - Answer: 23% ± 2%
  - The capability relies on SDO/HMI vector magnetic field observations
- Is there any signature prior to an active region's appearance?

- One day prior to emergence:
  - From helioseismic holography: 34% ± 8%
  - From magnetic field signatures: 38% ± 7%

These specific examples demonstrate both the progress in using observations to develop predictive capabilities, but also the fact that our existing capabilities need to be advanced further before predictive capabilities with high success rates will emerge.

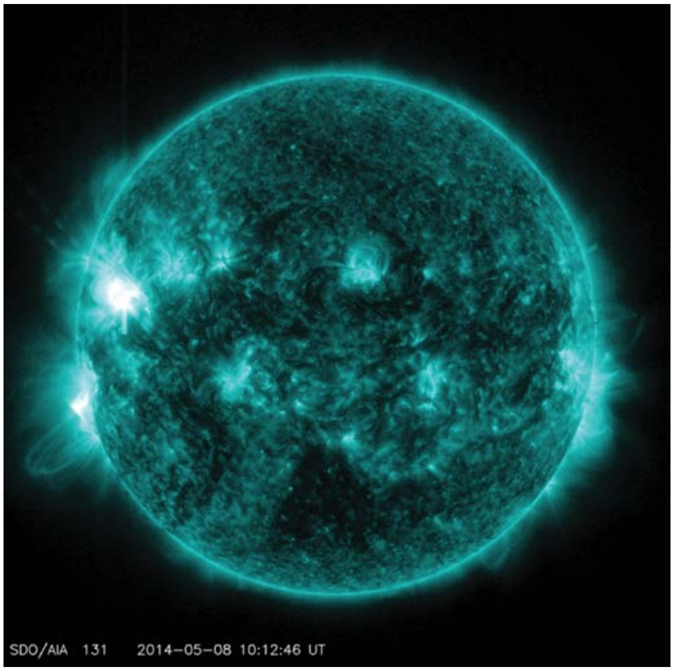


Figure 11. SDO Sees M5.2 Solar Flare. The bright light on the left side of the sun shows an M5.2-class solar flare in progress on May 8, 2014. This image, captured by NASA's SDO, shows light with a 131 Angstrom wavelength, which highlights the extremely hot material in a solar flare and which is typically colorized in teal. Credit: NASA/SDO

In achieving the next level of predictive capabilities for solar flare prediction, we require long-term comprehensive investment in the facilities and research for data acquisition, analysis and modeling. Longer-term, higher-dollar awards would promote stability and achieve closure on critically needed deliverables from projects. Further, LWS must begin the process of establishing community standards such as test cases and benchmarks for algorithm evaluation, event lists for comparisons, and publications that report successes and failures of specific techniques and applications.

Anticipating Future LWS Needs: While the LWS community currently has access to comprehensive data, there is a lack of a detailed plan for developing targeted products and data in the future. There is no assurance that data acquisition in the future will continue, let alone be sufficient to develop and advance predictive capabilities. The potential lack of continuity in data acquisition poses a threat to LWS and to Heliophysics as a whole.

No single mission will in the future provide all needed LWS observations. However, data needs are acute for LWS because advancement of predictive goals simply cannot occur without an expansion of the types of available observations. This highlights the criticality of implementing new LWS-DRIVE initiatives involving a combination of small satellite programs, science centers and grants programs, and needed instrument development that would target the next generation predictive needs for LWS science.

International collaboration offers another vital avenue for achieving the next generation observations critical for LWS predictive capabilities. The potential for new international synergies was highlighted in a recent 2015 report, Advancing space weather science to protect society's technological infrastructure: a COSPAR/ILWS roadmap published in Advances in Space Research, Volume 55, Issue 12 (http://www.sciencedirect.com/science/article/pii/S0273117715002252). The highest priority recommendations from the ILWS roadmap highlight the research needs for observational, computational, and theoretical advances. The roadmap elaborates on the necessity for improved teaming to foster a coordinated collaborative research environment in the national and international community. Finally, the report finds that there is a need to bridge the communities that exist at different funding agencies and research communities.

A number of specific pathways for research are outlined:
- Forcasting Ground Induced Currents more than 12 hours ahead.
- Deployment of new/additional instrumentation to add to existing observational resources and expand modeling capabilities.
- Major advances are possible with moderate investments in state-of-the-art observations and models, through interagency and international coordination.

5b. Innovative Use of Ground Measurements

There exist numerous ground-based instruments and networks that obtain measurements that are related to the state of the ionosphere, magnetosphere, and sun. These instruments include magnetometers, all-sky cameras, scanning Doppler imagers, LIDAR systems, Fabry-Perot interferometers, GPS arrays, and radars, such as SuperDARN and solid-state Incoherent Scatter Radars (ISR). For observing the sun, there are solar telescopes in the National Solar Observatory (NSO) network, including Rapid Oscillations in the Solar Atmosphere (ROSA), neutron monitors, coronameter/coronagraphs, GONG, BBSO, and NAS. Some of these instruments and networks are supported by the National Science Foundation, and others are supported by NASA through the Living With a Star or other programs.

There has been a significant expansion of ground-based instrumentation over the past decade. At the same time there have been advances in numerical and empirical modeling, data assimilation techniques, as well as an expansion in software, communication, and internet technology. These ground measurements and infrastructure are presently under utilized for both nowcasting and predicting space weather. These instruments and related technology are assets that could deliver far more with a relatively low cost investment.

In the future other ground-based assets could become available, such as Coronal Solar Magnetism Observatory (COSMO), the Frequency Agile Solar Radio telescope (FASR), and the Advanced Technology Solar Telescope (ATST). NSF's long-range plans include a Whole Atmosphere Observatory: OASIS, Observatory for Atmosphere Space Interaction Studies, to deploy and operate a network of 40 autonomous stations extending from pole to pole, with heterogeneous instrumentation and regional concentrations. Global networks of interactive, autonomous, and smart sensors will provide the critical long-term data bases necessary to understand the entire system and how it changes on multiple temporal and spatial scales. Ground networks that measure plasma properties of the ionosphere, and wind sensors that measure thermospheric circulation, need to be maintained and expanded. In addition, NSF is exploring crowd-sourcing as a viable means of acquiring space weather data (weather oriented efforts are already operating) which potentially brings in a host of additional measurements at densities impossible to achieve before. More detailed observations from fewer, globally distributed sites such as from incoherent scatter radar and lidar, also play important roles in resolving specific process questions, but these sparser measurements must be complemented by evolving global networks.

Ground-based radio can be used for many aspects of studying the sun and heliosphere, from the radio sun itself to solar radio bursts relatively near the sun. Faraday rotation (FR) measurements provide diagnostics in the corona and inner heliosphere, and interplanetary scintillation (IPS) provide information both close-in to the sun in the low-to-middle corona all the way out to beyond 1 AU. IPS is also used in conjunction with tomographic methods for space-weather forecasting at the Earth, the inner planets, and at various NASA spacecraft within the inner heliosphere. All of these forms of radio investigations are in some way supported through NASA funding and have been for some years.

Heliospheric FR is a novel idea and preliminary tests are expected to be carried out in Europe and Australia through 2014/2015. IPS has demonstrated proof-of-concept as a space-weather forecasting tool, but a more-rigorous assessment and validation of the approach needs to be carried out. These are two (FR and IPS) key areas where NASA funding would move science into operations more effectively.

There has been much development with respect to the design and capabilities of ground systems used for research. Early development focused on increasing the size of the individual dishes and telescopes including those in Jodrell Bank UK, in Effelsberg, Germany, the largest steerable dish in Greenbank USA, and the largest dish of all in Arecibo, Puerto Rico. More recent steps forward in radio arrays are completely software driven and pointed. These innovative telescopes (that also form precursors or pathfinders to the highly-advance Square Kilometre Array, SKA) include the novel LOw Frequency ARray (LOFAR) based across Europe, the Murchison Widefield Array (MWA) based in Western Australia, and the Long Wavelength Array (LWA) based in New Mexico. Additionally, there are various current dedicated IPS systems around the world based in Japan, India, Russia, and Mexico, as well as a set of radioheliograph systems for solar and solar radio-burst investigations, most-notably, the Nobeyama radioheliograph in Japan.

Increased capabilities for utilization of radio data requires additional support to scientists innovating scientific applications for radio solar, heliosphere, and space-weather capabilities including their transition to operations. New capabilities should be demonstrated and tested for space-weather predictions using IPS and FR. For example, FR will likely provide a reliable method to remotely-sense and predict the three-component magnetic fields of the solar wind and CMEs. In addition, there is opportunity for expansion of worldwide radio systems in conjunction with other programs. The Nobeyama radio-heliograph is presently at risk of closure.

Collection and dissemination of potentially useful data in real time should be strongly encouraged, in order to increase the usefulness. Presently, there is a need for a clearinghouse or catalog of the data that are available. The current “virtual observatory” model, that only lists data availability and locations, is not sufficient. Each unique dataset should be housed and distributed with available software utilities in commonly used software languages. These utilities should automatically import requested data streams with minimal effort, regardless of the format. Recently NASA has initiated a movement towards general API access to the CDAWeb data archive. Similar capabilities should be encouraged for ground-based, real-time measurements in order to achieve the most cost-effective use in space weather monitoring and predictions.

Advanced cyber-infrastructure (CI) would help researchers assimilate, explore, and understand observations obtained from disparate databases. NSF’s “EarthCube” infrastructure, that is under development for use in geophysical sciences, may be helpful. Partnerships between NASA and NSF partnerships would promote a better and more innovative use of these datasets in the LWS program.

5c. Sun-Planet and Star-Exoplanet Connections

The physical processes by which the dynamic sun impacts the environment of Earth are the same processes by which the sun impacts the environments of other solar system bodies and by which stellar variability impacts the environments of exoplanets. Consequently, comparative studies of sun-planet and star-exoplanet connections can improve predictive capabilities related to sun-Earth connections.

Our own solar system presents an excellent opportunity to test the physics-based models that will advance LWS science under conditions rarely encountered at Earth. At NASA, such activities lie on the interface between the Heliophysics and Planetary Science Divisions. We may find more extreme conditions at other planets that will inform us about rare but possible space weather that occurs on Earth, thus improving our fundamental understanding of extreme events.

The importance of interplanetary space weather to Heliophysics was recognized in the 2014 Heliophysics Roadmap. In its Science Traceability Matrix, the majority of top-level science investigations look beyond Earth, including: How are plasmas and charged particles heated and accelerated? How are planetary thermal plasmas accelerated and transported? What governs the coupling of neutral and ionized species? How do coupled middle and upper atmospheres respond to external drivers and to each other? How do planetary dynamos function and why do they vary so widely across the solar system? What is the composition of matter fundamental to the formation of habitable planets and life? How are mass and energy transferred from the heliosphere to a planetary magnetosphere? What are

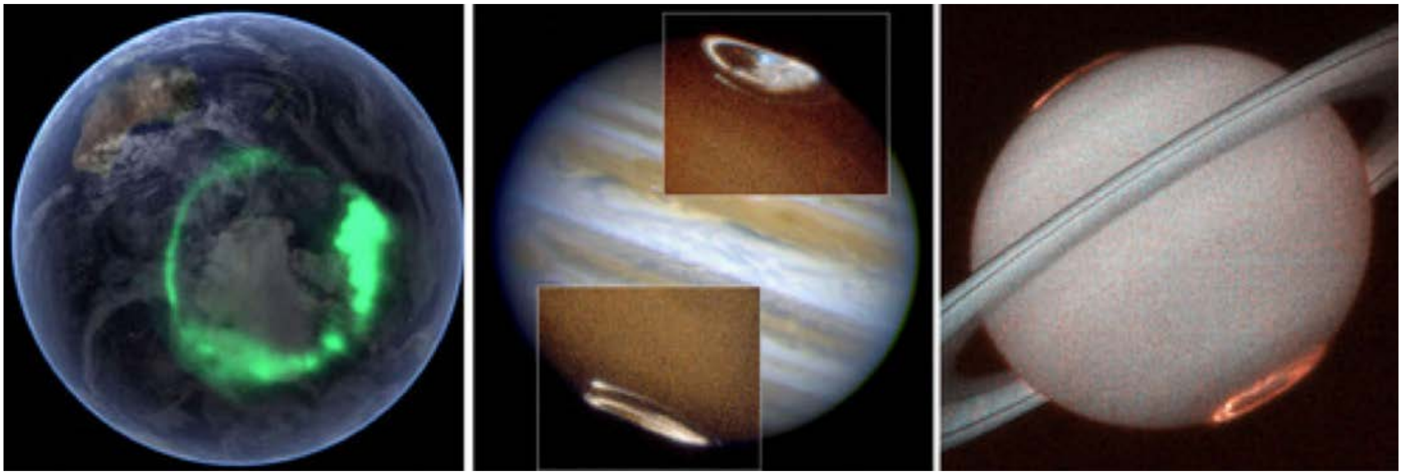


Figure 12. Auroral processes at Earth, Jupiter and Saturn reveal the universality of heliophysical properties throughout the solar system. The physics of the aurora control hazards that play a critical role in understanding the upper atmosphere of Earth, the planets and exoplanets.

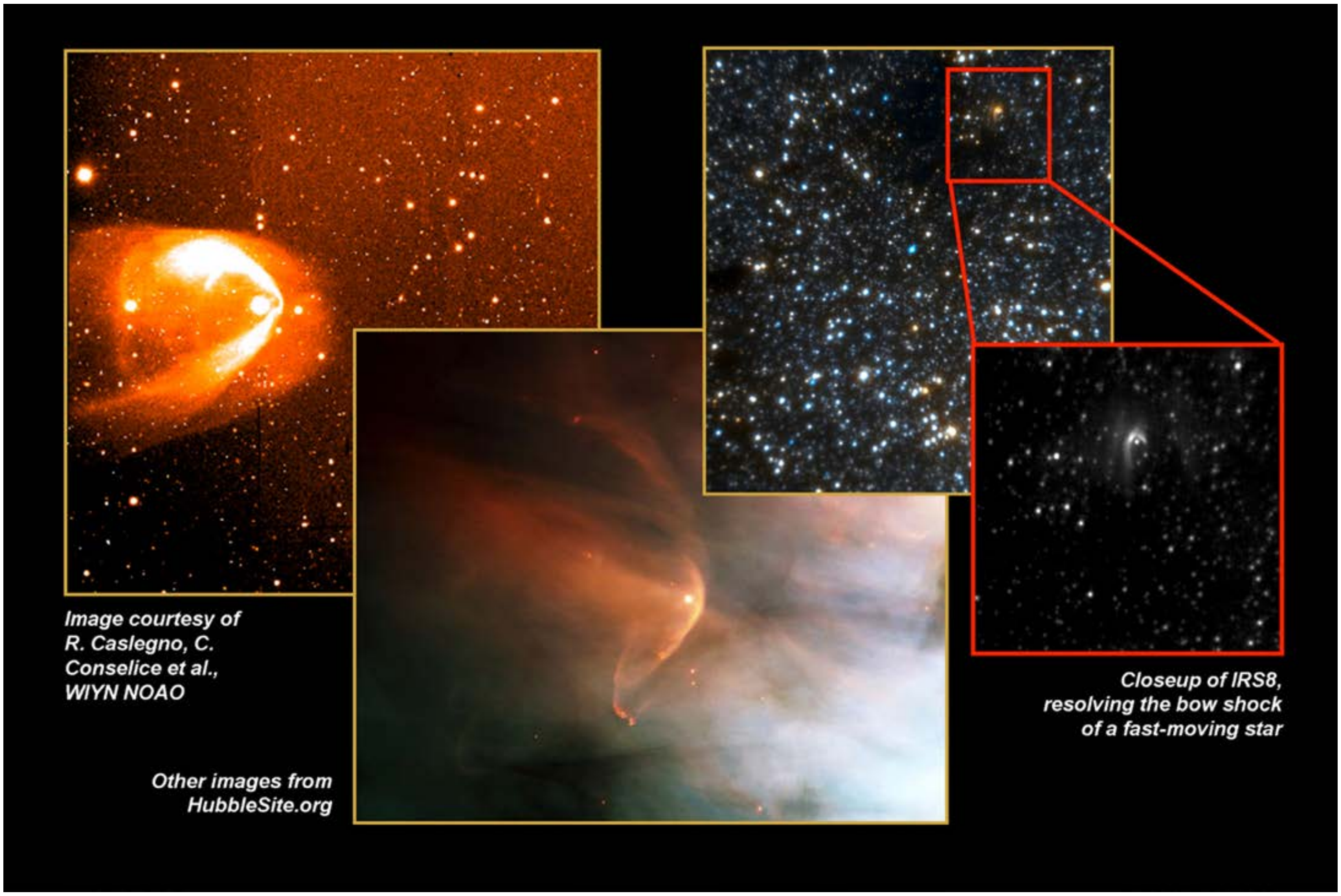


Figure 13. Astrospheres are the analogs of our heliosphere surrounding other stars. Like the heliosphere, astrospheres play a fundamental role in determining the radiation and plasma conditions of exoplanetary environments. Astrospheres play a fundamental role in determining the habitability of exoplanetary environments. Astrospheres provide significant new information about the history and future of our own heliosphere and the habitability of our home in space.

the transport, acceleration, and loss processes that control the behavior of planetary magnetospheres? What is responsible for the dramatic variability of the ionosphere-thermosphere-mesosphere region? How do the magnetosphere and the ionosphere-thermosphere systems interact with each other?

The other terrestrial planets, which share similar origins to Earth, yet differ so markedly from it, are particularly compelling examples. Questions regarding the fate of Venus and Mars and how their present conditions relate to their historical exposure to evolving solar influences have already been recognized as important by recent NRC and NASA reports—and are the key subjects of current missions such as MAVEN. Atmosphere-less bodies in the inner solar system provide opportunities to study how solar wind-magnetosphere coupling arises in the absence of an appreciable ionosphere and atmosphere. The

MESSENGER spacecraft is in orbit at Mercury, which has an unusually strong magnetic field, and the LADEE spacecraft is in orbit at the Moon, which lacks any magnetic field of its own, but which passes through Earth's magnetosphere on its orbit. Space weather also impacts the outer solar system. Both the Juno spacecraft, which is about to reach Jupiter, and the Cassini spacecraft, which is in orbit at Saturn, contain comprehensive suites of fields and particles instruments, making them well-suited to observing space weather effects on the rotation-dominated magnetospheres of the giant planets. Even further afield, New Horizons is currently observe how the space environment at Pluto responds to the solar wind. It is clear that a substantial and growing body of planetary observations exists concerning sun-planet interactions.

Numerical models have been applied in the study of space weather beyond 1 AU, many of which originated in Earth-based studies. Testing these models under physical conditions never encountered at Earth has proven valuable for identifying and remedying model weaknesses. Collectively, existing models can investigate all aspects of inter-planetary space weather, including solar wind, magnetosphere, ionosphere, and neutral atmosphere.

A key finding is that a joint Heliophysics and Planetary Science program to investigate the effects of space weather throughout the solar system, especially at Venus, Earth, at Mars, would be timely and potentially game-changing for our view of planetary systems with stars like our own. The data and models necessary for progress already exist; all that is needed is a program to catalyze scientific activity.

The emerging field of space weather at exoplanets presents further opportunities to advance LWS science by comparative studies involving conditions never encountered in the solar system. At NASA, such activities lie on the interface between the Heliophysics and Astrophysics Divisions.

As research into extrasolar planetary systems grows to become a major part of NASA's mission, our understanding of how planets in general interact with, and are affected over time by, their stellar hosts takes on broader importance. In particular, Kepler observations of thousands of sun-like stars—some of which are known exoplanet hosts—have shown that the issue of sustained habitability must consider not only the classical habitable zone, but also the level and nature of stellar activity. In cases of young sun-like stars, extreme flares are apparent—begging the question of what is happening to the young planets in orbit around them. It is becoming increasingly clear that space physics at exoplanets may be an important tool for detecting certain molecular species, such as oxygen, that shine brightly in the UV part of the spectrum and may be detectable from Earth. Auroral emissions at other planets, including in the radio spectrum, may become an important tool for probing exoplanet atmospheres and the solar conditions that influence the exoplanetary systems.

Recent discoveries by Voyager and IBEX concerning the boundary of our sun's heliosphere are complemented by observations of astrospheres around other stars. The locations, morphologies, and other properties of these boundaries between stars, including the sun, and the surrounding interstellar medium will change over time as stellar activity rises and falls.

Another key finding is the development of a joint Heliophysics and Astrophysics program to investigate the effects of stellar variability on astrospheres and the exoplanets within them. This would enable tests of theories developed in light of the Voyager and IBEX discoveries concerning the sun's heliosphere and would take advantage of the unprecedented Kepler stellar observations to shed light on how dynamic stars affect the long-term sustained habitability of planets.

5d. Forums for Model Validation, Testing, Forecasting and Evaluation

Model validation is critical to LWS. The appropriate forums for model validation must be established to enable the LWS program to have continued success over the next 10 years.

LWS is emphasizing Strategic Science Areas that help bridge the gulf between science and user needs and that demonstrate the benefits of the LWS targeted science approach. To use LWS capabilities effectively for these SSAs requires new forms of validation that diagnose model uncertainty. The use of coupled models with diverse data sources complicates making useful validations. To improve models towards predictive capabilities, it is necessary to validate how well components of coupled models perform. Quantification of uncertainty, based on uncertainties in input parameters/data as well as inherent model uncertainties, is crucial.

Validation requires a strong foundation in observations. Therefore, continued LWS progress requires data streams used to validate progress towards LWS goals. We cannot decouple validation from the need to obtain continuous measurements. Since the Heliosphere is always changing, relying solely on a past "golden age" when more monitoring data are available is risky. Models must be validated against current conditions as those conditions, and the models, evolve.

We recognize two broad categories of validation:

1. Assessment of a model's ability to reproduce space environment phenomena
2. Assessment of the predictive capability of a model for user-defined metrics

Assessment of state-of-the-art modeling ability to reproduce space environment phenomena

The goals of these metrics are not to meet specific operational needs, but to provide insight into a model's ability to reproduce the underlying physical processes leading to model output and potentially forecast. Such assessment is essential for ongoing model improvement, and should occur in parallel with assessment with user-oriented metrics. The community has recognized that due to the maturity and increasing complexity of global space weather models, there is a need for the systematic and quantitative evaluation of different modeling approaches. Using observations to identify and quantify physical phenomena represented in the models, and defining an approach to model intercomparison, requires careful consideration. Sensitivity of the model output to external drivers (input parameters), boundary conditions, modeling assumptions and adjustable parameters (so-called "fudge factors") must be considered. Community workshops are one approach for addressing these challenges. During the past few years a series of community-wide activities (aka Modeling Challenges) have been initiated and supported by CCMC.

One example is the GEM-CEDAR Challenge aiming to quantify geospace storm impacts on the ionosphere and thermosphere. In concert with community input, eight physical processes were identified, for example quantifying the storm energy input and expansion of the magnetosphere-driven convection pattern to lower latitudes. A systematic comparison of observable manifestations of these processes, and comparison of their representation between models, is used to provide insight into physical processes, eventually leading to model improvement and understanding how these processes might affect specific forecast metrics.

Another on-going community-wide model validation activity is the SHINE Modeling Challenge. There is a large and growing number of models with different algorithms, data sources and levels of approximation being applied to study the corona and inner heliosphere. The community has begun to establish a systematic effort to compare these different models and evaluate their absolute and relative performance. It was acknowledged that assessment of modeling capabilities of ambient conditions is a first necessary step. The first set of problems is focused on ambient conditions, coronal structure and the structure in the inner heliosphere. The problem sets include solar minimum and solar maximum times and tests the influence of different magnetic map sources. The coronal model runs are analyzed to compare field topology (including coronal hole locations and current sheet streamer base size), and EUV and X-ray emission in selected lines or broad-band ranges for comparison with full disk observations. Additional metrics might include differential emission measures of selected features such as loops, coronal holes, etc.) and possibly line-cuts through the emissivity profiles. Features to be tested against might include, sector boundaries, CIR and SIR location and structure, helmet streamer location. The inner heliospheric models should be tested both in and out of the ecliptic.

Assessment of the scientific capabilities of models should be open to as much of the community as feasibly possible and facilitated if possible by ongoing LWS research.

Assessment of the predictive capability of a model for user-defined metrics

Defining metrics appropriate to specific applications that are useful for a specific group of end users is a challenging research project that requires understanding of both science and engineering sides of the space environment impact problem. User-oriented metrics are strongly dependent on end user needs. In most cases, users of space weather products are interested in forecasting space environment impacts rather than in predictions of specific physical parameters. Thus, end-user metrics may differ significantly from the scientific metrics defined in the previous section. Linking of space environment models with engineering models calculating impacts on technological and biological systems is an important step in transition of research to operations and is a key to defining appropriate quantitative metrics (quantitative measure of usefulness). Understanding which aspects of spatial and temporal characteristics of space environment parameters are the most important for user impacts is also a challenge. In addition, model performance may depend significantly on the metric used. For example, models that rank highly for one set of metrics may perform poorly for another physical parameter and/or metrics format.

Effective communication between science, operational and engineering communities, mutual education, and joint development are activities still in their infancy, and will benefit from organizing working groups and periodic workshops. For example, the geospace model validation activity (in support of operational geospace models selections by NOAA/SWPC) was built upon the ground magnetic perturbations (delta-B) metrics study that was a part of the GEM Modeling Challenge Project initiated by CCMC in 2008.

Availability of accessible space environment impacts databases and linking them with databases of predicted space environment events is another important element that will facilitate assessment of space weather forecasting. Engagement of the commercial sector and NASA mission specialists will significantly facilitate progress.

Due to their importance, outcomes of validation activities should be broadly accessible. Prototyping facilities with easy community access and tight coupling with a variety of models are valuable, including demonstrating operational potential of innovative forecasting techniques. Such facilities might provide the following elements:

1. Forums that bring together modelers, data providers and users of space environment prediction models to enhance communications, facilitate collaboration and education between communities.
2. Forums for metric definition.
3. Web-based systems for the submission, analysis and public dissemination of community-wide validation projects.
4. On-line archives of validation results.
5. Access to observational data, model results, and metrics tools.
6. Databases of space weather impacts

5e. Data Exploration and Assimilation

Developing physical understanding ultimately to the point of predictive capability is a goal of the LWS Science program. In other areas, for example, terrestrial weather, it is widely recognized that predictive capability requires some form of data assimilation into the computational models used for prediction. Data assimilation is currently used in several areas within Heliophysics as a way of initializing boundary conditions for computation. Two examples are: solar magnetogram inputs to potential-field source-surface models used to drive models of the solar wind such as WSA-ENLIL, and the Assimilative Mapping of Ionospheric Electrodynamics model (AMIE) used to initialize general circulation models of the thermosphere-ionosphere system.

A significant new challenge is integrating assimilative methods throughout the Heliophysics enterprise. This is most well developed in the upper atmosphere, where assimilative models have been transitioned to operations and are also under active research as a strategic capability. There is no question that data assimilation must be part of any predictive capability. The key question for the future of LWS is to what degree it becomes part of the goal of targeted scientific advancement that is at the heart of LWS.

LWS has created new community tools by developing models that describe key aspects of the connected sun-Earth system. The Steering Committee recognizes that tools focused on analysis and interpretation of large data sets could similarly become important community tools that advance LWS objectives. The committee specifically finds that such “big data” initiatives be considered by the LWS community and future LWS development areas.

5f. Applied Research and Transition to Operations

A major challenge to accurate space weather models is crossing the large valley between research and operational codes, and putting in place efforts that lead to continuous forecast improvement as science advances. Table 3 highlights the significant differences between research models versus operational codes. Operational codes require rigor in software versioning, validation, and documentation that is absent in research codes. Other issues arise with operational codes concerning intellectual property and algorithmic development that pose significant challenges to the common research mode in which many models are developed.

Table 3. Transition from research to operational codes.

Research Code	**Community Code**	**Operational Code**
Run and analyzed by a small group of scientists	Run by highly trained scientists at CCMC, analyzed by community members	Run and analyzed by non-scientists
Often “hacked” together with no software discipline	Streamlined version of research code	Highly controlled software product
No manual, few comments	Occasional manual, some comments	Extensive manual and detailed comments
No version tracking, bug fix history	Version tracking, some bug fix history	Version tracking, bug fix history
Validation by developer	Independent validation	Continuous validation, skill score evolution
Code changes as the developer wishes	Occasional code updates	Highly controlled regular code update process
No intellectual property concern	CCMC “rules of the road” apply, but no contractual agreement	Intellectual property is major concern, lawyers involved
Developers guard source code as a trade secret	Source code is available only to CCMC staff	SWPC treats code as government property
Only limited information is published about boundary and initial conditions	CCMC staff does not implement new boundary/initial conditions	All algorithmic and model details must be clearly stated

The successful application of scientific advances towards societal needs for space weather information requires both targeted applications-oriented research and focused efforts to facilitate the transfer of research products to users.

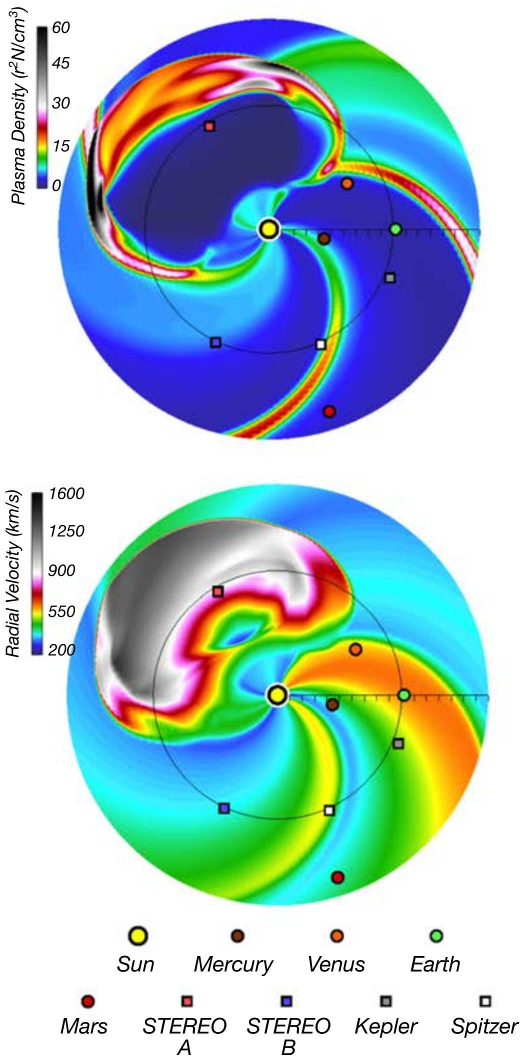


Figure 14. Computer models of these, “3D CMEs” allow us to calculate the trajectory and arrival times of solar storm cloud throughout the solar system.

There are currently no applied sciences programs in the US applicable to space physics and space weather. The US needs a viable Applied Sciences Program in the field of space physics and space weather in order to develop the space weather capabilities required today, as well as to remain competitive with, for example, European activities. Europe has its Space Situational Awareness Program that does support applied sciences projects in our field. LWS Science can play a major role in US applied space weather research activities, but LWS activities must be augmented with applied-sciences research programs that develop improved models from the latest scientific advances. These programs are also important to provide quantitative information on how present and future observational capabilities will lead to desired space weather outcomes. Both government and commercial activities can play a role in tailored applications that generate actionable information for specific end-users/customers.

Key to the success of the Science program will be establishing partnerships across multiple groups such as the user community, commercial service providers, government agencies, and international groups. For example, an LWS Institute (LWSI) is currently being envisioned to facilitate Working Groups (WG) to develop a bridge between current productive heliophysics research and a societally-important technology area that is affected by space weather and hence requires targeted heliophysics investigations. This will be accomplished by bringing together key members of the research and forecast communities to define and scope the new research that will make a critical difference to this technology.

In addition, the NASA's Applied Sciences Program within Earth Science has supported space physics and space weather work that resulted in two major applied sciences advances in the field: NAIRAS and Solar Shield. There may be an opportunity for LWS Science to partner with the NASA Applied Sciences Program to facilitate more efficient applied sciences research in the field of space weather. Applied research provides an opportunity, in the LWS Science context, for a wide interagency partnering and cost-sharing between, for example, NASA, NOAA, USGS, DoD, DHS, DOE and industrial partners. There are existing examples of such partnering for GIC-related applications (DHS-NASA-NOAA-industry).

As described in the LWS TR&T Science Definition Team Report, the key mechanisms that will facilitate the transfer of research products are the ready access to models and data and the availability of verification studies. Models and tools to be transitioned from research to operations need to be robust and scientifically valid, and they need to be evaluated in a standardized fashion through agreed-upon metrics procedures. Such science-based validation and metrics activities are also essential to assess overall program success and to track the development of overall capability. These evaluations should be performed by an unbiased entity that does not have a stake in the performance of any specific model undergoing testing.

The development of space weather applications is also being facilitated by a growing involvement of the commercial sector. In the recent 2013 Solar and Space Physics Decadal Survey it was noted that, during the first decade of the 21st Century, a vibrant commercial sector has emerged that is engaged in space weather providing services and products for customers ranging from agencies and commercial aerospace to consumers. The American Commercial Space Weather Association (ACSWA), formed in 2010, is comprised of many of these companies and represents private-sector commercial interests nationally and internationally. Its formation was a milestone for maturity of the commercial space weather sector.

The commercial sector pillar of the space weather enterprise continues to develop tailored services and products in response to societal space weather needs. Their personnel include scientific and engineering researchers as well as users of services and products.

The activities of this commercial sector are primarily directed toward understanding, measuring, and managing the impacts of space weather upon technology. There are a broad number of societal impacts from space weather that account for a significant part of the national GDP. These represent the domain of potential customers for commercial space weather services and products. Example costs to industry from space weather events include loss of a GEO communications satellite from charging (>$500M), diversion of one commercial airline polar flight due to HF loss and radiation from solar events (>$100K/plane/diversion), power loss from transformer failure and regional electric grid outage (>$400M/unit with >$3B from regional economic losses). It is the recognition that space weather can significantly affect technology in major industries, and that there can be economic loss from not only low-frequency, high-consequence events but also high-frequency, low-consequence events, that motivates the commercial sector to provide services and products for managing space weather risks as described below.

5g. Space Debris

The problem of forecasting collisions between operational satellites and the vast number of objects that have accumulated in low Earth orbit (LEO) over the past 60 years is related to many of the goals and challenges of the LWS program. The last such collision occurred in February 2009, when a defunct Russian spacecraft destroyed Iridium 33, an operating communications satellite.

The U.S. Strategic Command Joint Space Operations Center, which is responsible for tracking and cataloging orbital debris, issues approximately one thousand conjunction warnings every day to operators of military and civilian spacecraft in low earth orbit. These warnings require operators to evaluate the available information and plan for possible evasive maneuvers. Even when such maneuvers are successful (in the sense that no collision occurred; it is rarely possible to know whether the maneuver was truly necessary) they incur significant costs. For example, when the Japanese-led international solar mission Hinode executed an avoidance maneuver in 2012, the spacecraft unexpectedly went into safe mode and required a week of recommissioning before normal science operations could resume. Another LWS-relevant satellite, NOAA-NASA Suomi NPP, has conducted four avoidance maneuvers since its launch in 2011, each time expending fuel needed for its strict station keeping requirements.

Spacecraft in LEO experience periods of increased drag that causes them to slow, lose altitude and finally reenter the atmosphere. Short-term drag effects are generally felt by spacecraft <1,000 km altitude. Drag increase is well correlated with solar Ultraviolet (UV) output and additional atmospheric heating that occurs during geomagnetic storms. Solar UV flux varies in concert with the 11-year solar cycle and to a lesser degree with the 27-day solar rotation period. Geomagnetic storms are sporadic, but most major storms occur during solar maximum years.

Most drag models use radio flux at 10.7 cm wavelength as a proxy for solar UV flux. (Before long, the GOES spacecraft will have continuous UV monitoring) Kp is the index commonly used as a surrogate for short-term atmospheric heating due to geomagnetic storms. In general, 10.7 cm flux >250 solar flux units and Kp>6 result in detectably increased drag on LEO spacecraft. Very high UV/10.7 cm flux and Kp values can result in extreme short-term increases in drag. During the great geomagnetic storm of 13-14 March 1989, tracking of thousands of space objects was lost and it took North American Defense Command (NORAD) many days to reacquire them in their new, lower, faster orbits. One LEO satellite lost over 30 kilometers of altitude, and hence significant lifetime, during this storm.

Atmospheric drag due to the finite density of the thermosphere and exosphere is the primary nonconservative force acting on LEO objects, and is typically the largest source of uncertainty in the trajectory predictions needed for collision risk assessment. Thermospheric density is strongly driven by seconds-to-decades variations in solar extreme ultraviolet and soft X-ray radiation (which originates in the magnetically dominated solar chromosphere, transition region, and corona); by solar wind and magnetospheric disturbances associated with CMEs, corotating interaction regions, and the interplanetary magnetic field; and by terrestrial weather propagating up from the lower atmosphere. The uncertainties in forecasts of these drivers, and in the thermospheric response, accumulate rapidly in the prediction of orbital trajectories, making collision-risk assessment very difficult.

The LWS program can contribute to the problem of conjunction assessment in a number of ways, some of which are outlined in the 2012 NRC report "Continuing Kepler's Quest: Assessing Air Force Space Command's Astrodynamics Standards. Research that leads to improved measurements, models, and forecasts of thermospheric and exospheric density is the most direct path. Research that improves our understanding of the near-term (1-7 days) evolution of solar activity would contribute significantly to this problem. Such research is likely to focus on the evolution of surface magnetic fields as well as on local helioseismology, which could aid in forecasting the emergence of magnetic flux. Also required is the continued development of models that include forcing from the lower layers of Earth's atmosphere, as well as the thermosphere/exosphere response to solar forcing.

LWS can also contribute to the task, crucial to risk assessment but neglected in current operations, of characterizing the density forecast uncertainty. To achieve the mathematical rigor needed for this task, it is essential to treat the thermosphere, solar activity, and the lower atmosphere as a coupled problem. Finally, LWS can contribute to long-term (decades to centuries) forecasting and remediation of the debris population itself, Atmospheric drag is currently the only mechanism by which space objects are removed from orbit, and the long-term evolution of the sun and Earth's atmosphere may have profound effects on the future size and characteristics of the debris field.

5h. Sun-Climate

The potential pathways by which solar magnetic activity can couple into the Earth's climate system have been subjected to a diverse multitude of studies over the past several decades. The sun's impacts range from the topmost layers of Earth's atmosphere at the very interface of space down to the coupled systems of atmosphere, oceans, cryosphere, and landmasses that support human society. A recently released workshop report by the U.S. National Research Council, The effects of solar variability on Earth's climate: a workshop report, National Academies Press (catalog entry 13519), found that "no satellite measurements have indicated that solar output and variability have contributed in a significant way to the increase in global mean temperature in the past 50 years." On longer time scales, extending to well before the Industrial Revolution, such effects appear to exist, however. Moreover, the NRC report notes that "[locally, however, correlations between solar activity and variations in average weather may stand out beyond the global trend; such has been argued to be the case for the El Niño-Southern Oscillation, even in the present day."

The NRC report notes that both the long-term sun-climate couplings and the regional effects require an improved understanding and quantification on two key fronts: (1) the solar spectral irradiance (SSI) and its integral over all wavelengths, the total solar irradiance (TSI), and (2) the effects of the solar wind on the galactic cosmic ray (GCR) population. Calibrating the direct measurement of TSI and the incomplete measurement of SSI against decades-long climate runs as well as the reconstruction of TSI and SSI over multiple centuries provides an important test bed for global climate models in a variety of circumstances. Knowledge of the GCRs is important because of the possible impact of GCRs on climate through effects on cloud formation and atmospheric conductivity. It is also important because GCR-induced radionuclides offer the potential of extending sun-climate studies into a past that extends well beyond the century of measurements of solar activity and well beyond the four centuries of direct sunspot records. The NRC report states the following: "A key area of inquiry deals with establishing a unified record of the solar output and solar-modified particles that extends from the present to the prescientific past. The workshop focused attention on the need for a better understanding of the links between indices of solar activity such as cosmogenic isotopes and solar irradiance. A number of presentations focused on the time scale of the solar cycle and of the satellite record and on the problem of extending this record back in time."

Solar variability provides a pathway to explore climate patterns and climate models on a range of time scales that are not involved in other processes: "The importance of the solar cycle as a unique quasi-periodic probe of climate responses on a time scale between the seasonal and Milankovitch cycles was recognized in several presentations. The signal need only be detectable, not dominant, for it to play this role of a useful probe."

Expanding our knowledge beyond the directly measured TSI and SSI variability presents an important and exciting new challenge. Once again, according to the NRC report: "Some workshop participants also found encouraging progress in the 'top-down' perspective, according to which solar variability affects surface climate by first perturbing the stratosphere, which then forces the troposphere and surface. This work is now informing and being informed by research on tropospheric responses to the Antarctic ozone hole and volcanic aerosols. In contrast to the top-down perspective is the 'bottom-up' view that the interaction of solar energy with the ocean and surface leads to changes in dynamics and temperature. During the discussion of how dynamical air-sea coupling in the tropical Pacific and solar variability interact from a bottom-up perspective, several participants remarked on the wealth of open research questions in the dynamics of the climatic response to TSI and spectral variability."

Many of the links in the physical chains from sun to climate that are being investigated are poorly understood, with measurements covering only part of that range of processes, and with multiple simplifying assumptions being made when, from modern observations, we know that the situation is quite complex. The latter is particularly evident in the relationship between sunspots, faculae and total solar irradiance (TSI), as well as in the chain from galactic cosmic ray modulations in terrestrial records (and their potential chemical signatures) to solar activity which involves poorly known heliospheric-field variability, geomagnetic field variations, and climatic effects on the deposition of nuclides into the biosphere and ice sheets.

Research Needs and Opportunities for the Near Future

The following are the most important areas in which the LWS Science program can effectively contribute given the expertise of the researcher pool that fall within its domain and the available research budget:

- Establishment of a reliable SSI record that combines all

available measurements collected during the space age, and that is associated with quantified uncertainties. This project should be executed by two or more independent groups in order to ensure that independent validation of the results is performed.
- More work is needed in the area of understanding atmospheric impacts of solar spectral irradiance variations on the upper and middle atmosphere on the time scale of the 11-yr solar cycle. Such understanding will contribute to improved GCM simulations of the sun-climate coupling on centennial time scales.
- Development of the understanding and tools needed to transform radionuclide and sunspot records over past centuries to millennia into estimated SSI values, with an assessment of the associated uncertainties. This effort includes:
- The study of recent minimum-activity states of the sun in comparison with the state during the Maunder Minimum to provide a baseline reference level for TSI and SSI variability over multiple centuries.
- The utilization of observations of sun-like stars from X-ray to infrared to guide and test the SSI model(s) developed for the sun.
- Study of the chemistry and dynamics of the middle and upper terrestrial atmosphere subject to X-ray, (E)UV, and energetic-particle exposure, in order to effectively couple such SSI models to global circulation models. Such studies are needed to deepen our understanding of couplings with the terrestrial climate system from oceans and landmasses up to the top of the thermosphere (including the different roles and efficiencies of top-down and bottom-up mechanisms).
- The separation of responsibilities for the NASA Heliophysics and Earth Science divisions now lies at the stratopause. Research shows that the climate system couples across this rather arbitrary administrative divide. Hence, we observe that the impact of the division of responsibilities within NASA's SMD on sun-climate science be assessed and ways be identified to minimize its negative effects while optimizing utility of available resources: collaborative efforts between NASA's Earth Sciences and Heliophysics divisions should be strategically developed to effectively meet the needs of sun-climate science and should be designed to provide the necessary resources to address the outstanding questions.
- In partnership with NOAA and NSF establish the variability in regional climates and correlate these with SSI records over the time interval over which reliable SSI information is available. On the short term, this means focusing on the most recent three decades. Once the proxy-based SSI data are demonstrated to be accurate and reliable, the period can be extended to the beginning of the 20th Century for which many solar observations are available. Eventually, this work can be extended to multiple centuries once it has been demonstrated that SSI records can be reliably based on sunspot numbers or even radionuclide data.
- In partnership with NSF and SMD's Astrophysics Division, support the development of a predictive dynamo model of the sun that incorporates both the small-scale near-surface dynamo and the deeper-seated global dynamo, guided by both solar and stellar observations.

Pathways for the Future of the LWS Science Program

The sun-climate theme within LWS Science has a unique societal relevance. It also is a uniquely challenging inter-disciplinary theme that extends well beyond the traditional heliophysics domain by involving many aspects of the geo-sciences. Despite the complex web of physical processes to be studied, the LWS Science theme has proven to play an important role in the overall study of climate and climate change in particular because it stimulates the expertise close to the core of the LWS goals: understanding of solar and heliospheric activity, and the physical processes that couple that activity to the uppermost layers of the Earth's climate system. The knowledge and the modeling capabilities that are founded on those two aspects are key to the successful study of the impacts of solar activity on the complete terrestrial climate system on time scales of decades to millennia. We emphasize that knowledge in the sun-climate field flows in multiple directions. For example, in developing the knowledge of solar and heliospheric activity based on radionuclide studies, the attribution of geomagnetic, climatic, and solar/heliospheric influences supports the establishment of a long-term record of solar/heliospheric activity that could not be derived otherwise. Another example of information flow concerns that of the solar dynamo in which information exchange between heliophysics and astrophysics are beneficial to both fields.

One foundation for the success of the sun-climate theme within LWS is effective coordination with the funding organizations that support research in climate modeling. Another is the development of reliable products (such as TSI and SSI data, and GCR spectra, all over decades to millennia) as input to the climate community, a better understanding of the response of the middle and upper terrestrial atmosphere subject to SSI and GCR changes as input to global climate models, and forums for joint activities (including research and workshops) in which the heliophysics and climate communities can interact and improve their communication and exchange of information and ideas.

Among the specific findings for future inter-agency efforts are:
- Improvement of standardization and sharing of data products;
- A broad assessment of available proxy data for both climate and solar and heliospheric activity;
- Intercalibration of satellite-based atmospheric remote sensing measurements for missions supported by NASA Earth Science and Heliophysics to provide a combined assessment of solar cycle signals in key parameters such as ozone,
- A coordinated effort to combine solar and stellar information on dynamo processes and on spectral irradiance variability, and
- Laboratory experiments on cloud nucleation.

The resources of the NASA/LWS program preclude, by itself, the formation and funding of research projects that range from the solar drivers to long-term global circulation models. Unless partnerships can be developed that enable such comprehensive research efforts, the LWS TR&T program should stimulate key independent projects that are well defined by the proposing team and judged to be feasible by the review team. We observe that the formation of teams after the proposal selection as is done in the FSTs might be detrimental: the range of expertise needed for sun-climate studies is so wide that the likelihood of successful formation of a team based on post-selection grouping appears dangerously small and detrimental to the project success. On the other hand, we find that the development of a process by which PIs feel stimulated to assemble larger teams to address promising and important projects that require a more substantial investment than that commonly requested for smaller projects. The selection process should fairly judge scientific importance and likelihood of success in the ranking of larger and smaller proposals.

LWS support of interdisciplinary meetings or of LWS sessions within, e.g., AAS, AGU, AMS or climate-centric meetings is to be encouraged.

5i. High-Performance Computing

Computational modeling, simulation, and data analysis have been among the most important drivers of scientific discovery during the last three decades. This progress has been enabled by remarkable leaps in computing technologies, producing parallel computers of great power and speed which have been brought to bear on increasingly sophisticated software and efficient algorithms. We anticipate a transition from the present-day terascale and petascale systems to the exascale in the near future, empowering the science community further to undertake challenges that can be potentially transformational.

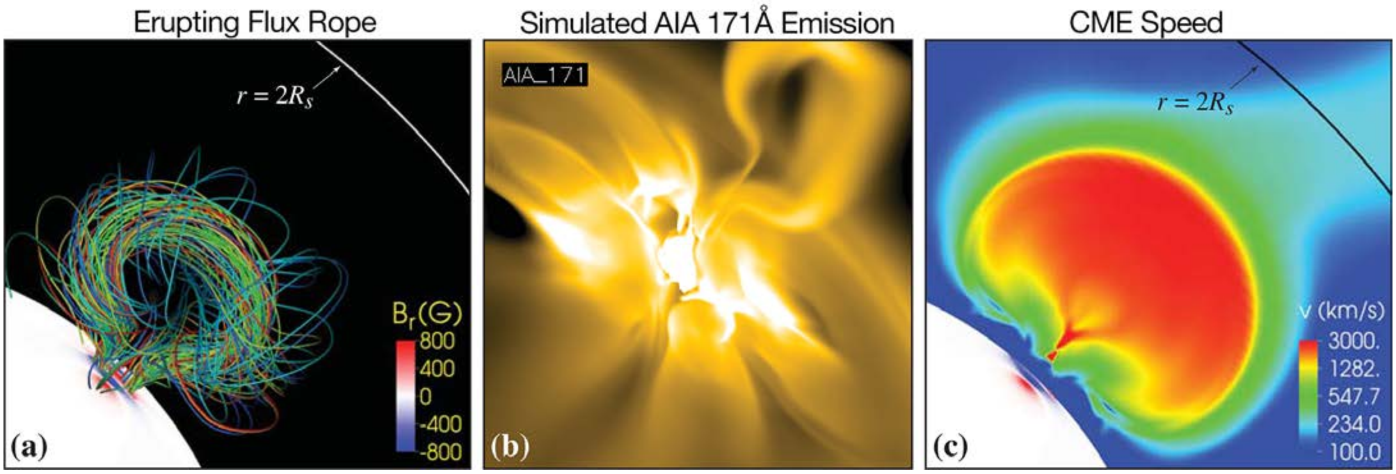
The heliophysics science community is experiencing a rapid and radical transformation because of vast increases in the sophistication of instruments and in data volumes. Progress in our understanding of heliophysical processes requires that data analysis be combined with computational modeling, numerical simulation, and data-assimilation programs. The effectiveness of our community-wide theory, modeling, and data assimilation and analysis efforts depends critically on the development of innovative numerical algorithms and their use on high-performance computing platforms, as we see happen in other scientific disciplines (such as astrophysics, high-energy and nuclear physics, plasma and fusion science, and climate prediction and change), which are well-positioned to exploit fully the power of new computing technologies. We cannot rely on the slow diffusion of the fruits of the efforts made by other scientific and engineering disciplines, but need to actively work on advancing our discipline's capabilities to meet the demands for scientific breakthroughs, the design of next-generation space missions, and to tap into the pool of new and young talent, eager to bring the power of new computing technologies and methodologies to bear upon heliophysical science challenges.

Progress on some of the most exciting scientific challenges in heliophysics is awaiting the development of new computational techniques and the full utilization of petascale computing. Looking across the various sub-fields, the basic requirements for new tools and approaches share many common themes. Researchers seek to understand systems with vast disparities in spatial and temporal scales. This requires accurate models governing large-scale evolution, which may yet depend on kinetic processes. New petascale machines and other advanced hardware such as general-purpose graphical processing units (GPU) and Intel Xeon Phi now offer the potential for tremendous progress on these multi-scale problems. The ability to fully exploit these computers will permit calculations 100-1000 times larger than previous efforts. However, the spatial and temporal scale separations are so large that simply adapting existing algorithms to the new hardware is not sufficient. New breakthroughs will require improvements in multi-scale algorithms and adapting the modern advancements in algorithms. In addition, new approaches are needed to deal with the large quantity of data generated by both simulations and observations. We have identified four basic categories of computational tools to address these needs:

High Performance Solvers and Advanced Algorithms for Fluid Simulations

Fluid simulations play a critical role in all sub-fields of heliophysics, including neutral fluids in the atmosphere/thermosphere, electrostatic fluid models in the ionosphere, and MHD models in magnetospheric, interplanetary and solar physics. These range from 1D regional models (such as solar wind acceleration), to 2D codes (such as magnetotail reconnection models) to fully 3D global codes (such as global magnetosphere and heliosphere codes). Most of these codes were written by scientists with deep understanding of the physics but limited background in modern algorithms, and before massively parallel machines were widely available.

Efforts to develop modern fluid simulation capabilities should include three key components: improved physics and closures, advanced solvers, and the ability to fully utilize existing and future computer hardware. Depending on the specific science focus, the optimum mixture may differ. For example, how to properly capture kinetic effects within fluid calculations or describe the effects of turbulence remain key issues for accurately modeling magnetic reconnection, but improvements in solver


Erupting Flux Rope

Simulated AIA 171Å Emission

CME Speed

Figure 15. High performance computing plays a fundamental role in LWS science. Shown here are the conditions leading to an eruption of a coronal mass ejection at the sun. Simulated images can be directly compared to remote observations to test theories and models of the transient events that create dangerous solar energetic particles and coronal mass ejections that propagate through space, disrupt the magnetosphere and create globally induced currents at Earth.

technology and/or computer hardware are also very important for performing the high-resolution simulations required to test improved fluid closures and subgrid methods. Most heliophysics simulations are physically far under-resolved, and would benefit greatly modern adaptive mesh refinement (AMR) methods and implicit time stepping. However, in order to simulate physically relevant large systems, the parallel and algorithm scalability is crucial. For explicit codes, parallel scalability is typically quite good using simple domain decomposition, and remains good for enhanced methods like block-structured AMR. While more difficult, recent work has demonstrated that implicit MHD algorithms showing such optimal algorithmic properties are possible. These issues are also important for electrostatic fluid treatments in the ionosphere, where there is a critical need for highly scalable 3D Poisson solvers on non-uniform meshes.

Advanced Kinetic Simulation Approaches and Algorithms

While fluid models have been very successful in modeling the macroscopic structure of many phenomena, there are many important science questions in heliophysics that require a kinetic description. A range of different kinetic simulation approaches have been employed including fully kinetic (ions and electrons), hybrid (fully kinetic ions and fluid electrons), gyrokinetic models, and kinetic-neutral models used for the thermosphere and global heliosphere. Most kinetic simulations still employ a uniform mesh, with simple explicit algorithms. On the positive side, these simple well-tested algorithms can achieve excellent performance and scaling on modern computer architectures. Recent 3D fully kinetic simulation studies of magnetic reconnection have employed over ~1 trillion computational particles running on 105 computational cores, with an additional factor of ~10 anticipated in the next few years. These capabilities are leading to a range of new insights into the physics of reconnection, and may be extremely useful for addressing basic physics issues in shocks and turbulence. However, for many problems the spatial and temporal scale separations are so large, that simple explicit approaches (with uniform mesh) will always be limited due to rigid stability constraints and the long-time scale accuracy of the solution. While investments are clearly needed to help researchers exploit new architectures, there is an equal need for targeted investments in algorithms and multi-scale techniques. This includes asymptotic-preserving discrete numerical formulations, non-uniform structured mesh, AMR, and implicit time stepping and/or discrete-event multi-stepping techniques. The scientific payoff will be high if researchers can effectively combine the raw power of petascale to exascale computing with modern advances in algorithms.

Computational Framework: Coupling Physics Across Disparate Scales

Development of a general simulation approach to handling multi-physics, multi-scale problems described by different models (codes) remains an outstanding research topic in computational physics. Problems in heliophysics will likely require software frameworks that include a superstructure layer that drives the coupled-model application, and an infrastructure layer that provides utilities and data structures for model developers. There are an abundance of heliophysics applications that will benefit from new investments in these capabilities. As one example, researchers have already successfully coupled ionosphere/thermosphere dynamics to global magnetospheric MHD codes. With petascale computers, global hybrid calculations are becoming increasingly realistic, but will still need to be coupled to ionospheric models. While hybrid calculation can properly treat the structure of ion-scale transition layers and shocks, neither approach (hybrid or MHD) can correctly capture the microphysics of magnetic reconnection. Future efforts in computational frameworks may allow researchers to couple more complete kinetic descriptions within the thin current sheets, and thus move towards a more predictive understanding of the global dynamics.

Analysis Tools, Parallel Visualization and Data Mining and Assimilation

Both simulations and space observations are producing increasingly larger data sets that are challenging for researchers to study with existing tools and approaches. New missions such as the Solar Dynamic Observatory have a data rate of 1.4 terabytes per day, while recent 3D kinetic simulations using the newest petascale computers are generating ~40 terabytes in a single run. Extracting new science from these enormous data sets is becoming progressively more difficult. Researchers are drowning in the over abundance of data, and legacy tools and approaches have failed to keep pace. The largest simulations are performed at a few leadership class facilities around the country, and the resulting data sets are now far too large to move. To utilize these new machines, researchers need parallel tools to remotely visualize and manipulate the data, and to easily allow access to teams of researchers working in a collaborative fashion. Although there have been efforts in recent years in extending simulation capabilities to petascale computers, less attention has been paid to the data analysis and visualization of the resulting large data sets. In terms of spacecraft data, researchers have introduced data mining techniques and have worked with experimentalists in their analysis. This effort has met with considerable success and is rapidly gaining adoption. However, funding is required for further expansion of these techniques, as well as the integration of these new methods with the existing data analysis software used by experimentalists.

Chapter 6

Global Cooperation in LWS Science

Space weather is a natural hazard of global proportions, requiring effort to monitor the sun and near-Earth space, as well as impacts on Earth and throughout the solar system, and perform research to enable and improve space weather prediction. Space weather involves global phenomena driven by large solar eruptions that impact large areas of Earth simultaneously, and at the same time it involves local disturbances that can vary significantly from place to place. Participation from countries around the globe is required to effectively monitor and to understand both the drivers of space weather as well as the impacts on Earth and in space. More and more countries are establishing their own procedures for mitigating the risks of space weather, warranting international coordination to ensure that consistent information is available across borders.

The international scientific community involved in space weather research organizes itself under three entities: the International Living with a Star (ILWS) program, the International Space Weather Initiative (ISWI), and the Scientific Committee on Solar Terrestrial Physics (SCOSTEP). These three organizations have overlapping interests, but their focuses are complementary. ILWS is primarily involved in cooperative development and deployment of space instrumentation. ISWI has been spearheading the deployment of low-cost instruments for sun-Earth connection studies in developing countries. SCOSTEP runs long-term (typically 5 years) scientific programs on solar terrestrial physics using space- and ground-based data from all sources and assessing the progress during its quadrennial symposia.

ILWS

The primary objective of ILWS is to bring together spacefaring nations to develop partnerships in solar-terrestrial space missions that enable heliophysics connected system studies relevant to life and society. Such partnership is also required for establishing concrete data sources (including dissemination, storage, and distribution), theory and modeling. NASA actively participates in ILWS activities and has helped to organize science workshops that help achieve the objectives of the ILWS program (e.g., http://cdaw.gsfc.nasa.gov/publications/ilws_goa2006/ is an online book that resulted from one of the ILWS workshops.

ISWI

ISWI is a program of international cooperation to advance space weather science by a combination of instrument deployment, analysis and interpretation of space weather data from deployed instruments in conjunction with space mission data, and communicate the results to the public and students. The ultimate goal is to develop the scientific insight necessary to enhance forecasting capabilities for near-Earth space weather. Currently, ISWI has helped deploy more than 1000 instruments in about 100 countries. There are 17 instrument concepts developed and implemented by many countries in the world, US being the most active. The instruments fall under telescope networks (optical, radio), particle detector networks, VLF networks, ionosondes, Global Navigation Satellite System receiver networks, and atmospheric imagers. One of the key aspects of the ISWI program is to fill gaps in the current space weather data, e.g., information of the ionosphere over Africa. ISWI brings together instrument providers from developed countries and hosts developing countries to arrange deployment and training.

ISWI has been the main activity aligned with the Space Weather Agenda of the Science and Technology Subcommittee (STSC) of the United Nations Committee on Peaceful Uses of Outer Space (UNCOPUOS). UN-ISWI collaboration has been effective over the past several years in deploying space weather instrumentation in many developing countries that have been useful in promoting heliophysics science.

SCOSTEP

SCOSTEP is an interdisciplinary body of the International Council of Scientific Unions (ICSU). SCOSTEP origins date back to 1966 when it was established as the Inter-Union Commission of ICSU on Solar-Terrestrial Physics. SCOSTEP interacts with national and international programs involving solar terrestrial physics elements to:

1. Run long-term (4-5 years) international interdisciplinary scientific programs in solar-terrestrial physics;
2. Engage in capacity building activities; and
3. Disseminate new knowledge on the connected sun-Earth system and how the sun affects life and society through public outreach activities.

The current scientific program of SCOSTEP is known as “Variability of the Sun and Its Terrestrial Impact” or VarSITI for short. The VarSITI program is established after a collective effort by the international scientific community, including an ISSI Forum to finalize. The VarSITI program focuses on four major themes: solar magnetism and extreme events, Earth impacting solar transients, magnetospheric changes, and consequences and processes in Earth’s atmosphere. In order to make progress on these themes, four scientific projects headed by international experts have been defined, i.e., Solar Evolution and Extrema (SEE), International Study of Earth-Affecting Solar Transients (ISEST)/MiniMax24, Specification and Prediction of the Coupled Inner-Magnetospheric Environment (SPeCIMEN), and Role Of the Sun and the Middle atmosphere/thermosphere/ionosphere In Climate (ROSMIC).

VarSITI has great synergy with NASA’s Living With a Star (LWS) program and NSF’s SHINE, GEM, and CEDAR programs. Both NSF and NASA can benefit from the international effort that will enhance the science return from NSF ground-based instruments and NASA space science missions. There are a huge number of VarSITI project leaders from the US, whose participation greatly enhances the global cooperation in LWS Science using data, models, and theory developed from all over the world.

Conclusion

ISWI and SCOSTEP have been effectively using the UNCOPUOS forum to promote the importance of space weather among member countries. This collaboration was successful in conducting space science schools in many parts of the world and has helped young people evolve into practicing scientists. The instrument deployment is usually coordinated during UN-sponsored ISWI workshops, although it is an ongoing activity during other times as well. While there is close cooperation between ISWI and SCOSTEP on capacity building activities, an effective coordination among ILWS, ISWI, and SCOSTEP can eliminate duplication in the area of data, modeling, and theory. In particular, coordination for developing databases for space weather research is needed.

Chapter 7

Deliverables to Address Societal Needs and User Communities

While space weather is a broad umbrella encompassing science, engineering, applications and operations, from the societal perspective, the ultimate goal of space weather activities is to generate products or services (referred to here as "deliverables") that enable end-user action. The deliverables can be applied by the end-users, for example, in space weather hazard assessments, general situational awareness and protective mitigation actions. Consequently, and not forgetting the intrinsic value of basic non-applied scientific research, the work toward actionable deliverables should be one key element guiding our work in the field of space weather.

From its inception, the LWS TR&T program was designed to be targeted (LWS Targeted Research and Technology Science Definition Team Report, November 2003). It was intended to have prioritized goals and objectives that focus on practical societal benefits. The Science Definition Team (SDT) made a number of recommendations to guide the implementation of the TR&T program, including a focus on deliverables.

Findings by the SDT for the successful implementation of TR&T include:
- Providing mechanisms for monitoring how well products that result from the program are transferred into societal benefits;
- Determining the compliance of individual TR&T-funded projects with appropriate metrics, milestones and deliverables;
- Ascertaining that TR&T research products are made available for transitioning to users, where appropriate;
- Require all TR&T-supported activities to identify deliverables with clear relevance to the program's goals and establish schedules and milestones for delivery;
- Every TR&T proposal review panel include one or more members who are potential users of the program's products; and,
- Proposals be ranked on the basis of scientific merit, perceived value to the TR&T mission and its targeted priorities, the description of a credible set of deliverables, success metrics and milestones, and the track record of the proposers.

Among the targeted goals established by the TR&T Steering Committees that program deliverables should address are (LWS TR&T Steering Committee Report for 2006-2007):

- Modeling required for useful prediction of the variable solar particulate and radiative environment at the Earth, Moon, Mars, and throughout the solar system;
- Modeling required for effective forecasting/specification of magnetospheric radiation and plasma environments; and
- Predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation and to coupling above and below.

The continuous improvement of space weather deliverables must be based on knowledge of the impacts, the collection of quality data, and an understanding of potential customer actions. Space weather is different from terrestrial weather in two important respects. First, in many cases the impacts caused by space weather are not well understood today, even among the industries that are directly affected. This is partly attributable to the fact that some of the impacts have only recently become important, for example as high precision applications of satellite-based navigation are implemented. A second difference is that customer needs for space weather services can change rapidly. There is a continuous revision of deliverable needs as technologies and applications evolve and as new mitigation measures are discovered.

There is need to identify and communicate broadly the current and near-term future customer needs, and second, to identify mechanisms that will ensure that our applied research and service efforts keep up with the changes in customer needs and are communicated to users as technologies evolve. A comprehensive space weather strategy should build on the risk assessments that have been conducted to date, identify priorities for near-term service targets, and suggest approaches to maintaining an ongoing effort to collect, analyze, and prioritize the needs of the diverse set of industry and government activities impacted by space weather.

It is clear that much more work is needed to better understand the requirements for specific space weather services and products. However, a number of well-known key needs and deliverables can readily be identified for a number of different end-user groups. Table 4 communicates our current understanding of space weather needs of major end-user groups. The table has four columns: end-user group, impacts on the corresponding group, end-user needs for addressing the impacts and LWS deliverables that address the specified end-user needs. It is emphasized that the goal here is not to detail the requirements for the deliverables but rather to provide a high-level summary of some of the well-known needs associated with major end-users groups.

We note that in the US, USAF has been the central engine behind the deployment of many operational space weather products through its procurement of space weather specification capabilities. This is because, more than any other U.S. Government agency, it has enabled the crossing of the TRL gap from 7 to 9, sometimes referred to as the "valley-of-death" for the lack of funding to move systems from demonstrated performance in operational environments to successfully deployed operational systems. Since October 1957 with the launch of Sputnik and because communication and navigation of space assets are key components, the specification at the current epoch and the forecast for near-term out to 72-hours of the neutral atmosphere and the ionosphere have been the main focus of the USAF related to space weather in the last two decades.

In addition to items in Table 4, many end-user groups also have a great need to better understand extreme space weather impacts, which is also a topic that the LWS program can help address. As an example, there is ongoing work for generating extreme geomagnetic storm scenarios for the power grid industry. These storm scenarios will be used to guide regulatory action in the US and Canada. Further, another common theme for LWS deliverables is the need for tailored products for specific locations of interest. While global indicators such as the Kp index are useful for general specification of storm conditions, space weather impacts can vary substantially from one region to another. For example, ring current plasma populations can have major spatiotemporal fluctuations that can expose spacecraft at specific locations to elevated levels of surface charging hazard. The “ultimate” LWS deliverables and space weather products should take into account the location-specific variability of space weather by allowing tailored specifications of hazard to individual end-users.

Finally, it cannot be over-emphasized that all modeling and predictive capability should include quantification of the uncertainties. Without communication of the “error bars”, end-users have no means to gauge the value of the corresponding space weather product. The lack of error bars can render the provided space weather information practically useless from the end-user standpoint. For example, one will not carry out potentially costly mitigation actions without knowing how large uncertainties are associated with the provided space weather prediction. In the most elementary level, the question about model uncertainties can be addressed by means of rigorous metrics-based validation and verification (V&V) of the deliverables.

Table 4. A high-level summary of key space weather end-user groups, corresponding space weather impacts, end-user needs and LWS deliverables that can be used to address the identified needs. See the text for details.

End-user group	End-user Impacts	End-user need	LWS Deliverable
Aviation	- HF communications problems - Degraded GPS-based positioning inaccuracy - Elevated radiation levels and dose due to solar energetic particles	Observational and model-based real-time and predictive characterization of HF, GPS and atmospheric radiation conditions.	- Observations of upper atmospheric plasma conditions pertaining to HF and GPS signal propagation. - Observations such as SEP fluxes pertaining to atmospheric radiation conditions. - Predictive models that allow global specification of HF and GPS signal propagation conditions. - Predictive models that allow specification of atmospheric radiation conditions.
High-voltage Electric Power Transmission	- Voltage instability - Transformer heating	Observational and model-based real-time and predictive characterization of geomagnetic conditions regionally. Characterization of local ground conductivity structures.	- Observations of geomagnetic variations. A good spatial and temporal coverage the ultimate goal. - Predictive models that allow regional specification of geomagnetic variations on the ground. - Specification of ground conductivity structures.
Spacecraft Operations	- Radiation impact in terms of surface and deep-dielectric charging and single event effects. Total dose effects - Drag effects at LEO - Spacecraft-ground communication effects due to ionospheric disturbances - Disturbances on attitude determination devices such as star trackers and magnetic sensors	Observational and model-based real-time and predictive characterization of upper atmospheric plasma conditions, space plasma and radiation conditions as well as upper atmospheric drag conditions. Importantly, information needed at the locations of impacted spacecraft some of which are in the interplanetary space and/or planetary environments.	- Observations of upper atmospheric plasma conditions and neutral mass densities. - Observations of space plasma (especially ring current and auroral precipitation) and radiation conditions (e.g., radiation belts). - Predictive models that allow global specification of upper atmospheric plasma conditions and neutral mass densities. - Predictive models that allow specification of space plasma and radiation conditions in space.
Human Space Exploration and Commercial suborbital Flights	- Radiation dose effect on the crew - Vehicle effects; see “spacecraft operations”	Observational and model-based real-time and predictive characterization of radiation conditions (currently at LEO). Vehicle-related needs; see “spacecraft operations.”	- Observations of radiation conditions. - Vehicle-related deliverables; see “spacecraft operations.”
Geophysical, Oil and Gas Surveys	- Geomagnetic storms disturb directional drilling and surveys based on magnetic methods	Observational and model-based real-time and predictive characterization of geomagnetic conditions.	- Observations of geomagnetic variations. A good spatial and temporal coverage the ultimate goal. - Predictive models that allow specification of geomagnetic variations on the ground.
Auroral Tourism	- People wish to see auroras	Observational and model-based real-time and predictive characterization of auroral emissions. This may include information about terrestrial weather, for example, in terms of cloud coverage.	- Observations of auroral emissions. - Predictive models that allow specification of aurora viewing conditions
Mobile Communications	- Solar radio noise can cause dropped calls and other interference	Observational and model-based real-time and predictive characterization of solar radio noise conditions at GHz range.	- Observations of radio noise conditions at GHz range. - Predictive models that allow specification of radio noise conditions at GHz range.

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