Table of Contents

I. GENERAL INFORMATION ........................................................................................................... IV

1A. LIST OF INSTITUTIONS: ........................................................................................................ IV

EXECUTIVE SUMMARY ............................................................................................................. 1

INTRODUCTION .............................................................................................................................. 1

RESEARCH ..................................................................................................................................... 3

EDUCATION ................................................................................................................................... 8

KNOWLEDGE TRANSFER .............................................................................................................. 10

DIVERSITY WITHIN CISM ........................................................................................................... 11

DIVERSITY WITHIN CISM ........................................................................................................... 12

CENTER MANAGEMENT ............................................................................................................. 12

LEGACIES .................................................................................................................................... 13

II. RESEARCH ............................................................................................................................... 15

1A. OVERALL RESEARCH DESCRIPTION .................................................................................. 15

1B. PERFORMANCE AND MANAGEMENT INDICATORS ............................................................ 15

1C. PROBLEMS ........................................................................................................................... 15

2A. SOLAR/HELIOSPHERIC THRUST ......................................................................................... 16

2B. MAGNETOSPHERIC THRUST ............................................................................................... 43

2C. IONOSPHERE-THERMOSPHERE THRUST ........................................................................... 63

2D. CODE COUPLING THRUST ................................................................................................. 69

2E. MODEL VALIDATION AND METRICS THRUST .................................................................. 72

2F REFERENCES ............................................................................................................................ 76

III. EDUCATION ............................................................................................................................. 79

IV. KNOWLEDGE TRANSFER (KT) ............................................................................................. 86

V. EXTERNAL PARTNERSHIPS ...................................................................................................... 96

VI. DIVERSITY ............................................................................................................................... 97

VII. MANAGEMENT ....................................................................................................................... 99

A1. ORGANIZATION .................................................................................................................... 99

A2. PERFORMANCE AND MANAGEMENT INDICATORS ........................................................... 100

B. PROGRESS, PROBLEMS, AND CHANGES ......................................................................... 100

C. COMMUNICATION WITHIN CISM ........................................................................................ 100

D. CISM ADVISORY COUNCIL .................................................................................................. 102

VIII. CENTER WIDE OUTPUTS AND ISSUES ............................................................................. 103

1A. CENTER PUBLICATIONS ..................................................................................................... 103

1B. CONFERENCE PROCEEDINGS ........................................................................................... 107

2. AWARDS AND HONORS ........................................................................................................ 119

3. GRADUATES ............................................................................................................................ 120

4. PARTICIPANTS ........................................................................................................................ ERROR! BOOKMARK not defined.

6. INSTITUTIONAL PARTNERS .................................................................................................. ERROR! BOOKMARK not defined.

7. SUMMARY TABLE ................................................................................................................... ERROR! BOOKMARK not defined.

X. BUDGET .................................................................................................................................... ERROR! BOOKMARK not defined.

1. CUMULATIVE EXPENDITURES/PROJECTIONS ................................................................... ERROR! BOOKMARK not defined.

3. REQUESTED BUDGET ............................................................................................................ ERROR! BOOKMARK not defined.

4. CENTER SUPPORT FROM ALL SOURCES ............................................................................ ERROR! BOOKMARK not defined.

5. OTHER NSF FUNDING ............................................................................................................ ERROR! BOOKMARK not defined.

6. ADDITIONAL PI SUPPORT ................................................................................................... ERROR! BOOKMARK not defined.

7. COST SHARE CERTIFICATION .............................................................................................. ERROR! BOOKMARK not defined.
### 1a. List of Institutions:

<table>
<thead>
<tr>
<th>Institution</th>
<th>Role of Institution at Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>Institution 2</td>
<td>AAMU will work with Boston University on model validation and with Florida Institute of Technology on education and increasing diversity.</td>
</tr>
<tr>
<td>Institution 3</td>
<td>Dartmouth College will lead the magnetospheric modeling effort.</td>
</tr>
<tr>
<td>Institution 4</td>
<td>George Mason will work on atmospheric modeling.</td>
</tr>
<tr>
<td>Institution 5</td>
<td>The Applied Physics Laboratory assists with code coupling.</td>
</tr>
<tr>
<td>Institution 6</td>
<td>NCAR will lead the ionosphere/thermosphere modeling effort.</td>
</tr>
<tr>
<td>Institution 7</td>
<td>PSI will work with University of California, Berkeley on the solar/solar wind effort and with Boston University on code coupling.</td>
</tr>
<tr>
<td>Institution 8</td>
<td>Stanford will work with University of California, Berkeley on the solar/solar wind effort.</td>
</tr>
<tr>
<td>Institution 9</td>
<td>University of California, Berkeley will lead the</td>
</tr>
<tr>
<td>Institution 10</td>
<td>University of Colorado, Boulder</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td><strong>Role of Institution at Center</strong></td>
<td>The University of Colorado will lead the knowledge transfer and empirical model efforts and will work closely with NOAA/SWPC to ensure our models are transitioned into the forecasting community.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Institution 11</th>
<th>University of Maryland</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Role of Institution at Center</strong></td>
<td>Maryland will provide code coupling development.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Institution 12</th>
<th>Univ. Texas, Arlington</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Role of Institution at Center</strong></td>
<td>Univ. Texas, Arlington will lead the diversity efforts and will work with Boston University on model validation.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Institution 13</th>
<th>William Marsh Rice University</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Role of Institution at Center</strong></td>
<td>Rice will work with Dartmouth College on magnetospheric physics and with Boston University on code coupling.</td>
</tr>
</tbody>
</table>
Executive Summary

Introduction

“Space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health,” (National Space Weather Program Strategic Plan, 1995). Space weather can cause satellites to fail, disrupt radio communications, cause navigation errors, overload electrical power distribution systems, and expose astronauts to dangerous levels of radiation (Lanzerotti, 2001; Baker, 2002). Mitigation of these effects requires both a better understanding of the space environment and the ability to predict and forecast conditions in space. In turn, the development and testing of physics-based models clarifies key physical processes that are currently controversial or poorly understood.

The Center for Integrated Space Weather Modeling (CISM) focuses its activities around one of the core requirements of the National Space Weather Program (NSWP) Plan, developing space weather modeling capabilities. CISM is developing a suite of ever-improving comprehensive, physics-based simulation models that describe the space environment from the Sun to the Earth. After testing and validating these models, we use them for research, make them available to the wider research community, help transition them as appropriate for use as operational specification and forecasting tools, and use them as learning tools. This shared vision and task binds the geographically distributed and scientifically diverse CISM team into a tight center with everyone doing their part towards the common goal.

The comprehensive models provide the means of achieving CISM's overarching vision: “To understand our dynamic sun-earth system and how it affects life, and society.” Within this greater vision, CISM sees as its mission: to introduce into space physics and space weather research the first comprehensive community model suite analogous to the community models that exist in other fields such as climate research; to introduce into operational space weather prediction and forecasting the use of physics-based numerical simulation models in the same way as they are used in, for example, tropospheric weather forecasting; and to introduce in education, particularly undergraduate and graduate education, the notion that sun-earth science must be viewed as a single, unified field of research and study and not several separate disciplines.

The NSWP was formed in response to the important national need for a coordinated effort to mitigate the effects of space weather, by several Federal agencies, including NSF, representing the research, operational, and user communities. “The overarching goal of the program is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space weather warnings, observations, specifications, and forecasts within 10 years.” (NSWP Implementation Plan, 2000; see also Space Weather Architecture Study Transition Strategy, 1999; Report of the Assessment Committee for the National Space Weather Program, 2006). The NSWP consists of six key elements – forecast and specification services, research, observations, modeling, education, and technology transition and integration. CISM substantially supports this national effort by playing a leadership role in four of these six key elements. As in CISM, the goal of the NSWP research is “to understand the fundamental physical processes that affect the state of the Sun, solar wind, magnetosphere, ionosphere, and atmosphere, with a focus on resolving research problems that impede improvements in forecasting capability.” Similarly, “A primary goal [of the NSWP] is to develop physics-based
specification and forecast models covering the forecast period out to 72 hours for solar events and 48 hours for near-Earth space weather phenomena." The key goals of the NSWP education element are to "enhance public awareness of space weather and its impacts, help insure a sufficient supply of educated scientists and engineers to maintain expertise in all space weather related fields, and improve training of forecasters, observers, and system operators," all three of which CISM’s education program addresses. The goal of the NSWP technology transition element is “to facilitate the transfer of tools, techniques, and knowledge from the research or commercial communities to the operational forecasting activities.” CISM’s use of observations, particularly solar observations, helps define and test the critical observational needs of the NSWP. Thus CISM is directly addressing an identified national need, and our configuration as a center provides the means to address these needs in a systematic, coordinated manner, and to provide leadership to the community as a whole.

An understanding of space weather begins with the Sun. The two solar phenomena that cause the largest space weather effects are solar flares and coronal mass ejections (CME). Both are driven by changes in the solar magnetic field. Flares give off intense bursts of ultraviolet light, X-rays, and energetic particles, while CME’s produce the interplanetary structures responsible for most geomagnetic storms and solar energetic particles (SEP). Even at quiet times the outer solar atmosphere expands and accelerates to supersonic speeds forming the outflowing solar wind that controls the structure of near-Earth space. This tenuous solar wind blows with a highly variable speed that averages about 400 km/s at Earth. The solar wind plasma and magnetic field interact with the geomagnetic field and the Earth's atmosphere to form the magnetosphere, a large obstacle that deflects most of the solar wind flow around Earth. The boundary of the magnetosphere, the magnetopause, lies between 5 and 15 Earth radii (R_E) upstream of the Earth. On the antisunward or nightside of the Earth the magnetosphere stretches back probably 1000 R_E in a wake called the geomagnetic tail or geotail. The Earth's uppermost atmospheric layers, the mesosphere and thermosphere, are partially ionized by the Sun's ultraviolet and X-ray radiation to form the ionosphere. This combined system, the ionosphere, thermosphere, mesosphere (ITM), forms the earthward boundary of the region dominated by space weather, although intense electric currents flowing in the ionosphere induce large currents in the solid Earth that can affect technological systems on the ground itself.
Research

CISM’s research is focused around its unifying goal to develop a reliable and well-validated, comprehensive, physics-based numerical simulation model suite that describes the space environment from the Sun to the Earth. CISM’s research objectives, i.e., the development, improvement, and scientific use of these coupled system models, are integrated by this unifying goal. This means that CISM’s research program must be considered and managed as an integrated whole. For the purposes of research management we have divided this task into components, which we identify as our research thrusts. However, these components are all interconnected, and the boundaries between them are necessarily fluid, and in some cases not easily defined. Some thrusts are identified by areas of science, others by the capabilities needed to build the comprehensive model suite.

CISM’s modeling strategy is to build comprehensive models out of separate component models of parts of the overall system, and to couple these together using a computational framework. This approach allows each of the component models to concentrate on the physics or physical processes important to that particular piece of the system. The development of coupled models will proceed through a series of versions. Versions are distinguished by the number and type of included component models, by the improved physics within the component models themselves, and by the method and sophistication of the computational coupling technology or framework.
Core Models: The core of the CISM model suite consists of four fluid codes that form a chain from the Sun to the Earth, shown by the center row of four dark blue boxes in Figure ES1. The solar corona is modeled by MAS, a magnetohydrodynamic (MHD) model of the solar corona developed by Jon Linker, Zoran Mikic, and others at PSI, which describes solar corona dynamics from the top of the chromosphere out to a radius at which the solar wind flow is entirely supersonic and superAlfvenic. MAS couples to the heliosphere model, ENLIL, an MHD model of the solar wind developed by Dusan Odstrcil at the University of Colorado, which is optimized for supersonic and superAlfvenic plasma flow. This code models the time dependent 3-D structure of flows and fields in the solar wind from the MAS outer boundary to well beyond the orbit of Earth. When coupled together these models become CORHEL (CORona/HELiosphere). The magnetosphere model is LFM, an MHD model developed by Lyon, Fedder, and Mobarry (LFM) that models the global dynamics of the magnetosphere to a distance far enough down the geomagnetic tail (300 Re) that all flow is again supersonic away from Earth. The magnetosphere is strongly coupled to the ionosphere and upper neutral atmosphere or thermosphere. The CISM core ionosphere/thermosphere model is the National Center for Atmospheric Research (NCAR) Thermosphere/Ionosphere Electrodynamic General Circulation Model (TIEGCM). (Our early coupled models used the Thermosphere-Ionosphere Nested Grid (TING) version of this model.) CMIT (Coupled Magnetosphere Ionosphere Thermosphere) denotes coupled versions of these models.

Other Component Models: There are several regions and particle populations in the space environment whose physics is not well described by fluid codes. So other component models, also shown as dark blue boxes in Figure ES1, must be coupled to the core fluid codes in order to properly include their physics into the comprehensive model. All these regions and populations either have important space weather effects or have a direct influence on particle populations that do have space weather effects. Some of these models are very well developed, including the Rice Convection Model (RCM) which models the ring current, the hot plasma that provides most of the pressure in the inner magnetosphere. The RCM/LFM coupling is two-way, as is the LFM-TIEGCM coupling, representing the complex physical interactions between these populations. We refer to the coupled magnetosphere/ring current/ionosphere-thermosphere model as LTR (LFM-TIEGCM-RCM). The more energetic particles trapped in the radiation belts are described by the radiation belt model developed by Mary Hudson and others at Dartmouth. Other important components of the comprehensive model, such as the solar energetic particle (SEP) module, existed only in conceptual form prior to CISM. These models are being developed as part of CISM’s research program.

Observations: The light blue circles in Figure ES1 show observations that can be used to drive or modify the model chain. The coronal model must be fed at its inner radius with parameters derived from solar observations, the most critical of which is the solar magnetic field obtained from solar magnetograms. These data are sufficient to drive the end-to-end model and provide a 3-day forecast, however its accuracy is improved with other data inputs. Observations of coronal mass ejections can be used to launch transients in the heliosphere model. The LFM code can be driven directly with solar wind data obtained from in situ spacecraft near the L1 Lagrangian point such as WIND and ACE, which allows for more accurate short-term predictions. Observations are also used to test and validate models. The L1 observations are used to validate solar and heliospheric models, while observations made within the magnetosphere or ionosphere/thermosphere can be used to validate the geospace models. Observations also provide data that can be assimilated into models. CISM has a data assimilation plan to apply those techniques that most effectively advance the model characterizations of the system.
Empirical Models: Finally the yellow boxes in Figure ES1 show how empirical or other simpler models can be coupled into the chain or used independently for comparison. For example the WSA (Wang-Sheely-Arge) solar-heliosphere model can be used in place of MAS to drive Enlil, or in place of CORHEL to drive the geospace models. Similarly, empirical geospace models can be driven by CORHEL or by WSA.

Science Thrusts and Model Development Plan: The research required to build, validate, and improve the comprehensive models lies in two broad areas – space science, and model development and computational science. For the purposes of management these are further divided into research thrusts. The three space science thrusts -- Solar/Heliospheric Physics led by co-director Janet Luhmann, Magnetospheric Physics led by co-director Mary Hudson, and Ionosphere/Thermosphere Physics led by co-director Stan Solomon -- are responsible for the targeted research required to bring our understanding of the fundamental physics to the level required for the CISM model suite, and for developing the component models that will incorporate this physics. The areas of physics currently recognized as needing work are particle acceleration, magnetic reconnection, and the generation, transformation, propagation, and dissipation of energy in the solar corona and heliosphere. These thrusts also study the processes responsible for coupling regions of the geospace environment, such as the photospheric control of chromospheric and coronal process, and the thermospheric control of ionospheric and magnetospheric processes, so that these processes can be appropriately included in the comprehensive model. Finally, these thrusts use the coupled models scientifically, supporting assessment and validation of model capabilities.

The code coupling thrust, led by co-director Michael Wiltberger, is responsible for identifying and/or developing the computational science tools, the framework, needed for efficiently coupling the component models together and then applying these tools to coupling the models. The validation and metrics thrust, led by co-director Harlan Spence, is charged with testing and validating the functioning coupled models. This thrust performs both validation and metric or skill tests, that is, it both compares detailed model output against research data sets in order to evaluate the model against reality (validation) and makes standardized comparisons between the accuracy of the model predictions and the accuracy of predictions made by a standard or baseline model that provide a direct comparison between the effectiveness of different models or prediction schemes (metrics). This latter allows progress between generations of models to be evaluated. This thrust’s first task was to define the set of metrics to be used, which was accomplished early in the second year. (See table in Validation section of report.) The validation and metrics thrust couples intellectually to the science thrusts in that studying the model outputs is one way of exploring the science questions being addressed by those thrusts. This thrust also feeds back to all the others by pointing out where the models most need improvement.

The CISM Model Development Roadmap provides details of the model development plan. It is available at http://www.bu.edu/cism/Publications/Model_Devel_Roadmap.pdf
Research Plans and Goals:

CISM’s science goals are driven both by modeling needs, which require us to develop scientific understanding in order to develop certain models, and by modeling capabilities, which allow us to study quantitatively for the first time the effects of the various couplings of the components of the solar-terrestrial system. Hence science goals are intimately coupled to the progress of model development. In this section we list our research plans and goals under broad topics.

Solar Active Region Evolution and CME Initiation: Solar active regions are the ultimate cause of almost all space weather effects. They undergo considerable evolution during their lifetime, as magnetic flux emerges, is transported by surface motions, and cancels along polarity-inversion lines. We will focus on simulating observed active region evolution within the corona model, aided by more accurate specification of the photospheric boundary conditions from sequences of vector magnetograms. These studies will lead to a better understanding of Coronal Mass Ejection (CME) initiation, which in turn will allow more accurate modeling of the evolution of CMEs in the low corona.

Particle Acceleration: Solar Energetic Particles (SEP), and the energetic particles trapped in the Earth’s radiation belts are two of the most important space weather hazards. In the solar-terrestrial system particles are accelerated: in solar flares; at shocks in the corona, in the solar wind, and standing upstream of planets; at magnetic reconnection sites and similar current sheets; by Fermi and betatron acceleration in radiation belts; and by wave-particle interactions. We will focus on particle acceleration at coronal and interplanetary shocks with the goal of developing parameterized models for the production of SEP within the global solar and solar wind models. These particles will then be transported from their shock sources within the global models to predict their distribution in geospace. Radiation belt electron modeling and SEP transport and trapping will be incorporated into the LFM code where the effects of both ULF and VLF waves will be modeled. We will incorporate the effects of the SEPs on the upper atmosphere. The SEP problem is an excellent example of a problem that needs the full range of scientific expertise available within CISM to solve, as it includes SEP generation, propagation through both the heliosphere and magnetosphere, and deposition in the upper atmosphere.

Solar Wind Physics: The solar wind stream structure is responsible for quiet to moderate space weather conditions, and also affects the propagation, evolution, and geoeffectiveness of CMEs. We will include important thermodynamic processes (e.g. radiation, coronal heating, and anisotropic thermal conduction) to more accurately model solar wind structure and parameters (velocity, density, magnetic field) based on solar magnetic field observations, and simulate its effects on our model CMEs. The shock waves generated by the CMEs in the corona and solar wind in these simulations will be better characterized (shock capture) and then used as the foundation for the coupled solar energetic particle (SEP) model. Observational tests of the solar wind/CME/SEP model will be carried out using L1 monitor observations. We will couple the solar wind model to the coupled LTR models to simulate the solar wind interaction with geospace.

Magnetic Reconnection: Reconnection occurs under different circumstances and in three distinct places in the sun-earth system: at the sun where it causes solar flares, it could well be the cause of CMEs, and may contribute to coronal heating; at the magnetopause where it controls the energy transfer from the solar wind into the magnetosphere; and in the geomagnetic tail where its energy conversion powers substorms. In order to include reconnection explicitly in the global models, we use our expertise in reconnection physics to develop parameterized reconnection models that can be linked to the MHD models. In the magnetosphere we will extend the LFM model to include Hall physics, which has been shown to accurately capture the global aspects of reconnection.
**Outer-Inner Magnetosphere Coupling:** Important new science goals can be accomplished when the physics of the inner magnetosphere, as represented by the particle drift physics in the RCM, is embedded in the global MHD magnetospheric code. The magnetospheric component of the physics-based CISM code will be able to generate ring current and region 2 currents and associated shielding of the low-latitude ionosphere from high-latitude convection electric fields. This code will be able to resolve long-standing issues in magnetospheric physics by examining the time-dependent response and topology of the region 1 and region 2 current systems and its dependence on the interplanetary magnetic field. In order to fully incorporate these effects in the LFM code, we will incorporate multifluid physics to allow for both multiple temperatures and multiple species (heavy ions, protons and electrons). This will also permit the realistic inclusion of ionospheric outflow and the formation of a plasmasphere.

**Magnetosphere/Ionosphere Coupling:** The magnetosphere and upper atmosphere are closely coupled systems that pose a number of modeling challenges. The first order goal is to determine the role and impact of MI coupling on the establishment and maintenance of the basic state of the ionosphere and magnetosphere. Our studies will clarify the causes of the variability seen and the limitations of predictability. Using the LFM code coupled to the thermosphere-ionosphere general circulation model (TIEGCM), a host of important science studies will be undertaken. At high latitudes, the global thermospheric response to magnetospherically driven Joule heating and energetic electron precipitation will be determined, including changes in ion and neutral composition, convection, ionization, and neutral, ion and electron heating, as well as its feedback on the magnetosphere via the thermospheric “flywheel.” The evolution and spatial distribution of the auroral electrojet during storms and substorms will be simulated. Inclusion of field-aligned plasma flows, initially via empirical parameterized models, and, ultimately, using physical transport models, will enable studies of dynamic density stratification in the ionosphere and low-altitude magnetosphere and the effects of ionospheric outflow on the global magnetospheric system. Finally, precipitation-induced ionization and ionospheric outflows are significantly enhanced by collisionless ion and electron energization processes that occur in the lower magnetospheric region between the upper boundary of the TIEGCM and the lower boundary of the LFM. Empirical and physical transport models of these processes will be developed and included in the low-altitude LFM boundary conditions.

**Thermosphere/Ionosphere Physics:** The global interaction between ionization and heating induced by solar EUV and X-rays and the effects produced by MI coupling will be determined. This interaction will have immediate applications to forecasting atmospheric drag on satellites, especially during storm-time conditions. The effects on ionospheric structuring, variations in ionospheric content along specified slant paths, and the evolution of geomagnetic induced currents affecting ground-based electrical transmission systems will be investigated. At low latitudes, where interhemispheric flows arise, studies of penetration electric fields on plasmaspheric structure and the role of light ions at and above the exobase will also be enabled when the RCM is coupled with the LFM and TIEGCM models as described above.

**Magnetic Storms:** Magnetic storms are the premier space weather events, and the cause of many catastrophic space weather incidents. Magnetospheric behavior during magnetic storms is not well understood both because it is poorly sampled since storms are relatively rare, and because the coupling between the solar wind, magnetosphere, and ionosphere is much stronger, and perhaps of different character, during storms. CISM models will let us explore this coupling under extreme conditions in ways that are just not possible presently. Determining the role of the convection electric field on the storm-time ring current is a problem of central importance to understanding magnetic storms. We will investigate the phenomenon of “undershielding” which happens when the solar wind electric field changes suddenly thereby
exposing the low-latitude ionosphere to electric fields from high latitudes and modifying the ionosphere’s radio propagation properties. This is very important for understanding the erosion of the plasmasphere during storms and the location of the auroral electrojet. These are enabling issues to make substantive advances in treating storm conditions.

**Model Development:** To explore the critical space weather issues outlined above, and incorporate their effects within our models, we must continue to develop and extend the component models and add new physics within the model couplers. This will be a major part of our effort in years 6-10. Examples include thermodynamic processes in the transition region and low corona; the initiation of faster CMEs that form shocks in the low corona; refined processing of input data and the assimilation of new magnetograms into time-dependent models of the ambient corona and solar wind; adding multifluid capabilities and anisotropic pressure to the magnetosphere; including ion and electron energization in the magnetosphere/ionosphere coupling region; integration of the SEP and radiation belt models, and adding SEP effects in the upper atmosphere; auroral and cusp plasma sources and a plasmaspheric extension to the ionosphere; ionospheric data assimilation using GAIM specifications; inclusion of stratosphere/troposphere forcing using NCEP analysis; and inclusion of near-real-time solar irradiance inputs to the thermosphere and ionosphere. The component models will also be improved computationally, for example, to increase numerical efficiency or to improve modularization for easier component substitution.

**Model Coupling and Computational Science:** CISM’s model coupling technology will remain based on the InterComm and Overture software packages. The InterComm package is developed at the University of Maryland for interprocess communication, and that team provides CISM with expertise and adapts the package for our use as necessary. The Overture framework is developed at the Lawrence Livermore National Laboratory to handle translation from one code’s grid and variables to another. InterComm and Overture provide a flexible and modular approach to code coupling, allow the component models to run as separate executables, and allow the parameters of component models, such as grid resolution, to be changed without modifying the coupling software. During years 6-10, as our component models become more sophisticated and require greater computer resources, we will extend these tools to allow component models to run on a distributed network of heterogeneous computers such as the TeraGrid.

**Data Assimilation:** Data assimilation is a powerful technique that can keep real time simulations tied to observations and the true state of the system. These ideas are well developed in the meteorological community, and are commonly used in meteorological forecast models; they are beginning to be used in upper atmospheric simulations, but have yet to be widely used in space physics applications. Because of the widely varying natures of the physical regimes contained in CISM’s modeling and of the precision and number of observations, the effective use of data assimilation requires a diverse range of approaches. CISM is developing and exploiting a variety of techniques for ingesting observational data in its numerical models. Our goal is to identify and apply those techniques for using measured data that most effectively advance the model characterizations of the system The CISM Data Assimilation Plan is available at http://www.bu.edu/cism/Publications/Data_Assimilation_Plan_CISM.pdf

**Education**

The CISM education mission is to recruit and train the next generation of space physicists and imbue them with an understanding of the Sun & Earth as a system. The next generation of space physicists will come from diverse backgrounds, be capable of using the tools of
computational science to study the space environment, and approach problems from an interdisciplinary viewpoint.

In order to accomplish its education mission, CISM has the following objectives: to provide graduate students with opportunities for broad-based research in CISM related fields and with professional mentoring and role models; to provide undergraduates with research opportunities (academic year and summer) as well as mentoring and role models; to provide graduate and undergraduate students with opportunities to develop professional relationships with peers and working scientists in CISM related fields; and to provide space weather resources and professional development for 6-14 teachers and provide information about space weather to the general public. The CISM Education Plan is available at: http://www.bu.edu/cism/Publications/Education_Plan.pdf

Research and education are integrated in multiple ways throughout CISM. Each component of our education plan feeds from and is integrated into our research effort. All CISM students, both undergraduate and graduate, are involved in the research program, immersing them in research at a critical time in their careers, particularly for undergraduates, and teaching them what being a scientist is all about. The graduate summer school uses the models and tools developed in our research program to prepare students to use these tools in their graduate careers and beyond. Results from our research feed directly into our teacher workshop and curriculum development programs

The CISM Education Program has four core elements that are designed to meet the CISM Education Objectives in substantial, measurable ways. Three of these are highly specific to CISM. The fourth uses CISM content to engage the broader education and public communities through a variety of means, often leveraged with other efforts. We use appropriate methods of assessment for all elements of the CISM Education Program, and ensure alignment with national standards where applicable. The four elements are listed in order of the seniority of the students they serve.

Building a CISM Graduate Student Community: The CISM graduate students form an important cadre of the next generation of space scientists. CISM provides the means for broader professional development and peer interactions beyond what each student would normally experience at a single institution with a single mentor. Specific examples are the annual graduate student retreat, all-hands meetings, graduate student Access Grid (AG) sessions, the graduate student e-Newsletter, and taking part in cross-institutional interdisciplinary research interactions. The annual graduate student retreat allows the CISM graduate students to share their research and build community which is reinforced throughout the year by the other activities. The rotating program at the annual retreat focuses on professional development items not normally taught in a formal graduate curriculum, such as the funding and management of research, and how to prepare research proposals, career development, science ethics, or teaching methods and physics education. The entire program provides CISM graduate students with a strong sense of community and a unique, holistic view of the Sun-Earth system. Through these close interactions the students are forging the foundation for career-long professional relationships and developing expertise that will provide a core of space weather researchers to carry forward the CISM legacy.

The CISM Summer School: Each year CISM organizes a space weather summer school. The CISM Summer School is aimed primarily at students entering graduate school in space or solar physics, or at the end of their first year of graduate study. However some undergraduates, a high school teacher, and particularly professionals entering the field have also benefited from
attending. In two weeks the school provides an overview of the space environment, space weather hazards, and models that are used to understand, specify, and predict the space environment. Hands-on use of space weather models is a core component of the school. The goal is to provide students with a comprehensive overview of the Sun-Earth system, space weather, and the various types and uses of models in order to provide the context for their subsequent more detailed and theoretical study in graduate school. Proven innovative teaching methods, such as interspersing concept questions in all the lectures, and a summative jigsaw learning experience, are used throughout the school.

**Building a CISM Undergraduate Student Community:** Academic year research projects provide undergraduates with valuable skills and experiences within the unifying CISM context. Interactions with mentors and graduate students provide a sense of belonging to a community devoted to solving a set of challenging relevant problems. Throughout the year CISM provides opportunities for undergraduates to share their research and engage in professional development. A yearly event for undergraduates as well as summer research opportunities at CISM institutions other than their home institutions solidifies a sense of membership in the CISM community.

**Grade 6-14 Education and Increasing Science Literacy:** CISM pursues specific contributions to grade 6-14 education and science literacy by developing partnerships with existing programs which provide both resources and training for classroom teachers, and develop highly visible programs and electronic media for the general public. For classroom teachers, CISM supports the Stanford Space Weather Monitors program that provides inexpensive equipment for monitoring space weather events in the classroom, along with curricular materials and professional development programs for the teachers using the equipment. For informal education, CISM provides content and/or support for both portable full dome planetarium shows, and a major planetarium show. Informal education is also enhanced by CISM support for the addition of space weather and CISM content to two science e-learning websites: the San Francisco Exploratorium website and the Windows to the Universe website at NCAR. Both the formal and informal education activities are integrated through shared content and resources, and the informal science education component is expected to reach millions of people over the life time of CISM.

**Knowledge Transfer**

The CISM knowledge transfer plan has three major objectives: transition of forecasting tools to operational environments (e.g., the NOAA/Space Weather Prediction Center (SWPC) and the Air Force); providing the wider scientific community with models and visualization tools; and training and interacting with CISM’s partners within the aerospace industry, government, and others who must cope with or mitigate against space weather effects. Daniel Baker is CISM co-director for Knowledge Transfer. Our close cooperation with SWPC is strengthened by having dedicated CISM personnel at SWPC. Our strong partnership with CCMC (Community Coordinated Modeling Center) helps us make our models available to the wider community. We have an ongoing partnership with AFRL, and are forming relationships with our industrial partners to learn their needs. Several government and industrial employees typically attend the CISM Summer Schools. The CISM’s support of its three major objectives is summarized in the Knowledge Transfer Matrix [http://www.bu.edu/cism/Publications/CISM_KT_Matrix.pdf](http://www.bu.edu/cism/Publications/CISM_KT_Matrix.pdf).

**Forecasting and Specification Tools:** The development and transition of specification and forecasting tools is a major component of the overall CISM plan. This goal has a tremendous
benefit to CISM in that it serves to focus research into areas most relevant to society’s space weather needs. This goal is fostered through the close partnership between CISM and the NOAA SWPC. CISM-supported scientists based at NOAA/SWPC, support the primary day-to-day interaction between SWPC and CISM. They work closely with SWPC staff to affect the transfer of models into the forecasting arena.

Knowledge Transfer within the Space Physics Community: The integrated models developed by CISM can be used to test new ideas and explore the complex space environment in ways not possible using only observations. Visualization of a global model provides the best way of understanding the complex 3-D structure and dynamics of the space environment. CISM makes these models available to the space physics community, both through archives of model run results for various standard conditions, and versions of the models that are sufficiently user friendly for other scientists to run them with their own inputs to simulate particular events or conditions of interest to them. We are working closely with CCMC to provide community access to our models.

Industrial and Government Partners: Interaction with industrial and government partners occurs in various ways, including participation in the annual summer school, CISM presence at NOAA’s Space Weather Week, and a program of two-day short courses whereby CISM members visit government and industrial partners to present on-site seminars and other training. We also have attended DoD “War Game” sessions and other such events to share space weather knowledge.

Diversity within CISM

The CISM diversity mission is to increase the diversity of participants in space weather research at all levels. All CISM components attempt to promote diversity and increase the involvement of women and underrepresented minorities in space science and help build a vigorous research program at minority serving institutions. We specifically target applications from underrepresented minorities for the graduate summer school, with a target of at least 8 women students or students from underrepresented minorities.
**Diversity within CISM**

The CISM diversity mission is to increase the diversity of participants in space weather research at all levels. All CISM components attempt to promote diversity and increase the involvement of women and underrepresented minorities in space science and help build a vigorous research program at minority serving institutions. We specifically target applications from underrepresented minorities for the graduate summer school, with a target of at least 8 women students or students from underrepresented minorities. Similarly we target applications from underrepresented minorities for the undergraduate researcher positions, with a target of at least 5 women students or students from underrepresented minorities at all times. CISM also has a presence at the annual SACNAS and NCBPS/NSBP meetings in order to recruit students and provide information about space weather to a diverse audience. The CISM co-director for diversity is Ramon Lopez. The CISM Diversity Plan is available at http://www.bu.edu/cism/Publications/DiversityPlanCISM.pdf

CISM has the specific diversity-promoting goal of supporting the creation and development of a graduate program in space science and a vigorous space research program within the Alabama A&M University physics department. This new program provides a route for African American students to enter a field within which they are very poorly represented, and will remain a lasting legacy of CISM. AAMU hired two new tenure-track Solar Physics faculty members, Amy Winebarger and T.-X. Zhang, in 2005. AAMU graduated its first M.S. student in 2006, and initiated a Ph.D. program and recruited two students into the program.

A space weather weekend primarily for African American students considering graduate school is held annually. The Space Weather Weekend was held at AAMU each year since April 2006.

**Center Management**

The CISM management structure is designed to address the challenges of running a multi-institutional center that has clear integrated goals and timelines. To achieve these goals requires close communication, cooperation, and collaboration between institutions and research groups. The CISM management structure, described in the CISM Organizational Chart, is designed to achieve these goals.

CISM’s central administration consists of Director Jeffrey Hughes, Executive Director Jack Quinn, and Assistant Director Kathryn Nottingham. Jeffrey Hughes, as the Director of CISM, is ultimately responsible for the direction and management of CISM. Jack Quinn, as executive director, works closely with the director to manage the activities of CISM. Assistant director Kathryn Nottingham is responsible for all administrative functions, including budget management, overseeing the collection of management data, and maintaining the databases required for evaluation and to monitor progress.

The CISM Executive Committee, CISM’s principal executive body, consists of the CISM director, deputy director, and co-directors and three senior modelers. The executive committee confers bi-weekly by means of a telephone conference call, and meets several times a year in person, either at scientific meetings that we all attend, or in conjunction with other CISM meetings. The Executive Committee develops the strategic policies of CISM including definition of tasks and time lines, monitors progress against these goals, and develops priorities. The director, in consultation with the Executive Committee, is responsible for the allocation of
resources between areas and tasks, and for resolving conflicts. Implementation of CISM policies and the day-to-day management of CISM is the responsibility of the director and executive director.

The CISM Advisory Council provides independent guidance to the CISM director. The Council meets annually in the early spring to review the activities of CISM, and to provide guidance, advice, and oversight of Center management and all Center objectives.

**Communication within CISM:** Communication is key to the success of CISM. Frequent, efficient, and productive interaction of CISM personnel is critical to achieving our research, education, and knowledge transfer goals and to our smooth operation as a Center. CISM communications utilize periodic in-person meetings supplemented with a variety of electronic means during the periods between.

CISM holds an annual “all-hands” meeting in the early Fall to provide an occasion for the whole CISM team to meet to discuss and report progress and to develop plans for the following year and beyond. Some of the sessions are plenary at which overviews of progress are given to the entire team, other sessions are held in smaller groups at which more detailed reporting and planning can take place. This meeting also provides a venue for ethics training sessions, and for all CISM graduate students to meet.

CISM holds a series of regular meetings, including the annual Advisory Council Meeting in February or March and the annual NSF Site Visit in May or June. In addition CISM has a large presence at Space Weather Week, organized by NOAA/SWPC, which brings together space weather researchers, forecasters and end-users. CISM is also well represented at the annual SHINE, GEM, and CEDAR workshops each June or July, and at the two AGU meetings (December and May). Each of these meetings provides an opportunity for meetings of the CISM Executive Committee and/or other specialized CISM groups such as the solar, magnetospheric, or ITM teams at SHINE, GEM and CEDAR. Finally the CISM Summer School brings together another group of CISM participants each summer. A variety of topical meetings and electronic meetings are held throughout the year as described in the Management section of the annual report.

Performance and Management Indicators: The CISM *Performance Indicators* are drawn from a diverse set of sources that are enumerated and referenced in the Performance Indicators descriptive document, which is maintained on the CISM web site. The Performance Indicators address the Center’s performance in five overarching areas: research, education, diversity, knowledge transfer, and function of the Center.

The CISM *Strategic and Implementation Plan* was developed by the Executive Committee with input from the whole CISM team. The Plan defines goals and milestones for the individual thrusts within CISM and for CISM as a whole. The status of these goals and milestones, which is one of the Performance Indicators, is included as Appendix A. The director and co-directors are responsible for Center wide execution of the plan, and for engendering effective collaboration and close cooperation of the team in achieving these goals. The performance of the CISM management team, including the co-directors and local PIs, is to a large degree indicated by their ability to achieve the goals and milestones laid out in the *Strategic and Implementation Plan* and the other specific goals and that are reflected in the *Performance Indicators* for the Center.
Legacies

The lasting legacies that CISM will leave behind are:

- The development of a new interdisciplinary science that views the sun-earth system as a single closely coupled system.
- A new generation of well-trained space physicists from diverse backgrounds that is capable of using the tools of computational science to study the space environment and who approach problems from an interdisciplinary viewpoint.
- A new graduate program in space science at a historically black university.
- The introduction of community models and their validation into space physics and the use of numerical models as research tools by the broader research community.
- Advances in space science, particularly in our understanding of processes critical to the development of the global model.
- Advances in computer science brought about by our need to efficiently couple disparate numerical models and assimilate observational data.
- New models and understanding of the space environment that will lead to improved specification and forecasts at the nation’s space weather operations centers.
- Ongoing model development after STC support ends that continues to improve and augment the CISM initiated models.
- A suite of physics-based forecasting and specification tools.
- A better public understanding of the Sun and its affect on the Earth’s space environment.

Executive Summary References


II.  Research

1a. Overall Research Description
The CISM research overview is given in the Executive Summary.

1b. Performance and Management Indicators.
The CISM Performance Indicators are drawn from a diverse set of sources that are enumerated and referenced in the Performance Indicators descriptive document, which is maintained on the CISM web site. The Performance Indicators address the Center’s performance in five overarching areas: research, education, diversity, knowledge transfer, and function of the Center. The indicators are compiled and reported annually in various sections and appendices of this report. The entire set is extracted and maintained in separate binders that are available at the Site Visit.

1c. Problems.
We have not encountered significant problems.
2A. Solar/Heliospheric Thrust

Goals:

The ultimate science and simulation/modeling goal of the Solar thrust group of CISM has been the production of a physically realistic solar wind at 1 AU, into which simulated coronal mass ejections (CMEs) can be launched and propagate. This goal requires our calculations to reproduce coronal and interplanetary magnetic fields, plasma densities and bulk velocities in 3D that can be used to validate the Solar-Heliospheric models against measurements and to drive CISM magnetospheric MHD simulations in lieu of those data. The MHD models are also expected to provide the underlying framework for parameterized models of interplanetary shock production of Solar Energetic Particles (SEPs). Our most accurate simulations of even the undisturbed corona and solar wind based on solar magnetic field observations have taken years of effort to develop and test. CISM’s CORHEL model couples the results of the solar magnetogram-based coronal MHD model (MAS) to the solar wind MHD code (ENLIL) inner boundary to obtain the plasma parameters and interplanetary field throughout the inner heliosphere. An added option to inject a simulated CME disturbance, based on coronagraph images together with the Cone Model of CMEs, into the ENLIL domain has provided a routinely usable scheme for launching realistic interplanetary shocks. This archived code is used within CISM for research, education, and knowledge transfer, and is available for broader community use at the CCMC. Specific solar thrust goals in 2010 included further development of the ambient solar wind models to better match critical space weather parameters (e.g. interplanetary field, and solar wind density and speed), and further applications of the cone model for ICME shock production and SEP model development. The availability of new data sets including EUV images and magnetograms from Solar Dynamics Observatory (SDO), continuing data sets from the ground based magnetographs (at GONG, NSO-SOLIS, and MWO in particular) and STEREO mission multi-perspective images and multipoint in-situ events has provided an exceptional basis for 3D model case studies and data comparisons. A few of these are described below.

Activities:

This past year we continued to exercise and develop CORHEL, participating in a CISM end-to-end study of the solar wind structures associated with corotating interaction regions (CIRs) and their geospace effects. Both coronal and solar wind models were applied to several selected Carrington Rotations with especially well developed solar wind stream structure. The effort to reproduce the observed velocities and interplanetary fields revealed specific challenges for the models that are part of ancillary studies in progress. Such targeted applications demonstrate the interest of and value of examining the end-to-end picture, adding to our understanding of what solar/heliospheric models can and cannot do in producing various geospace response(s). The cone model option has also been exercised on some recent CME events in conjunction with further experiments with the SEP model. The availability of STEREO and ACE mission measurements of SEPs at widely separated 1 AU locations inspired both extension of the SEP model to lower proton energies, and improved methods for both generating and transporting the ENLIL ‘simulation data’ used in the SEP model calculations. The ENLIL/cone and SEP models are now better positioned for more routine use on real CME events.

PSI and Dusan Odstrcil (now at GMU and NASA) continue to have primary responsibility for the core solar/heliospheric MHD code developments and deliveries. AAMU has participated in the related coronal emission modeling research and CISM partners at Rice U. now run the MAS
coronal code locally with the assistance of BU postdoc Michael Stevens. Stanford continues to improve the options for the coronal models’ critical magnetogram-based inner boundary, and for the coronagraph image-derived cone model parameters. UCB continues to be responsible for the SEP model code whose success relies on the above. Other CISM solar science collaborators are located at NCAR/HAO, Air Force Research Laboratory, and the University of Colorado. PSI, Stanford, and UCB regularly have student assistants engaged in CISM-related work. UCB CISM graduate student Christina Lee completed her PhD in May 2010 and is currently an AFRL postdoctoral fellow working on cone model validation and knowledge transfer issues. Recent BU PhD Sarah McGregor continues her heliospheric research as a postdoc at Dartmouth.

**Significant Accomplishments:**

The accomplishments of the past year contribute to several solar thrust milestones:

**Coupled Simulation Area:**

- Exercised the cone model on a number of new, real events
- Provided SEPMOD results to geospace modelers

**Corona and CME Model Area:**

- Improved the derivation of cone model parameters from solar images
- Implemented improved thermal equation treatment in CORHEL corona

**Solar Wind Model Area:**

- Improved the cone model-initiated shock identification in ENLIL
- Participated in CISM end-to-end CIR study

**SEP Model Area:**

- Tested SEPMOD on new, widely separated SEP event observations
- Participated in CISM end-to-end SEP event study

In addition, members of our group continue to:

1. Carry out targeted validations to guide model developments
2. Work with CCMC and NOAA SWPC in Knowledge Transfer-enabling roles (see that section of this report)
3. Report CISM solar/heliospheric modeling progress at a broad range of conferences and workshops

**Highlights from the past year:**
Synchronic maps: A better representation of the entire-surface photospheric magnetic field.

Success in reconstructing the solar corona and heliosphere with CISM’s CORHEL model depends on the inner boundary condition of the WSA and MAS models, i.e., the heliographic distribution of the photospheric magnetic field over the entire solar surface. In the past year we constructed synchronic maps from the new SDO (Solar Dynamics Observatory) HMI (Helioseismic and Magnetic Imager) photospheric magnetic field data to improve the boundary conditions used by coronal and heliospheric models. The HMI observations of the photospheric magnetic field provide unprecedented high-resolution and high-cadence full-disk line-of-sight and vector magnetograms. HMI is replacing the MDI data that has been available since 1996. In order to use the new observational HMI data from the Solar Dynamics Observatory (SDO) satellite, we have adapted the procedures for correcting the effects of differential rotation (i.e. constructed synchronic maps from synoptic maps) and for filling-in the polar data gap. We have constructed HMI synchronic maps and frames to provide a better proxy of the true heliographic distribution of the entire-surface radial photospheric magnetic field (Liu et al., 2011; Sun et al., 2011; Zhao and Hoeksema, 2010; Zhao et al., 2010a,b). Some examples are shown in the two figures below.
The HMI synchronous maps with grid spacing of 3600x1440 can be used to monitor the spatial and temporal variation of both small and large scale magnetic features on the entire solar surface. For constructing coronal field, the spatial resolution can be reduced to save computation time. We found the coronal structure calculated using synchronous maps with grid spacing of 360x180 is the same as 3600x1440, agreeing with observations better than grid spacing of 72x30 (Zhao and Hoeksema, 2010a).

It is well known that coronal features are most strongly influenced by the photospheric magnetic field directly underlying them. The synchronous frames, which use an inset of data from the most
relevant observation time in the center of a synoptic map, are therefore expected to provide a better input than the synoptic maps in modeling coronal holes observed simultaneously by SDO/AIA, STEREO EUVIA and STEREO EUVIB. The figure below shows that the coronal holes predicted using HMI synchronic frames agree with coronal holes observed both by SDO/AIA and STEREO/EUVIA and EUVIB (Zhao et al, 2010b).

Figure 2: Comparison of coronal holes modeled using 2010.08.25 360x180 HMI synchronic frame with those observed by SDO/AIA 193 (left) and STEREO A & B/EUVI 195 (right). The left column shows that the holes calculated using spherical harmonics of order Nmax=45 are the same as those calculated with order Nmax=90.
Global MHD Modeling of the Solar Corona and Inner Heliosphere for the Whole Heliosphere Interval

Global coronal and heliospheric MHD simulations are still under development, even for the quiet Sun, because of the many physical details they must capture. In an effort to understand the three-dimensional structure of the solar corona and inner heliosphere we have developed a global MHD solution for Carrington rotation (CR) 2068 for the “Whole Heliosphere Interval” (WHI), a period selected for study by the larger heliophysics community. Our model, which includes energy-transport processes, such as coronal heating, conduction of heat parallel to the magnetic field, radiative losses, and the effects of Alfvén waves, is capable of producing significantly better estimates of the plasma temperature and density in the corona than have been possible in the past. With such a model, we can compute emission in extreme ultraviolet (EUV) and X-ray wavelengths, as well as scattering in polarized white light. Additionally, from our heliospheric solutions, we can deduce magnetic field and plasma parameters along specific spacecraft trajectories. We studied the large-scale structure of the solar corona and inner heliosphere during WHI, focusing, in particular, on: (i) coronal helmet-streamer structure and its consequences; (ii) the location of the heliospheric current sheet; and (iii) the geometry of corotating interaction regions. We also compared model results with: (i) EUV observations from the EIT instrument onboard SOHO; and (ii) in-situ measurements made by the STEREO-A and -B spacecraft. Finally, we contrasted the global structure of the corona and inner heliosphere during WHI with its structure during the “Whole Sun Month” (WSM) interval. Overall, our model reproduced the essential features of the observations, however, several discrepancies were revealed. The results from this study were reported in detail by Riley et al. (2011). This work illustrates the importance of specific case studies and the broader forum of study groups in the development and testing of these state-of-the-art simulations.

![Image of large-scale properties of the inner heliosphere](image)

**Figure 3:** Illustration of the large-scale properties of the inner heliosphere (out to 1 AU) for (left) WSM and (right) WHI time periods. The two meridional slices in each panel show the radial velocity and radial magnetic field strength, scaled to 1 AU. The slice in the equatorial plane shows the scaled number density. The sphere at $30R_\odot$ shows the scaled radial magnetic-field strength.

Interpreting the Structure of the Corotating Interaction Regions during the recent Unique Solar Minimum.
The recent solar minimum, which ended in December 2009, has been unique in a number of ways. From the perspective of corotating interaction regions, high-speed streams upstream of Earth were found to have been stronger, longer in duration, and more recurrent than during the previous minimum (Gibson et al., 2009). Strong periodicities were also found in early-mid 2008, with periods of 9, 13.5, and 27 days (Emery et al., 2008), with no comparable patterns from the previous minimum. Using coupled global MHD models of the solar corona and inner heliosphere, we investigated the connection between phenomena observed at the Sun and in-situ measurements at 1 AU. We found that much of the stream structure observed in interplanetary space was driven by low-latitude coronal holes, in contrast to the minimum associated with the end of solar cycle 22, which was driven by extensions of the polar coronal holes. We compared our model results with observations to: (1) better interpret the observations; and (2) validate and improve the input and free parameters within the model. Although there remains considerably more work to be done, these comparisons indicate that global models can reproduce the primary features of in-situ measurements, such as high speed streams and magnetic sector boundary crossings, as illustrated in the Figure below.

Figure 4: Comparison of model results with in-situ measurements at STEREO A and B and Earth (ACE) for Carrington rotation 2060. The solid lines are model results and the symbols are spacecraft measurements. At this time, the two spacecraft were separated by ~28° in latitude.

**Magnetic Field Predictions at 1 AU**

As part of the CISM CIR study, we discovered that the CORHEL model was significantly underestimating the average magnetic field magnitude (|B|) in the ecliptic at 1 AU. While the results differed when different observatories were used to obtain the solar boundary conditions,
this underestimate was a persistent effect. Further investigation revealed that this underestimate was already present in the coronal solutions, and occurred in both the WSA and MHD models. For observations in the ecliptic, there are many factors that the underestimate could arise from. Some examples include low resolution of the HCS, systematic underestimate of the measured photospheric $B$ by all of the observatories, choice of model parameters, and fundamental inadequacies of the polytropic MHD and/or potential field models. To sort through these different possibilities in the least complicated situation, we decided to investigate how well the models predicted the polar values of the interplanetary magnetic field. To accomplish this task, we computed CORHEL coronal solutions for time periods when the Ulysses spacecraft was at extreme helio-latitudes and compared the average high latitude magnetic fields from the model with Ulysses magnetometer data, both scaled to 1 AU. That study revealed that polar field strength at the outer boundary of the coronal model varies for different observatories but is systematically low (see first figure below). The effect appears to be significant larger in solar cycle 23 than it was in cycle 22 (see second figure below). We have found that choosing a slightly larger temperature at the coronal base opens more magnetic flux in the corona and removes this underestimate for a particular rotation (CR1951). We are presently investigating how well the new parameters match for other time periods.

![Figure 5: Radial magnetic field estimate from CORHEL for different observatories.](image)

![Figure 6: Comparison of the radial magnetic field estimate for minima at the end of cycle 22 and cycle 23.](image)
Improvement of WSA Model Parameters and their Implication

For many applications the WSA semi-empirical model of the corona, which has been tuned for best agreement with observations still produces the best results (Owens et al., 2008). However in this model parameters other than the original Wang-Sheeley open flux tube expansion factor are used to describe the solar wind velocity in the vicinity of coronal hole boundaries. In particular, Arge and Pizzo (2000) found that an additional term that depends on distance from the boundary produced a better model result than the original. A similar term is also the main feature of the CORHEL velocity description at the MAS/ENLIL boundary. Coronal hole boundaries are thought to be sites where both quasi-steady and transient components contribute to the slow solar wind. Thus an examination and reassessment of this additional term for both its performance and physics implications was warranted.

We first recalibrated the WSA magnetic field-velocity relationship to better determine solar wind velocities in the inner heliosphere (0.1 AU) (McGregor et al., 2011). Once recalibrated, the velocity relationship was used as the inner boundary condition for the ENLIL heliospheric model. Using this recalibrated velocity equation in ENLIL produces better matches to both 1.0 AU ecliptic and Ulysses observations (see the left figure below). These comparisons provide confidence that this new magnetic field-velocity relationship is a more realistic representation of solar wind speeds in the outer corona (0.1 AU) and is therefore a better inner boundary for heliospheric models such as WSA/ENLIL or the new LFM-Helio Model.
The radial evolution of the solar wind speed was then used to help interpret the model assumptions. Once the calibration of the velocity equation was performed, the radial evolution of the solar wind speed between 0.1 AU and 1.0 AU was analyzed using an inverse-mapping technique. Flows were mapped from 1.0 AU back to the inner boundary of ENLIL at 0.1 AU. We showed that a significant amount of evolution of the solar wind speed can occur in the model and mainly does so within a few tenths of an AU from the Sun (see right figure above). The greatest evolution in solar wind speed occurs in solar wind with speeds at 1.0 AU of 400-500 km/s and is more prominent during solar minimum. Our results also support the idea that the slow solar wind at 1 AU has source contributions that depend on both the open flux tube expansion factor and the distance from the open/closed coronal magnetic field boundary. The physics based models of solar wind sources must ultimately allow for these different components, e.g. by explicit inclusion of time dependent boundary conditions at the Sun.
Mapping Solar Wind Streams from the Sun to 1 AU: A Comparison of Techniques

A number of techniques exist for mapping solar wind plasma and magnetic field measurements from one location to another in the heliosphere. Such methods are either applied to extrapolate solar data or coronal model results from near the Sun to 1 AU (or elsewhere), or to map in-situ observations back to the Sun. We have estimated the sensitivity of four models for evolving solar wind streams from the Sun to 1 AU, which, in order of increasing complexity are: i) ballistic extrapolation; ii) ad hoc kinematic mapping; iii) 1-D upwinding propagation; and iv) global heliospheric MHD modeling. We also investigated the effects of the interplanetary magnetic field on the evolution of the stream structure. The upwinding technique is a new, simplified method that bridges the extremes of ballistic extrapolation and global heliospheric MHD modeling. It can match the dynamical evolution captured by global models, but is almost as simple to implement and as fast to run as the ballistic approximation. The Figure below compares the 3-D MHD evolved solution with the simple upwind+acceleration technique. The results of this study, which provide another potentially useful modeling option, were described by Riley and Lionello (2011).

Figure 9: Comparison of radial velocity for CR 2068 at 1 AU with 1-D, upwind-evolved speed from 30 $R_s$ to 1 AU as a function of Carrington longitude.
The Interplanetary Signatures of Pseudo-Streamers

Pseudo-streamers are coronal structures that, at least in coronagraph images, are indistinguishable from the so-called “helmet streamers.” However, when interpreted with the aid of a magnetic field model of the solar corona, they can be shown to consist of a distinct system of loop arcades. While helmet streamers separate coronal holes of the opposite polarity and are the origin of the heliospheric current sheet, pseudo-streamers separate coronal holes of the same polarity and, therefore, are not associated with a current sheet. While it has been well established that helmet streamers are associated with the slow solar wind, models such as the Wang-Sheeley-Arge model based on potential field source surface (PFSS) coronal fields and MHD models disagree on the speed of the wind emanating from pseudo-streamers. The former predict fast wind, while the latter predict slow wind. The implications of this discrepancy may be profound since these two modeling approaches rely on fundamentally different interpretations of the origin of the slow solar wind. Our preliminary results, based on several cases studies, suggest that pseudo-streamers produce slow solar wind, and, by extension, that the slow solar wind is not fundamentally controlled by the areal expansion factor of the coronal magnetic field, but rather by the process of “interchange reconnection.” However, these tentative conclusions must be substantiated by more rigorous, statistical studies, which are currently underway.

Figure 10: Composite images of the photospheric magnetic field at the solar surface (saturated at ±1G), with a selection of magnetic field lines originating in the plane of the paper, and a color-contour of the coronal density (scaled by $r^2$) for CR1913 (Left) and CR2068 (Right). The pseudostreamers are most obvious in the northern hemisphere of CR2068, although one is also present on the west limb of CR1913 as well. These self-contained streamers are distinct from the helmet streamer belt that encircles the Sun and makes the more ‘dipolar’ coronal ray structure.
The Origin of the Slow Solar Wind

Both remote sensing and in situ observations have established two sources of solar wind. Fast wind originates in the nearly unipolar open magnetic flux regions of coronal holes (Zirker 1977; McComas et al. 1998). Slow solar wind is associated with the streamer belt (Gosling et al. 1995), and is characterized by greater variability and different composition from the fast wind. The origin of the slow wind is controversial. Models that assume slow wind originates from open fields near boundaries of coronal holes (Wang & Sheeley 1990; Arge & Pizzo 2000; Riley et al. 2001; Cranmer et al. 2007) predict the solar wind velocity reasonably well (Arge et al. 2003; Owens et al. 2008). However, slow wind has composition similar to that of closed loops (Zurbuchen et al. 1998; Schwadron et al. 1999). White-light observations from SOHO/LASCO (Wang et al. 2000; Sheeley & Wang 2002; Sheeley et al. 2009) and STEREO/HI (Rouillard et al. 2008, 2010) show evidence of plasma escaping from the streamer belt as transient ‘blobs’. These observations suggest that the slow wind may originate on previously closed field lines that have reconnected such as those at the helmet streamer belt boundary (e.g. Lionello et al., 2009). Thus, to understand the origin of the slow solar wind, we are invariably led to investigate the structure and topology of the coronal magnetic field. Our investigations have resulted in a new hypothesis for the origin of the slow solar wind.

Antiochos et al. (2007) argued that the boundary between the open and closed fields can be extremely complex, with narrow corridors of open flux connecting seemingly disconnected coronal holes, and that these corridors may be the sources of the slow solar wind (Linker et al., 2011). We have been examining in detail the topology of such magnetic configurations both analytically, using a source-surface model, and numerically, using the results from the MHD solutions. Our analysis revealed three important new results (Titov et al. 2011). First, a parasitic polarity region can disconnect a coronal hole into two parts. Second, the parasitic polarity region can produce multiple null points in the corona and, more importantly, separator lines that connect them. The separators lie at the intersection of a closed dome-like separatrix surface and a curtain-like surface that extends into the open corona. These topologies are extremely favorable for magnetic reconnection, which can occur over the entire length of the separators rather than being confined to a small region in the vicinity of coronal nulls. This reconnection can be the source of the slow solar wind. Third, the disconnected parts of coronal holes still remain linked by a singular line that coincides with the separatrix footprint of the parasitic polarity. This analysis suggests the need to consider the connections of coronal holes in a broader sense (Titov et al. 2011).
Our 3D MHD model is capable of simulating finer structure in the corona than ever before. These high-resolution simulations are beginning to reveal how small-scale structures in the magnetic field interact with the global structure of the corona and solar wind. The complexity of the magnetic field can be illustrated by plotting the “squashing factor” \( Q \) (Titov et al. 2002; Titov 2007). \( Q \) is a mapping function that measures the deformation of a flux tube from a circular to an elliptical cross section. It is obtained by mapping millions of magnetic field lines. Large values of \( Q \) indicate the presence of separatrices and quasi-separatrix layers (QSLs), and are believed to be likely sites for the formation of current sheets and concentrations of electric current. The figure above shows a map of \( \log(Q) \) in the plane of the sky from our high-resolution model of the total solar eclipse of August 1, 2008 (Rušin et al. 2010). We see that the separatrix and quasi-separatrix surfaces form an extremely complex network that is localized in the broad vicinity of the HCS in the solar wind, as shown in the right panel. We hypothesize that this region is the source of the slow solar wind.

Reconstruction of the true propagation direction for Earth-directed CMEs

A main cause of errors in CME model parameters obtained using the cone models applied to single-spacecraft coronagraph images is the error of the inferred CME propagation. The stereo CME images from COR1 and COR2 on STEREO A and B provide more information about 3-D CMEs than the single point observation. Based on triangulation (Pizzo and Biesecker, 2004) and the epipolar geometry (Inhester, 2006), several approaches have been developed for 3-D reconstruction of CMEs. Because of the complexity of CME phenomena and the difficulty in unambiguously identifying the same feature in the images used for reconstruction, these approaches usually rely on assumptions and a priori constraints (see the review by Mierla et al., 2010). We have tried a simple, direct and reduced-assumption approach to infer the true angular width, propagation direction, and speed of Earth-directed CMEs. The approach can also
be used to reliably recognize the same feature in the images of COR2A and COR2B, and is developed based on the following idea (also described by Zhao, 2011).

In a Heliocentric-Spacecraft-Ecliptic Cartesian coordinate system, $XsYsZs$, the $Xs$ axis points toward the spacecraft from the Sun, the $XsYs$ plane is the ecliptic plane in which the spacecraft is located, and the $YsZs$ plane is the perpendicular image-plane of the coronagraphs on the spacecraft. Any radial direction in $XsYsZs$ can be expressed by two parameters: the elevation angle from any plane, $XY$, $YZ$ or $ZX$, and the azimuthal angle from, respectively, the $X$, $Y$ or $Z$ axis in the corresponding plane. The elevation and azimuthal angles with respect to one plane can be easily transformed into another plane. If the spacecraft is SDO or SOHO, the image-plane $YsZs$ is specifically the sky-plane, and the elevation and azimuthal angles of a radial direction with respect to the $XsYs$ plane are those commonly called ecliptic latitude and longitude. The COR1 or COR2 coronagraphs on board STEREO A and B provide, with respect to the STEREO A and B image-planes, two azimuthal angles of the central axis of the two limb CMEs that each correspond to the same Earth-directed CME. By assuming only that both STEREO A and B are located in the ecliptic plane, the ecliptic longitude and latitude of the Earth-directed CME’s central axis, or propagation direction, can be calculated from the two observed azimuthal angles and the angular separation of STEREO A and B from the Earth.

![Figure 12](image)

(a) (b) (c)

**Figure 12:**

(a,b) The limb CMEs observed nearly simultaneously by Behind and Ahead COR2.

(a) The angles between the central axes and the blue Y axes can be measured, and are the azimuthal angles with respect to the image plane $YZ$ of the Behind and Ahead COR2, i.e., $\phi_{yz_B}$ and $\phi_{yz_A}$. The two angles depend on $\lambda_{xy_B}=\lambda_{xy_L}$, $\varphi_{xy_B}=\varphi_{xy_L}-\varphi_B$ and $\lambda_{xy_A}=\lambda_{xy_L}$, $\varphi_{xy_A}=\varphi_{xy_L}-\varphi_A$. Therefore, the unknown $\lambda_{xy_L}$ and $\varphi_{xy_L}$ can be directly calculated using the given $\phi_{yz_B}$, $\phi_{yz_A}$, $\varphi_B$, and $\varphi_A$. 

30
Schrijver and Title (2011) describe a "global solar storm" seen in SDO/AIA data obtained on 2010.08.01. The global storm included many forms of coronal activity, such as flares, disappearing filaments, and CMEs, that occurred nearly simultaneously at source regions separated by more than 180 degrees. It is a challenge to understand the cause(s) and trigger(s) of these events and to predict their occurrence. On the basis of PFSS modeling using HMI data, they showed that the source regions of the various activities were physically connected through magnetic linkages, and that locations of the coronal activities were connected by "magnetic faults", i.e., separatrices, separators, and quasi-separatrix layers. The magnetic faults before the onset of activity were in a metastable configuration where small changes in the surrounding plasma currents can result in widespread consequences.

The 2010.08.01 CME movies show two Earth-directed CMEs. The first CME with an angular width of ~50 degrees occurred around 07:50-08:11 UT, and the second with angular width of 140 degrees occurred at 08:26. The second larger CME showed the most global characteristics. All of the substantial coronal activity and associated magnetic faults were located within a great coronal closed region, with multiple bipoles sandwiched between the two legs of the second CME. It appears that the first CME broke out through the outer magnetic field lines that confined those metastable magnetic structures through magnetic stress, and it made those metastable configurations become unstable all at once, i.e., it triggered the global Earth-directed CME (Zhao and Hoeksema, 2011).

Two possible causes have been suggested in the literature for the sympathetic flares. One is the propagation of an impulse signal excited by one coronal event along the magnetic field lines that map to another active region. The second is the simultaneous occurrence of changes in the magnetic field in related but wide-separated source regions. The fact that the source regions are widely separated and the too-small difference in the onset times invalidates the second hypothesis, because it is impossible for signal carriers like hydrodynamic waves or particle flows to propagate so fast. We have made movies using the 45-second cadence HMI magnetograms and their various difference images, and find that there is no such parallel evolution of magnetic fields in these widely-separated source regions during this time interval. The nature of the metastable magnetic configuration must be non-potential. It is better to model the coronal field using MHD models than the PFSS model. Using the HMI synchronic frames as the boundary, we examined the global coronal MHD model field connectivity changes around 2010.08.01. We also used the daily-updated whole-sun magnetic field data set to test the capability to predict this global coronal event (Hayashi et al., 2011).

Figures below show the simulated coronal magnetic field lines in the lower corona for times before and after August 1. Only the closed-field lines are drawn. The changes in the magnetic neutral lines on the solar surface on the upper-left are notable, and this is due to the effects of AR 11092. This analysis illustrates that for studying the responses of the entire solar corona, the synchronic frames provides better coronal model boundary data.
Magnetic field evolution in eruptive regions producing extreme effects

Solar flares and CMEs are the coronal manifestations of rapid magnetic free energy release. Intense flares and very fast CMEs, which pose serious space weather threats, originate from large magnetic active regions. The magnetic field evolution and configuration of source active regions hold the key to understanding the cause of large solar eruptions. For recurrent flares and CMEs from the same source region, the eruptive stressed core field, magnetic field topology and the coronal plasma environment are similar for each eruption. The eruptive state can be reestablished and the time scale to introduce the free energy that drives a recurrent eruption is constrained by the occurrence of adjacent events. Li and collaborators have been analyzing the source region of four X-class flares and several extremely fast CMEs that occurred in January 2005. These also produced major Solar Energetic Particle events. By analyzing the time evolution of the active region in magnetograms, including the behavior of the Polarity Inversion Line (PIL) or neutral line, together with the apparent ‘flows’ of the flux elements derived from correlation tracking methods (FLCT), total flux in the active region and inferred Poynting flux, they are able to show that the major flare occurrence timing and intensity coincides with the buildup of Poynting flux (see Figures below). This result is potentially useful to both the simulations of active region eruption and to forecasters who wish to predict major events. Ongoing work will apply these techniques to more events and extend the approach to vector magnetograms, given their new more routine availability.
Figure 14: Active region evolution and analyzed features, showing from the top, overall field structure, focus on the neutral line and surrounding fields, ‘flow’ vectors inferred from magnetogram sequences using local correlation tracking methods.
Figure 15: Illustration of the apparent dependence of a flare occurrence sequence (violet x-ray time series) from the same active region on the buildup of active region Poynting flux inferred from magnetogram evolution. The various lines show:

Black: PIL region flux began increasing on the 13th with the emergence of AR10720, and ‘plateau’ed at the end of the 14th shortly prior to the first X-class flare in the series of large recurrent X-class flares;
Orange: AR total flux increased monotonically from emergence onwards;
Red: Pre-flare progressively integrated proxy-Poynting-flux;
Green: Proxy-Poynting-flux.

IMF Bz in ICME ejecta and the solar cycle

In a recent report in press in Solar Physics (Li et al., 2011) Li et al. extended the multi-solar cycle time series of observed ICME (Interplanetary CME) ejecta (magnetic cloud) field ‘polarity’, or north-south field direction, which has previously shown trends. The sign of the interplanetary field IMF) Bz determines the extent to which an CME is ‘geoeffective’ in producing a major geospace response. The fact that there is a solar cycle dependence of this cloud magnetic polarity, which defines whether the ICME ejecta have a leading positive or negative Bz, provides important information about both solar sources of CME ejecta and the predictability of magnetic storm effects for a particular solar cycle. The phasing of the ejecta polarity with various cycle indicators such as sunspot number also contains additional information about the CME initiation process which may change as a cycle progresses from minimum, into its rising phase, through maximum when the solar polar fields reverse, and in the declining phase when many of the major events occur. A figure from this work, reproduced below, shows that the field polarity change in the ejecta occurs gradually oversunspot cycle 23. There is no sudden change at the time of polar field or active region polarity reversals (the latter coincident with the butterfly ‘wings’ in the third panel). Rather, ICME ejecta of the new polarity coexist with those having the
old polarity as the transition occurs through the solar maximum. In addition, the duration of the evolution of ICME polarity cycles mirrors the duration of the active region belt and polar field cycles. This suggests there is a complex relationship between the active region and polar fields that allows CME initiation from different source regions (e.g. active region belt, polar crown filament channels) and still preserves the memory of the prevailing Hale (active region) and polar field cycle polarity. Studies such as this complement the CISM modeling of CMEs in providing background information on their source regions and effects in the heliosphere over solar cycle time scales.

Figure 16: Figure showing, from the top, the occurrence rates of bipolar magnetic clouds or CME flux rope-like ejecta with the Bz sequence of northward field first, and southward first cases in the panel below; Active region and polar field polarity cycles seen in longitudinally averaged photospheric magnetic fields; solar north and south polar field cycles, and sunspot number (SSN). The Bz sign phasing of the ejecta fields at the top evolves with the solar cycle in a way that is not solely determined by either the active region or polar field cycles, but likely related to some complex combination of the two that defines the different CME source regions over the cycle.
Automated Detection of ENLIL Interplanetary Shocks and Their Parameters

We have finalized development of the procedure enabling the automatic detection of heliospheric shocks in ENLIL and their parameters. This procedure uses multiple computational grids on which the heliospheric disturbances are solved simultaneously with the undisturbed solar wind to provide more reliable identification of the shock front. It takes advantage of the 3D information provided by numerical simulations to determine the shock inclination and jump conditions. We have started simulations of well-observed ICME-SEP events occurring during the STEREO era with an intention to create a portfolio of various scenarios suitable for validation and further development of the SEPMOD code. The top figure below illustrates the model magnetic field connectivity between the interplanetary shock and Earth and STEREO-B spacecraft. The figure below this illustrates the shock parameters automatically computed for the Earth connected field line.

![Figure 17: Global view of the ICME (shaded 3-D white iso-surface) propagating toward Earth together with the IMF lines (red lines) connected to the planets and spacecraft in the inner heliosphere. Normalized proton density is shown on the equatorial plane and at the inner boundary of the computational domain (translucent color scale given at the left bottom).](image-url)
Multiple-Event Initializations and Tracing of Heliospheric Disturbances in ENLIL

Cone model fittings of CMEs seen in coronagraph images enable us to determine the location, speed, and angular diameter of halo CME events using single spacecraft coronagraph observations. After the recent extended solar minimum, the Sun has become more active and CMEs have again become more frequent and violent. On 1 August 2010 the first multiple major CME-event, with four CMEs in one day, was observed remotely by SOHO and STEREO coronagraphs. These CMEs originated in different parts of the solar corona, generating a complex scenario of mutually interacting structures, and were later detected in-situ by ACE, WIND, STEREO-B, and the Venus-Express spacecraft. The figures below show the global ENLIL/cone model view and temporal profiles of interplanetary parameters at Earth. These figures illustrate that the resulting disturbance is quite complex and that some ICMEs completely overtake the preceding ones while others propagate on trailing parts of preceding events. Using a multi-grid approach in ENLIL enables unambiguous identification of the contributions of the respective ICMEs. This approach is also important for future development of a multiple-shock detection procedure.
Figure 19: Global view of the interacting ICMEs during early August 2010 (shaded 3-D white iso-surface) propagating into the inner heliosphere. Earth together with the magnetic field lines (red lines) connected to the planets and spacecraft are shown. Flow velocity is shown on the equatorial plane and at the inner boundary of the computational domain (translucent color scale given at the left bottom).
Figure 20: Four panels with the temporal profiles of flow velocity, density, mean temperature, and field strength (top to bottom in each panel) for ENLIL/cone model runs with 1 (top left), 2 (top right), 3 (bottom left), and 4 (bottom right) ICMEs. Observations are shown by red dots and numerical results for the undisturbed and disturbed scenarios are shown by dashed and solid blue lines.
Multipoint Modeling of Solar Energetic Particle (SEP) Events: Tests using ENLIL/Cone model results and STEREO observations

Since the previous annual report, the Sun has also become much more active in producing new SEP events. At the same time, the STEREO spacecraft have attained 180 deg separation, giving a widespread, multipoint measurement capability for testing our cone model-coupled SEP event codes. Several enhancements have recently been made including 1) an improved scheme for regular generation of the ENLIL cone model results on the shock and interplanetary magnetic field lines needed by the SEP event code; 2) an improved procedure for data reduction to avoid transferring large data sets produced by high time cadence ENLIL output; and 3) the introduction of an approximation to the treatment of lower energy protons (down to 1 MeV) that enables the phenomenology of scattering and diffusion effects near the shock (including the production of the Energetic Storm Particle ‘ESP' part of the SEP event) to be included. Several comparisons with widely spaced STEREO measurements and measurements by ACE near Earth have allowed further experimentation with both the cone model application to real events and the SEP model descriptions of the shock source. The Figures below illustrate one complex event from August 2010 where the ESP contribution to the SEP event was essential for reproducing what was observed at ACE in particular. As the number of significant STEREO/ACE events increases we will continue to experiment with enhancements such as the introduction of shock normal angle effects which may be substantial but have been difficult to examine with observations alone. We will also gain a better idea of the extent to which our SEP event model is able to describe the event at widespread locations, including at the planets where spacecraft are in orbit including Mercury, Venus and Mars.
Figure 21: Top left, ENLIL with cone model disturbance results showing velocity contours and an Earth-connected field line snapshot for the August 2010 CME event under study. Note the Earth is connected to a smaller second ICME shock. Top right, same event but showing the ENLIL snapshot for the STEREO B-connected field line. Both frames show the time history of connected ENLIL shock parameters for the entire event passage on the right. Bottom left, ACE energetic proton data (points) compared to the corresponding modeled SEP event (lines) for the same energy range. Bottom right, same but for STEREO-B showing the STEREO SEP data and model results. The cone parameters for this case were provided to D. Odstrcil courtesy of Curt DeKoning, U. of Colorado. Tests were also run with alternate parameters derived by Hong Xie (CUA).

Heliospheric context of energetic particles

In the course of modeling and forecasting energetic particle events, it is useful to establish a more global heliospheric picture of their occurrence. Lower energy populations are accelerated at solar wind Stream Interaction Region/Corotating Interaction Region shocks, although these are usually not regarded as a major space weather hazard. However the question of whether the coronal and solar wind context of ICMEs may play a role in where they propagate and produce shocks has been raised in the past. For example, it has been suggested that the heliospheric current sheet location may exercise some effect on particle transport or that shock production is enhanced by the slow solar wind belt. Now graduated CISM student Christina Lee carried out a survey of the solar wind context of energetic particle events using the same display format used earlier to analyze the solar wind stream structure. Her result for energetic particle event occurrence, now published in Solar Physics (Lee et al., 2010) shows that while the observed energetic particles from the stream interactions clearly follow the solar wind stream compression region tracks in this 1 AU overview of the declining phase of solar cycle 23 (right half of left panel below), the SEP events associated with the early ICME activity (left part of left
panel) show a much broader distribution within the streams. There is no evidence for a significant influence of the heliospheric current sheet or slow wind belt on occurrence or intensity for these events associated with the coronal transients.

Figure 22: From left to right, Carrington rotation-organized contours of energetic (> several hundred keV) ion fluxes from ACE EPAM (Log scale (particles cm\(^{-2}\) s\(^{-1}\))); corresponding solar wind velocities from the OMNI data base (scale is km/s); OMNI interplanetary field radial component showing the locations of stream compressions (stronger fields in ridges) and magnetic sector boundary crossings. The right half of the energetic ion flux plot shows features corresponding to the stream interaction related ‘CIR’ events of quiet solar times, while the left half is populated by many additional SEP (solar energetic particle) events which show no particular solar wind context. This gives a broad picture of how the energetic ion distribution in the heliosphere changes character with the solar cycle.

Goals and Activities planned for this coming year:

Our work this coming year will focus on the completion of key tasks and creation of legacy models:

4. Adoption of improved synchronic maps in models where possible
5. Completion of an improved MAS coronal model solar wind description
6. Adjustment of cone model runs toward improving shock timing and tracking
7. SEP model flare source implementation and tests
8. Heliospheric Simulation of new observed CME events, especially multispacecraft events, to demonstrate model 3D performance for cases where state-of-the-art observations are available.
9. Further analysis of geospace couplings of heliospheric model results
10. Delivery of codes, where appropriate and practical, to community and applications-oriented users for future exercising and development.

Our aim is to leave our CISM solar/heliospheric activity with a record of documentation and codes that enables broad benefits from the knowledge gained during the Center’s lifetime.
2B. Magnetospheric Thrust

LFM RCM Coupling
Frank Toffoletto, Asher Pembroke, Stan Sazykin, Mike Wiltberger, Pete Schmitt, John Lyon, Slava Merkin,

LFM-RCM – Current status

Over the past year, the focus of this work has been to understand the behaviour of the coupled LFM-RCM code. As part of his graduate work, Asher Pembroke, has developed a set of diagnostic tools to analyse output from the code. An example of these tools is the ability to accurately compute the specific entropy of the LFM. Asher is currently working with the LFM-RCM coupling team to on a paper, which we plan to submit soon to JGR. Our team continues to work closely, with weekly telecons and team meetings; the most recent meeting was at Rice in February, 2011.

Figure 23 shows a comparison of the LFM pressures and velocities from the double-resolution LFM both uncoupled (without RCM on the left) and coupled (right). This run is an idealized run that has an extended period of steady southward IMF. At the time interval shown in Figure 23, the IMF has been southward for 6 hours. Note the presence of a strong partial ring current and ionospheric shielding in the coupled code apparent in lower latitude Region 24 currents on the right.

Figure 24 shows the same configuration as figure 23 but with increased resolution. Both codes produce pairs of field-aligned currents in the ionosphere that appear around midnight and propagate towards the dayside. At this resolution both coupled and uncoupled codes show evidence of region-2 currents in the ionosphere, but with the coupled code exhibiting stronger currents and shielding. The coupled code also exhibits more dynamic behaviour and much of our focus has been on trying to understand the nature of the dynamics in the code.

It appears that increased resolution has significantly improved the fidelity and stability of the results, however the highest resolution (so called ‘quad-resolution’) is not currently a practical option for incorporation into LTR as it is very computationally expensive. It is expected that once the software library $p$MPI-INTERCOMM is implemented within the parallel LFM, we will be able to perform much higher resolution runs on a routine basis.
Figure 23: Top left panels show the LFM magnetosphere pressures (color), velocity vectors and $B_z=0$ line and the bottom left panel shows the MIX computed potentials and field-aligned currents for the standalone LFM. Right panels are the same but for the coupled LFM-RCM. In the coupled code, there are region-2 currents and shielding in the ionosphere due to the presence of the RCM.
The injection of kilovolt particles from the plasma sheet to the ring current has traditionally been believed to be the result of increases in convection. It is now becoming clear that the actual process is far more complex, involving processes such as convection, substorm injections and flux tubes with low entropy (plasma bubbles). However, major uncertainties remain about the exact nature of these transport processes, when they occur and when one process dominates over the other. How this relates to the behaviour of the LFM-RCM is still a subject of our ongoing investigations.

In MHD, the specific entropy $K$, which is a field line quantity, is defined as

$$K \equiv \left( \int_{\text{field line}} p^{\frac{3}{2}} ds / B \right)^{\frac{2}{3}}$$

which, in ideal MHD, is a conserved quantity along a particle trajectory.

(In static equilibria, where the pressure $p$ is constant along a field line, $K = p r^{\frac{3}{2}}$).

In the plasmasheet, $K$ is large, while in the inner magnetosphere, $K$ is typically and order of magnitude lower. In addition, the mass content in the flux tube, defined as
\[ M \equiv \left( \int_{\text{fieldline}} \frac{\rho ds}{B} \right) \]

is also expected to be conserved along a particle trajectory. Our recent modelling work has suggested that ring current injection comes from low entropy plasma (bubbles) and high entropy plasma is not found the inner magnetosphere.

An example of the dynamic structure in the LFM is shown in the four panel plot in Figure 25 for the standalone LFM, which shows the entropy parameter \( K \) (top left) along with flow vectors, and mass content \( M \) (top right) in color contours along with \( K \) as line contours. The bottom panel shows the ionospheric quantities of potential (left), (color contours \( K \)) and Birkeland currents (line contours \( K \)). The gray ball in the top left and bottom left are mapped along a fieldline to the corresponding footprint in the ionosphere (shown in the bottom left). Preliminary analysis indicates that the field-aligned current structures seen in the ionosphere are associated with the plasma bubbles. Figure 26 shows the same plot but for the coupled LFM RCM, which shows a lot more structure and dynamics.

From this preliminary analysis, the MHD code does not apparently conserve entropy, possibly as a result of a combination of numerical dissipation and lack of resolution. This is a common problem of all global MHD simulations. From the LFM results, both from coupled and uncoupled simulations, the plasma sheet is far from the more-or-less uniform medium indicated by early pictures of the magnetosphere. Low and high entropy (bubbles/blobs) plasma are constantly being generated in the tail. These bubbles/blobs are relatively fast moving, even as they approach the inner magnetosphere. These bubbles systematically make their way into the inner magnetosphere and resemble bursty bulk flows. Higher entropy ‘blobs’ also impact the inner magnetosphere and may be associated with the oscillations seen in the MHD code. For the RCM, which assumes a quasi-static slow flow, these fast flows are a problem. One solution that we have adopted is to restrict where the RCM operates to regions where its assumption of slow flow is valid. We have keyed on flux-tube averaged \( \beta (=1) \) to set the RCM boundary. Other choices are probably also valid, but this is the option that works best in terms of stabilizing the code’s behaviour. Recent work by Dick Wolf and Chuxin Chen using a filament code to test RCM assumptions also finds that the plasma beta is a reasonable criterion for deciding where the RCM approximations are valid [JGR paper in preparation]. This added criterion also keeps the entropy at the RCM boundary quite low. This boundary results in a much calmer inner magnetosphere, but with a more realistic ring current than standalone LFM.
Figure 25: From top, left to right shows the entropy parameter $K$, the total flux tube content in the equatorial plane, the ionospheric potential and entropy parameter $K$ and the field-aligned currents (solid contours) and entropy parameter $K$. This figure is derived from the standalone LFM.

Figure 26: Same format as figure 3 but for the coupled LFM-RCM
Recently, we have added a simple dynamic plasmasphere to the RCM by initiating a cold energy channel of the RCM using a Gallagher plasmasphere model. We then let the RCM convect the plasmasphere using the MIX electric field developed to improve the MI coupling calculation, and feed back the densities to the LFM. The results are plotted in Figure 27, which shows the RCM computed density. The structure in the plasmasphere shows indications of fingers, which are similar to what was seen by the IMAGE spacecraft as shown in Figure 27.

![Image of RCM computed densities with a simple dynamic plasmasphere model, and a IMAGE observation from Darrouzet et al. (Space Sci. Rev., 145, 55-106, 2009) (The sun's location on the right figure is indicated by the yellow dot).]

**Figure 27:** (Left) RCM computed densities with a simple dynamic plasmasphere model, and (Right) a *IMAGE* observation from Darrouzet et al. (Space Sci. Rev., 145, 55-106, 2009) (The sun’s location on the right figure is indicated by the yellow dot).

**Summary and Plans for the Coming Year**

We have developed a working solution for getting stable runs from the coupled code. In addition, the entropy parameter has become a key diagnostic for understanding the behaviour of the code. Overall, there are indications that these high-resolution MHD runs, despite their imperfect numerical accuracy, are providing us with a much more realistic picture of the real plasma sheet than has been available before. Further tests will show how well this solution works. We have also done runs where we have varied the IMF direction and the code is still stable. A real event driven by solar wind data is the next thing to try. There is other missing physics in the code that likely has some impact including: an ionosphere with a realistic conductance; an ionospheric source; loss through precipitation and charge exchange; adding a more realistic plasmasphere model. Progress in some of these areas is addressed with the Multi-Fluid LFM (MFLFM) and improvements to the LFM grid used in the inner magnetosphere, described below.
MHD Studies of the Inner Magnetosphere

Seth Claudepierre, Richard Denton, Mary Hudson, Bill Lotko, John Lyon, Mike Wiltberger

One of the keys to understanding radiation belt dynamics is the ability to characterize the ULF waves that promote radial diffusion of the high energy particles. Several observational studies suggest that solar wind dynamic pressure fluctuations can drive magnetospheric (ULF) waves on the dayside. Claudepierre et al. [2010] used the (LFM) global, three-dimensional MHD simulation code to study this mechanism for ULF wave generation. The simulations were driven with synthetic solar wind input conditions where idealized ULF dynamic pressure fluctuations are embedded in the upstream solar wind. In a series of simulations both monochromatic and continuum pressure perturbations were introduced in the solar wind over the frequency range from 0–50 mHz. The idealized solar wind input conditions allow study only of the effect of a fluctuating solar wind dynamic pressure, while holding all of the other solar wind driving parameters constant. The monochromatic solar wind dynamic pressure fluctuations drive toroidal mode field line resonances (FLRs) on the dayside at locations where the upstream driving frequency matches a local field line eigenfrequency. In addition, the continuum of upstream solar wind dynamic pressure fluctuations drives a continuous spectrum of toroidal mode FLRs on the dayside shown in Fig. 28. Both the $n=1$ and $n=3$ (mode number along field line) are seen in the simulations. Because of the symmetry of the driver only odd modes are excited and the modes also have a null in the subsolar region. The characteristics of the simulated FLRs agree well with FLR observations, including a phase reversal radially across a peak in wave power, a change in the sense of polarization across the noon meridian, and a net flux of energy into the ionosphere.

One of the issues with the Claudepierre results was the numerical limitation arising from the LFM grid structure in the inner magnetosphere, which is not at all aligned with the magnetic field. This leads to numerical diffusion of the modes. It is also seen in the relative weakness of Region 2 currents. For plasmapsheric studies, having accurate Region 2 currents is essential to accurately calculate the electric field that penetrates into the plasmasphere. The LFM code can use any hexahedral grid that is connected in a logically rectangular manner. We have developed a dipole grid for use in the inner magnetosphere shown in Fig 29.
Initially, the grid is being used for convection and field-line resonance studies related to the plasmasphere. Ultimately, this grid will be used as the interior of a global LFM calculation by using the Overture framework to embed the dipole grid within the usual LFM calculation.

One of the problems with fluid studies of the plasmasphere, and outflow in general, has been the inability of separate beam-like distributions to be modeled. A common problem, for example, is that flows coming out from separate hemispheres collide at the equator in a single fluid code causing a spurious shock layer to form. In reality the separate beams flow past one another. A similar problem occurs when distributions mirror at low altitude. We are working on a numerical scheme for supersonic beams from both ionospheric boundaries that do not lead to shocks. The idea is to use two fluids, one for northward traveling plasma and one for southward traveling plasma, and to split the boundary condition at both ends of field lines into symmetric and antisymmetric parts such that reflected plasma is transferred to the other beam. A 1D simulation code has been constructed and we are currently altering the boundary conditions to test this idea.
Electromagnetic Ion Cyclotron Wave Hybrid-Dipole Simulations

Richard Denton and Yonggang Hu

A two dimensional simulation of electromagnetic ion cyclotron (EMIC) waves in dipole geometry has been developed in order to understand the growth, distribution, and propagation of the waves and to provide an input for models of radiation belt electron scattering [Hu and Denton, 2009; Hu et al., 2010]. The particle population can be initialized using an equilibrium solution from an anisotropic MHD code. Major results of this research include demonstrations that the waves cluster in radial packets of size equal to about $10 \frac{c}{\omega_{pp0}}$, where $\omega_{pp0}$ is the proton plasma frequency at the magnetic equator, that the waves exhibit radial propagation in energy with a group speed equal to about 0.1 times the Alfven speed, that the heavy ion concentration has a strong effect on which waves grow and how much wave energy can propagate through resonances to the ionosphere, that the Poynting vector is generally toward the ionosphere even when there is some reflection, that waves do not tend to grow at the plasmapause itself, and that waves on either side of the plasmapause (in the plasmasphere or plasmatrough) can be quite different due to the different ion composition in the two regions. Figure 30 shows the steady-state power spectrum of EMIC waves for a driven simulation in which the initial particle distribution is continually replenished. This worked completed Yonggang Hu’s Dartmouth PhD thesis under Richard Denton’s supervision.

Figure 30: Plot of power spectrum (color saturation) of EMIC waves for a driven simulation with respect to the parallel coordinate (along the dipole field lines) $q$ and $r = L$ shell. Blue color corresponds to left-hand polarization, while green corresponds to linear polarization.
Radiation Belt Modeling

Mary Hudson, Thiago Brito, Anthony Chan, Scot Elkington, Brian Kress, Zhao Li, Mike Wiltberger

Characterizing Diffusive Transport of Radiation Belt Electrons

In the past year Scot Elkington (University of Colorado), Anthony Chan (Rice University), and Rice undergraduate Aaron Levine have been performing simulations of the radial transport of radiation belt electrons in model ULF wave fields. New calculations of radial diffusion coefficients show good agreement with analytic quasilinear theory results, provided there is sufficient phase randomization (either from the ULF waves or from cyclotron-frequency wave-particle interactions, for example), and provided the autocorrelation time of the ULF wave-particle interaction is sufficiently short. Further work is being carried out to better understand the radial transport, including (i) relative contributions of the electric and magnetic components of the ULF waves, (ii) radial transport in ULF waves that are limited in local time, (iii) effects of waves that are either co- or counter-propagating with the drift velocity of the electrons, and (iv) effects of more realistic power spectral densities (i.e., more realistic than the flat idealized spectral densities used so far).

Magnetospheric ULF Wave Power as a Function of Solar Wind Variations

Magnetospheric ULF waves at Pc-5 (mHz) frequencies may have profound effects on relativistic electron fluxes in the outer radiation belts by driving radial diffusion, a process which may either deplete the belts of electrons by allowing electrons to drift outward through the stable trapping boundary, or increasing the overall energy content of the belts through inward radial diffusion and energization of energetic electrons. The energy for most global-scale Pc-5 activity results from the driving action of the solar wind, either through shear interactions at the magnetopause flanks, or directly through pressure or IMF variations embedded in the background solar wind. However, the relationship between ULF power at a given point in the magnetosphere and the driving power of the solar wind is not simple: as a wave propagates through the magnetosphere, partial reflections from Alfvén gradients, magnetospheric field line resonances, and global cavity modes may all act to either enhance or suppress wave power at a given frequency and location in space.

We have used CISM global MHD simulations of the magnetosphere/solar wind interaction to probe the mapping function of fluctuations in the solar wind into Pc-5 ULF power in the inner magnetosphere and radiation belts. Broadband variations in solarwind conditions were imposed, and the resulting ULF activity in the magnetosphere characterized as a function of frequency and location. Example results are indicated in Figure 1, where we show the change in ULF wave power corresponding to a 50% increase in the background solar wind velocity. This ULF activity may then be used to characterize radial transport rates in the radiation belts in terms of relevant diffusion coefficients. By comparing the ULF power distribution in the magnetosphere during events driven by observed solar wind conditions to those characterized by our broadband mapping, we investigate the feasibility of empirically modeling magnetospheric ULF wave activity as it relates to ULF power in the solar wind.
Radiation belt losses and magnetospheric EMIC waves

The dynamical variations in the radiation belts are the result of a complex interplay of particle acceleration, transport, and loss. The combination of global models of the magnetosphere with test particle simulations of the radiation belts provides a physically-based means of modeling particle transport and the acceleration associated with time-changing large scale magnetic and electric fields. However, particle resonances with high-frequency waves not modeled in the MHD approximation can lead to finite particle lifetimes by scattering energetic particles into the atmosphere. In particular, electromagnetic ion cyclotron (EMIC) waves are known to effectively interact with radiation belt electrons and can lead to pitch angle diffusion into the bounce loss cone [e.g. Horne and Thorne, JGR, 1994]. Here we have undertaken to characterize the spatio-temporal and spectral characteristics of EMIC waves with the aim of incorporating these effects into global simulations of the radiation belts.

EMIC waves are generated from temperature anisotropies of energetic ring current ions in the presence of cold background plasmas. These anisotropies may result from preferential perpendicular energization due to transport of ring current ions into regions of stronger magnetic field strength. Our approach is to use the global magnetospheric models being developed under the auspices of CISM to track the 3d motion of magnetospheric hydrogen, helium, and oxygen populations as they evolve in time-dependent electric and magnetic fields. By assuming the phase space density associated with each test particle is conserved along its trajectory in accordance with Liouville’s theorem, we are able to model the time-evolving distribution function which may then be integrated over the second moment in velocity space to calculate plasma temperatures in directions both parallel and perpendicular to the local magnetic field. With these quantities we can compute the convective wave growth rate for EMIC waves [Kozyra et al., JHR, 1984] and determine the regions of the magnetosphere where waves are likely to occur, which might then be used to constrain energetic electron lifetimes in models of the radiation belts.

The physical origin of dayside temperature anisotropies is suggested in Figure 32. As warm ions drift into the noon sector of the magnetosphere, those at high-L may encounter regions where the $B_{min}$ plane bifurcates from the equatorial region to high latitudes near the cusp, producing Shabansky, orbits. This bifurcation is an effect of the dynamic pressure of the solar wind; particles traversing this region may experience a change in the adiabatic invariant associated
with bounce motion as a result of the change in field-aligned magnetic topography, leading to a transfer of parallel to perpendicular kinetic energy. Drift shell splitting is another effect resulting from the day-night asymmetry of the magnetosphere, and acts to enhance the temperature anisotropies that result from the bifurcated Shabansky orbits.

Figure 32: Ion temperature anisotropy in the noon-midnight plane. The crosses denote magnetic field minima. The field-aligned nature of the anisotropy and the off-equatorial locations of the minima suggest Shabansky orbits play a role in generating plasma temperature anisotropies.

**MHD-test particle simulations of radiation belt electron interaction with ULF waves**

Several storms, both CIR and CME-driven, have been examined using the LFM-MHD code to compute internal magnetospheric E and B fields from upstream solar wind parameters, combined with a 3D guiding center test particle code developed at Dartmouth to examine: radial transport and 2) enhanced precipitation losses into the atmosphere. Inward radial transport increases flux at a given energy and L value, while outward radial transport to the inward moving magnetopause produces loss, along with enhanced losses to the atmosphere. On the time scale of a storm, including buildup of the ring current, additional radial losses result from fully adiabatic and diffusive transport. Enhanced ULF wave activity can produce both coherent and diffusive transport and energy exchange with electrons in drift resonance with azimuthally propagating ULF waves. Coherent transport and energization can occur at a rate which exceeds nominal radial diffusion estimates but is slower than prompt injection on a drift time scale. Precipitation losses for the January 20, 2005 geomagnetic storm occur on the time scale of magnetosonic impulse propagation through the magnetosphere, following arrival of a CME-shock, much faster than the time scale for build up of the ring current and enhanced EMIC wave precipitation losses. Enhanced precipitation loss to the atmosphere is shown in Figure X, along with azimuthal electric field oscillations at two noon meridian radial locations in the LFM simulations. This ULF-wave modulated precipitation was measured by balloon-borne instruments over Antarctica and represents a new loss mechanism for radiation belt electrons associated with the coherent interaction of electrons with ULF wave fields. This interaction has also been shown to cause acceleration of electrons for a storm in November 2004 from in situ measurements by the Cluster spacecraft (Zong et al., 2009). Our 3D-test particle simulations confirm this coherent acceleration by poloidal mode ULF waves produced by CME-shock compression of the magnetopause. The balance between enhanced and decreased fluxes, depending on electron drift phase relative to the azimuthal electric field of the poloidal modes,
also observed by Cluster, is the topic of Dartmouth graduate student Thiago Brito’s PhD thesis study. This work is the first use of the 3D test particle code with LFM fields to study atmospheric loss as along with in situ acceleration.

Dartmouth graduate student Zhao Li continues to improve the radial diffusion code developed by her predecessor Feifei Chu (Chu et al., JGR, 2010) to quantify diffusive radial transport of radiation belt electrons, including a model for pitch angle scattering losses to the atmosphere. The radial diffusion model conserves the first and second adiabatic invariants and breaks the third invariant. For the radial diffusion coefficient, $D_{RL}$, the Brautigam and Albert (JGR, 2000) diffusion coefficient parameterized by Kp has been tested against other models using LANL geosynchronous phase space density as an outer boundary condition and compared with GPS fluxes at $L = 4.2$ for two storm intervals in July and November 2004. Her results indicate that the July storm, which included three successive drops in Dst over six days, is well-described by the radial diffusion code, however the November 2004 storm described previously, which was a stronger CME-shock driven event with greater drop in Dst, is not so well characterized by radial diffusion, indicating the effects of non-diffusive processes better-modeled by the MHD-test particle simulations. She is simulating both storm periods using the LFM code driven by ACE data, using the 2D guiding center test particle code developed by Elkington to model equatorial plane phase space density, for direct comparison with the radial diffusion code.

Figure 33: ULF oscillations seen in LFM–test particle simulations of MeV electron precipitation produced by the January 21, 2005 CME-shock driven storm. Top panel shows ACE data used as input to LFM.
Figure 34: lower right shows electron precipitation measured by X-ray instruments on the MINIS Antarctic balloons and lower left shows electron precipitation into the atmosphere from the test particle simulations in LFM fields.

Loss following Jan 21, 05 1845 UT shock

20 sec after shock

45 sec after shock

Figure 35: Above shows geographic distribution of the simulated losses.
The CISM-Dartmouth geomagnetic cutoff model

Brian Kress, Chris Mertens (NASA), Juan Rodriguez (NOAA), Mike Wiltberger

The CISM-Dartmouth geomagnetic cutoff code was originally developed to investigate changes in solar energetic particle (SEP) access to the inner magnetosphere during geomagnetic storms. With support from several leveraged funding sources, it is now being transitioned to a space weather forecast tool for modeling radiation dose in the upper atmosphere and in low Earth orbit. The CISM-Dartmouth cutoff code produces global grids of geomagnetic cutoff rigidities by computing Lorentz trajectories in model geomagnetic fields. Cutoff rigidities can be used to model SEP and GCR fluxes in the inner magnetosphere from a known interplanetary spectrum. The CISM-Dartmouth cutoff code may be run with geomagnetic fields from several different empirical and physics based geomagnetic field models including CISM’s suite of coupled ionospheric and magnetospheric simulation models. Two independently funded projects that contribute to the further development of the CISM-Dartmouth geomagnetic cutoff model are discussed below.

Cutoffs computed in real-time

The CISM-Dartmouth geomagnetic cutoff model is being used in conjunction with the High Energy and Charge Transport code (HZETRN) at the NASA Langley Research Center for the development of the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) model, supported by the NASA Applied Sciences Program. The NAIRAS model is a prototype operational model that provides global, real-time, data-driven predictions of atmospheric ionizing radiation exposure for archiving and assessing radiation levels at commercial airline altitudes. The CISM-Dartmouth cutoff rigidity model provides a dynamic outer boundary condition for the NAIRAS model. A real-time version of the CISM-Dartmouth cutoff code is currently under development. The real-time cutoff model updates cutoff rigidities on a five degree by five degree latitude-longitude grid, at 100 km, once per hour, using real-time ACE data provided by Space Environment Technologies, Inc.

Geomagnetic cutoff model comparison with GOES East-West SEP flux

In a study aimed at better understanding SEP access to geosynchronous orbit, CISM-Dartmouth geomagnetic cutoff model results are being compared with GOES observations. This work is being performed in collaboration with researchers at the NOAA Space Weather Prediction Center (SWPC), and is supported by the NSF National Space Weather Program.

The GOES 13 spacecraft carries a pair of the successor Energetic Proton, Electron and Alpha Detector (EPEAD) instruments, separately providing both eastward and westward field of view (FOV) measurements. While the EPEAD SEP flux measured by the westward looking FOV is seldom affected by geomagnetic activity, the eastward looking flux (corresponding to gyrocenters inside of geosynchronous) is observed to vary with geomagnetic activity. The time variations of the “inside” fluxes represent changes in the geomagnetic cutoffs driven by geomagnetic activity.

To determine if the observed east-west flux ratio (jE/jW) at geosynchronous can be understood in terms of cutoff variations, a preliminary study of the 7-11 December 2006 solar particle event was performed. Figure 36 shows (top to bottom) eastward and westward looking GOES 13 fluxes, the east-west flux ratio, solar wind dynamic pressure and IMF, and the AE index. It is seen from Figure 36 that during geomagnetically quiet periods SEPs arriving from the east are
geomagnetically shielded decreasing $j_E/j_W$. When geomagnetic activity is elevated the cutoff is suppressed and $j_E/j_W$ approaches unity.

Cutoff energies for protons arriving at GOES 13 from magnetic east ($E_{CE}$) and from magnetic west ($E_{CW}$) were computed once per hour for the period 7-11 December 2006. The results are shown in Figure 37. As expected, $E_{CE}$ is above $E_{CW}$, since $E_{CE}$ corresponds to proton guiding centers located well inside of geosynchronous where only the higher energy protons can penetrate.
The most notable feature in the cutoff variations, shown in Figure 37, is their daily variation due to the local time dependence of the cutoff. In December 2006 GOES-13 was at approximately 105° W (GEO), which is near midnight local time at ~7 UT. The minima in $E_{CE}$ and $E_{CW}$ are seen near 7 UT each day since, at a given radial distance in the equatorial plane, the geomagnetic field is weakest near the night side resulting in a lower cutoff there. The daily variation is most notable in $E_{CW}$, which corresponds to protons located outside of geosynchronous. Superimposed on the daily variation are changes in the cutoff due to geomagnetic activity. The local time effect plays a less dominant role in the $E_{CE}$ variations.

To make a quantitative comparison with observations we may consider the following two cases: (1) When both $E_{CE}$ and $E_{CW}$ are below the lower bound of the detector energy channel we expect that $j_E = j_W = j_{interplanetary}$, thus $j_E/j_W = 1$; (2) When $E_{CW}$ is below the lower bound of the energy channel and $E_{CE}$ is above it, we expect $j_E/j_W < 1$. Qualitative agreement can be seen between the modeled cutoff variations shown in Figure 2 and the observed $j_E/j_W$ ratios in Figure 1 in several cases:

The modeled cutoff variations qualitatively demonstrate that the observed $j_E/j_W$ may be explained by geomagnetic shielding. A modeled $j_E/j_W$ ratio can be obtained for direct comparison with the GOES observations by using the modeled cutoffs to constrain upper and lower bounds of an integral over the detector energy width. In future work a direct quantitative comparison will be performed for several solar particle events.
Magnetosphere-Ionosphere Coupling – Power Flow, Precipitation, Outflow

Development of physical models of collisionless dissipation and particle energization in MI coupling, that can be embedded in the LFM and CMIT global simulations, is a continuing priority. The objectives articulated in previous progress reports include development of models for:

- superthermal (“broadband”) electron precipitation induced by Alfvén wave activity;
- superthermal ionospheric ion outflows associated with Alfvén wave activity;
- thermal outflows including the polar wind; and
- collisionless Joule dissipation, upward field-aligned electron flow and energy flux in downward field-aligned currents.

As described below, substantial progress has been made on items (1) and (2) in the past year. Progress on item (3) requires completion of the MPI parallel version of the MFLFM code, which has received lower priority than RMC-LFM coupling in the last year and is incomplete at this time. Although conceptual progress has been made on item (4), implementation has been slower than anticipated due to a stubborn numerical instability of the model algorithm that has yet to be suppressed.

Advances in modeling capabilities and associated scientific results during the past year include:

- Development of a runtime algorithm for extracting bandpass-filtered Poynting flux in LFM simulations (nominally the 5 -180 s period band that includes Alfvén waves). The wave Poynting fluxes, evaluated on a geocentric simulation shell near 3 RE, are now being used to drive ionospheric outflows and “broadband” electron precipitation (see next bullets). An analysis by Dartmouth PhD candidate Binzheng Zhang on the origin, distribution and properties of the Poynting fluxes shows that they originate in braking, plasma sheet flow channels, which launch Alfvén-wave packets along the magnetic field. The frequency spectrum of the wave-packets closely resembles observed spectra from Polar-satellite measurements taken at altitudes 4-6 RE (Angelopoulos et al., 2002). The average distribution of Alfvén wave power (in the band 5 -180 s) flowing into the polar region also resembles the average pattern reported by Keiling et al. (2003). A first draft of a manuscript on this work has been completed (Zhang et al., 2011).

- These dynamic Alfvénic Poynting fluxes have been used by Dartmouth PhD candidate Oliver Brambles to drive ionospheric outflows based on an empirical relation derived from FAST satellite data. A series of simulations for steady interplanetary conditions produced the remarkable discovery that the sawtooth mode of magnetospheric convection occurs in MFLFM simulations only when outflows are included and that steady magnetospheric convection modes occur in the same simulations when interplanetary driving and, therefore, the outflow flux, is smaller. A paper on this work is in review at Science (Brambles et al., 2011). One result from the study in which a superposed epoch analysis of the simulated magnetic inclination angle near geostationary orbit is compared with GOES satellite data is shown in Fig. 38.
Renovation (and improvement) of the LFM precipitation model is nearing completion. Refinements and additions include: 1) addition of diffuse and direct-entry ion precipitation; 2) development of dynamically regulated, loss-cone filling based on the auroral oval location; this function specifies the decrease in the low-cone fluxes of diffuse electron and ion precipitation as their magnetospheric source populations are depleted on drift paths approaching the inner magnetosphere; 3) specification of the dynamically regulated cusp-area, which determines where the essentially full loss-cone fluxes of direct-entry cusp precipitation occur; 4) addition of secondary electron precipitation that accompanies monoenergetic electron precipitation; and 5) addition of Alfvén-wave induced broadband electron precipitation, using the Alfvénic Poynting fluxes described above and an empirical relation between the fluxes and electron precipitation characteristics derived from the FAST satellite data. Dawn-dusk asymmetry in diffuse precipitation attributed to eastward drifting electrons and duskward drifting ions is currently modeled by a simple function specifying dawn-dusk asymmetry. A paper on these developments including validation studies will be completed this summer. The work is being advanced by Dartmouth PhD candidate Binzheng Zhang who will spend the summer at NCAR/HAO implementing the precipitation additions in the CMIT model.

The effects of cusp outflows in the 31 August 2005 storm event have also been studied using the MFLFM model. Among other results, one study shows that, when a substantial portion of the outflow becomes entrained in the Dungey convection cycle, the enhanced ring current inflates the magnetosphere. The resulting blunting of the dayside boundary and increased standoff distance of the bow shock diverts a larger fraction of the upstream flow around the magnetopause, thereby reducing both the dayside reconnection potential and the cross polar cap potential (Brambles et al., 2010). This result is also confirmed in contrived simulations performed by CISM partners (Garcia et al., 2010) with controlled rather than event-based interplanetary parameters. The second study shows that increases in the solar wind dynamic pressure cause typically observed increases in the flux and fluence of cusp outflow by enhancing cusp region electron precipitation and the area of cusp outflow (Damiano et al., 2010). A related simulation study of the effects of a fixed patch of cusp region outflow shows that substorm dynamics are sensitive to the outflow properties (Wiltberger et al., 2010), a behavior also reported by Brambles et al. (2010) in the above mentioned storm event study.
The data archive of the two-month, CISM-LFM “Long Run” (Guild et al., 2008) has been used to study the statistical characteristics of MI coupling as diagnosed by the cross polar cap potential and the field-aligned current, dc Poynting flux and vorticity at the ionosphere. Comparisons with statistical patterns derived from SuperDarn line-of-sight velocity measurements, Iridium magnetometer data and the Weimer 2005 empirical model show that the LFM model does a reasonable job of capturing observed statistical patterns of field-aligned current and vorticity and cross polar cap potential as a function of IMF clock angle, but the currents in the “double resolution” long run tend to be weaker while the CPCP and Poynting fluxes are larger (Zhang et al., 2011). These statistical results from the earlier version of the LFM model will provide a useful baseline for future comparisons with outflow included and the renovated electron precipitation model described above. We envision developing another ~ two-month long simulation archive for this purpose by the end of the CISM project.
2C. Ionosphere-Thermosphere Thrust

The ionosphere-thermosphere modeling segment of CISM is primarily housed at the National Center for Atmospheric Research, but with affiliations to the Space Environment Center at NOAA, the University of Colorado, Utah State University, and Space Environment Technologies. In addition, partnerships with the Air Force Research Laboratory for studies of ionospheric scintillations and use of satellite drag measurements for neutral density validation have been initiated. Primary modeling tools include the NCAR Thermosphere General Circulation Models, auroral particle and photoelectron transport models, middle-atmosphere tidal and planetary wave models, and the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure for analyzing auroral region currents and conductances. The particular model component currently being used for CISM coupled model development is the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM).

The ionosphere, that small percentage of the upper atmosphere that exists as charged particles, is created and maintained mostly by solar extreme-ultraviolet radiation. However, its variability on daily and shorter time scales is largely driven by processes controlled by the solar wind and magnetosphere and coupled to the ionosphere through the auroral regions. Many other small-scale forms of ionospheric variability, such as irregularities in the equatorial region and traveling disturbance waves, are also important, but are less accessible at this time to global-scale thermosphere-ionosphere models. Therefore, the goal of the CISM project for the geospace regions is to create a coupled model of the magnetosphere and ionosphere that includes magnetospheric dynamics, upper atmosphere circulation, solar irradiance variation, and forcing by the lower atmosphere. This Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model is currently released as v. 2.5.

Year-Nine Goals

The following milestones were identified as primary objectives for the Ionosphere-Thermosphere modeling thrust during the ninth year of the CISM project. It is anticipated that most of these will be completed by the conclusion of year-nine (7/31/11).

• Verification and validation of TIE-GCM v. 1.93 at CCMC completed
• Community Release of TIE-GCM v. 1.94 scheduled for 5/09
• Release TIE-GCM v. 2.0 (2.5° grid) in progress as of 4/09
• Couple CMIT to TIE-GCM v. 2.0 and release new version in progress as of 4/09
• Continue validation and metrics studies continuing

Plans for Year-Ten

The following milestones are the tentative goals for year-ten, subject to discussion and evaluation at the all-hands meeting in September.

• Verification and validation of CMIT v. 2.5 at CCMC
• Participation in CEDAR/GEM metrics challenges
• Conclude validation and metrics studies
Magnetosphere-Ionosphere Coupling
Coupling between the magnetosphere and ionosphere was implemented during previous years through an exchange of auroral boundary conditions using the InterComm framework. Grid rotation and interpolation is handled by the MIX magnetosphere-ionosphere coupling module. During year-nine, CMIT v. 2.5 was upgraded to use the NCAR Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) v. 1.93 in the coupling framework. Transition of CMIT to the CCMC, was completed, including stand-alone capacity for running TIE-GCM v. 1.93. User guides and other documentation have been completed. Validation studies for the coupled model are continuing. The TIE-GCM is an MPI parallel code that incorporates model-generated electric fields at low latitudes, and uses Apex magnetic coordinates based on the International Geomagnetic Reference Field (IGRF) for electrodynamical calculations.

Ionosphere-Thermosphere Model Development
A new version of the TIE-GCM ionosphere/thermosphere component model (version 1.93) was released as a community model (http://www.hao.ucar.edu/modeling/tgcm/). Intercomm connections are included in the release, which enables coupling to the LFM model and maintains version control between TIE-GCM and CMIT. Extensive documentation is available online as well as release notes and a wiki, which allows users to update model information as needed. A number of users have downloaded the code since it was publicly released.

The primary development in the TIE-GCM during year-nine pertained to treatment of the ionospheric electric potential. The low-latitude ionosphere generates an intrinsic potential through solar heating and tidal forcing of the dynamo process. The high-latitude potential is mostly controlled by magnetospheric forcing. Therefore, these two regions must be either solved simultaneously or merged. In the current TIE-GCM and CMIT releases, these two potentials are merged by utilizing a cross-over between fixed magnetic latitudes (60 and 75 degrees) in the elliptical solver. However, investigations using the Weimer '05 empirical model of high-latitude potential variation revealed that these fixed cross-over latitudes are insufficient to capture global potential variation during significant geomagnetic activity. Therefore, a new method where the cross-over latitudes move dynamically towards the equator as the high-latitude potential pattern expands was designed, with the poleward boundary defined as five degrees below the auroral convection radius. This system was tested with the Weimer and Heelis empirical potential models, and is the principal modification in TIE-GCM v. 1.94, which is scheduled for community release and transition to the CCMC in May 2011.

The double-resolution version of the TIE-GCM (2.5° horizontal and H/4 vertical) has been tested, and this capability is included as an option in v. 1.94. When validation is complete, it will be included in the CMIT coupling framework and released to the community and to CCMC.
Highlights of Ionosphere-Thermosphere Scientific Studies

Activities related to the ionosphere and thermosphere thrust of CISM undertaken this year emphasized studies of solar high-speed stream and co-rotating interaction region impacts on the coupled geospace system. The Whole Heliospheric Interval (WHI) period in March-April 2008 was utilized as a campaign study interval. A paper published in Solar Physics [Wang et al., 2011] described ionospheric changes. In this paper, ionospheric F2 peak electron densities (NmF2) measured at 10 ionosonde stations were analyzed to investigate ionospheric day-to-day variability around the WHI in 2008. The ionosonde data show that there was significant global day-to-day variability in NmF2. This variability had 5-, 7-, 9- and 13.5-day periodicities. At middle latitudes, the ionosphere appeared to respond directly to the solar wind and interplanetary magnetic field (IMF) induced geomagnetic activity forcing, with the day-to-day variability having the same periods as those in the solar wind/IMF and geomagnetic activity. At the geomagnetic equator, the strongest ionospheric oscillation had a 7-day period, corresponding to the oscillations in the IMF Bz component with the same period. In the equatorial anomaly region, the ionosphere showed more complicated day-to-day variability dominated by the 9-day periodic oscillation. In addition, there were quasi 11-day and 16-day oscillations in the ionosonde data at some stations. These oscillations may have originated from lower atmospheric planetary waves. The ionosonde data were compared with the Coupled Magnetosphere Ionosphere Thermosphere (CMIT) simulations that were driven by the observed solar wind and IMF data during the WHI. The CMIT simulations showed similar ionospheric daily variability seen in the data. They captured the positive and negative responses of the ionosphere at middle latitudes during the first co-rotating interaction region (CIR) event in the WHI. The response of the model to the second CIR event, however, was relatively weak.
In another effort, Qian et al. [2011] investigated how the rise rate and decay rate of solar flares affect thermosphere and ionosphere responses. Model simulations and data analysis were conducted for two flares (X5.4 and X6.2) with the same location (limb) on the solar disk, except that the X6.2 flare had a longer decay time (5 hours versus 3.5 hours) and a longer rise time (40 minutes versus 15 minutes). Simulated and observed TEC enhancements to the X6.2 and X5.4 flares were ~6 TECU and ~2 TECU, respectively, while the simulated neutral density enhancements were 15~20% and ~5%, respectively. Using idealized flares, model simulations showed that for flares with a same location and a same intensity, increasing the decay time had a large impact on enhancing the thermosphere and ionosphere responses, whereas reducing the rise time had a relatively small effect on weakening the responses. In addition, model simulations showed that, the “Neupert Effect”, which causes a larger EUV enhancement during the rising phase of a faster-rising flare, caused a larger maximum ion production enhancement, but had little effect on the flare responses of the thermosphere and ionosphere. Furthermore, model simulations showed that the flare response of plasma transport due to ExB drifts caused a significant equatorial anomaly feature in the electron density enhancement in the F region, but a relatively weaker equatorial anomaly feature in the TEC enhancement, due to the dominant contributions by the photochemical production and loss processes.
Validation of the TIE-GCM for thermosphere densities employed data from the CHAMP and GRACE satellites. This enabled Xu et al. [2011] to study the recovery of the thermosphere as a function of latitude during the October 2003 storms. Results showed that the relaxation times, defined by the e-folding time of thermosphere density variations during the recovery phase, are about 6 and 8 hours for two recovery phases of the October 2003 superstorms, respectively; they are much shorter than the previously established recovery time of the thermosphere. A weak altitudinal dependence of the relaxation times between the CHAMP and GRACE altitudes was observed at middle and high latitudes, but no coherent latitudinal dependence was found. The MSISE00 and TIE-GCM neutral densities are compared with the observations to assess their capability in predicting the thermosphere response during the recovery phases of the extremely severe storms. Neither the MSISE00 nor the TIE-GCM reproduced the rapid recovery of thermosphere densities seen in the CHAMP and GRACE, although the TIE-GCM captured most of the salient features observed by the CHAMP and GRACE when AMIE convection and precipitation patterns were used to specify the high latitude drivers. The relaxation times of the MSIS-00 and TIE-GCM densities at 390 km are generally longer than that from the CHAMP observations by about 4 hours, and even longer in the geographic latitudinal range of 25°N-
No unambiguous explanation exists to fully understand the causes for the slow recovery of thermosphere density simulated by the TIE-GCM model.

Figure 41: Variations of (a) interplanetary magnetic field $B_z$, (b) $K_p$, (c) $D_S$, and neutral densities (in units of $10^{-12}$ kg/m$^3$) from (d) CHAMP, (e) NRLMSISE-00, (f) TIE-GCM simulation driven by high latitude forcing from the $K_p$ parameterization (TIE-GCM-gpi) and (g) TIE-GCM simulations driven by AMIE (TIE-GCM-AMIE) on 28-31 October 2003. The red and green shading curves represent thermosphere density on the dayside and nightside of the CHAMP observations or the modelled densities sampled at CHAMP local times.
2D. Code Coupling Thrust

The Code Coupling Thrust is responsible for developing and maintaining successive versions of the CISM coupled model suite, which simulates the entire solar terrestrial system. We are responsible for defining the code coupling strategy, adapting specific computational science tools to implement this strategy, and applying these tools to couple our component codes to create versions of our coupled models. We further perform an initial pre-Validation test of the coupled codes before freezing them for evaluation by the Validation and Metric Thrust. Finally, we are responsible for developing and implementing the code and data handling plans for CISM and for maintaining the CISM code repository.

Our basic plan, as described in Goodrich et al. (2004), is to build our comprehensive model suite from individual component codes representing different physical regimes and processes. Incremental versions of coupled models incorporate new or more sophisticated and comprehensive physics as new component codes become available. This approach allows us easily to improve or tailor versions of the coupled model suite by adding new components, and replacing existing ones with minimal modification. In practice, we have pursued two complimentary development paths. First, the initial coupling of all code combinations was done using the most convenient methods available, which generally were ad hoc ones commonly using transfer of data by files. As the ad hoc coupling codes are completed, tested, and transferred to the Validation team, we then implement them using our framework software, based on the Overture and InterComm packages, as appropriate to improve computational efficiency and flexibility.

Dr. Michael Wiltberger remained as the co-director for code coupling during this year. In this role he worked closely with model developers, software engineers and computer scientists throughout the CISM program to make sure that CISM is able to meet the milestones related to model coupling and development. In addition, he has coordinated the activities of this thrust with the Knowledge transfer thrust in supporting the transition of models to CCMC and SWPC.

The goals for the Code Coupling Thrust are outlined in the CISM Goals and Milestones and in the CISM Model Timeline. The goals are developed in more detail each year at our All Hands Meeting. Our major activities in the last year are:

- Framework Technology Development
  - Completed the Intercomm Portability Improvement Project
  - Developed Model Run Environment
  - Began development of routine testing protocols
- Enhancements to LTR 2.0
  - Began MPI-LFM Scaling improvement project
  - Initiated Parallel IO Study
- Continued support for LFM-RCM Coupling
  - Assisted with Beta Switch Coupling technology
  - CISM models on new Rice development platform
- Model transitions support
  - Fully-coupled Geopsace Models at CCMC

Framework Technology Development
As is known well known by readers of this report the CISM coupling framework is designed to create a flexible and efficient environment for coupling models together with the minimal amount of work required within the component models. The core components of the CISM framework are InterComm and Overture packages. InterComm provides an intelligent data channel between the coupled codes. The Overture package provides a series of C++ based operators for easily interpolating data between grids as well performing physical transformation, e.g. unit conversions, derived quantities. The details of these packages and how they are combined to create the CISM framework can be found in Goodrich et al. (2004) paper.

During this last year we completed a major improvement to the InterComm component of the CISM framework. Since InterComm was originally designed to support the linking of models running on heterogeneous platforms in used the Parallel Virtual Machine API at the low level to handle the passing of information between computational nodes. This API requires the starting of a daemon on each of the nodes and on modern supercomputers, with $10^6$ cores, this was becoming increasingly difficult if not impossible to conduct. To address this issue we have extended the capabilities of the InterComm API to utilize the widely used extension of the Message Passing Interface (MPI) known as PNMPI. This API is installed at the leading supercomputer facilities and allows multiple MPI applications to run concurrently in a single MPI environment. This new version of the InterComm library has been extensively tested and is now being utilized with the LTR models. It has allowed us to run on machines previously unavailable to our group and will allow runs at significantly higher resolution than possible on platforms to which we currently have access.

Also during this year we completed development of another major tool for the CISM community, namely the Model Run Environment (MRE). The MRE allows users to run any combination of LTR 2.0, e.g. LFM-MIX, LFM-MIX-RCM, LFM-MIX-TIEGCM, on all support platforms with a simple script. It allows any level of user to easily setup and run the models. For the novice user default parameters are supplied for the developer complete access to all model input parameters is preserved. In addition, based upon feedback from users with have added the ability to adjust input parameters or clone runs by altering a parameter file saved by the MRE script during execution. This has been quite helpful for groups using idealized runs to sample a wide parameter space. The MRE is built upon Python scripts that access YAML file descriptors for the codes and computational platforms. Experience within the past year has shown that adding additional computational platforms is trivial. While the majority of work on this project is now complete the Code Coupling Thrust will continue support improvements, bug fixes, and other enhancements.

As the development of LTR has progressed the software development team has noticed the need for routine automated testing the model components as well as the coupling interfaces. We have begun investigations into tools for accomplishing these tasks.

Enhancements to LTR 2.0

In the previous year the Code Coupling thrust help the Magnetosphere Thrust pass the major milestone of completing the coupling between the MPI-MFM and the RCM. With this milestone behind us a significant portion of our efforts during this year have been focused on improving the capabilities of the cornerstone MPI-LFM model.

In its current configuration the MPI-LFM code base has limits on scaling on performance especially at high processor counts. Small task forces of software engineers and model developers have begun work to address this issue. In particular, they are conducting profiling of
the model performance on a variety of computational platforms to identify key bottlenecks. One early area in need of improvement has been the communication structures used within the P++ portion of the simulation. Work has begun on ways of reordering the data layout within the code to reduce the number of messages while increasing their size. It is expected that this new structure will improve performance on high latency system such as Kraken at NCIS. Additional, work on improving computational performance of key subroutines will be conducted once the restructuring work is completed.

Another impending issue related the operation of the LTR modeling system is the growth in output file size as our ability to run higher-resolution simulations expands. The Code Coupling thrust is addressing this issue with a two-pronged approach. The first aspect of this approach is to deal with parallel IO from the LFM. Our group has begun a profile effort to study the performance characteristics of parallel IO libraries including HDF5 and CDF. Once these efforts are complete we will implement the best choice into the LFM. The second aspect of the large file sizes concerns the need to move files back to local sites for analysis that can be come quite problematic. We are addressing this issue by beginning an examination of remote visualization tools like Paraview and Visit to determine how well they meet our needs.

**Support for LFM-RCM Coupling**

As has been our tradition in the past the Code Coupling Thrust continues to work closely the Geospace Thrust on the coupling of the LFM to the RCM as part of the LTR 2.0 model. In the last year, we supported this thrust by helping them with the utilization of the MRE. This allowed them to complete a significant number of runs testing and evaluating the newly developed LFM-RCM coupling. As part of this process we have worked closely with team at Rice to support the deployment of the model on the newly purchased development nodes on the Rice Shared Tightly Integrated Cluster (STIC). We have also assisted the Geospace thrust in the implementation of a new mechanism for controlling the region where the coupling occurs. This new method, using the so called beta-switch, has proven to be quite effective in stabilizing the model leading to results that are now be prepared into a publication for peer review.

**Support of Model Transitions**

The Coupling Thrust has been working closely with the other science thrusts as well as the Knowledge Transfer Thrusts to support the transition of the CISM models to the CCMC and SWPC.

We have successfully implemented our plan to make the geospace model available for Runs on Request (ROR) on the CCMC website. The LFM-MIX model has been available for nearly a year and members of the community have completed nearly 30 runs. The TIEGCM model is also available for ROR on the CCMC with a limited number of runs by members of the community. It is also important to note that these versions of the models are being used to support metric and validation runs being conducted by CCMC to support campaign efforts conducted by GEM and CEDAR. We have also comleted the deployment of the CMIT 2.5 model to CCMC. It has just recently been made available to the community for ROR.
2E. Model Validation and Metrics Thrust

Activities

As CISM nears the end of its ten year life, the tasks of validation and metrics thrust are being increasingly embraced by the entire CISM team, and it is becoming less meaningful to single out particular individuals as validation team members. This embracing by the entire team is best illustrated by the end-to-end Corotating Interaction Region study that will result in a collection of twelve papers to be published in the *Journal of Atmospheric and Solar Terrestrial Physics* (JASTP).

Significant Accomplishments

Top-level accomplishments of our model validation/metrics effort are:

- Over a dozen different model versions have been delivered to the CISM repository, “frozen”, and are considered to be in pre-validation; another handful have been informally pre-delivered for validation pre-assessment.
- Systematic assessment of delivered models continues using a suite of quantitative metrics and baseline models for skill score evaluations of models.
- Validation studies of core component models as well as coupled models is leading to new scientific insights and model improvements.
- Publication of validation/metrics studies continues with an increasingly large number of papers submitted or in draft form for publication in the *Journal of Geophysical Research*, *Geophysical Research Letters*, *Journal of Atmospheric and Solar-Terrestrial Physics*, and *Spaceweather Journal*.

A major center-added component of our activities is a systematic, independent model validation process. We have established a formal process by which completed models are delivered by the modelers to the validation team. Once a model has been delivered, the validation team runs metric tests, computing a skill score for a particular parameter by comparing the prediction capability of the model with the prediction capability of a baseline model. The model validation work also provides important guidance to the development of future model generations. This process is establishing a community expectation and approach to evaluating space weather models and is fostering a community clarification of “what’s important” to characterize model performance.
Metrics Summary

The rationale for CISM metrics selection was developed and a list of 29 metrics, along with the baseline models, first-generation physics models, and the data sets needed to compute skill scores, were established by Spence et al. (2004). Every metric consists of four elements: a parameter, a “baseline” model (herein typically empirical) used to predict that parameter, an observation of that parameter for “skill score” computation, and finally, a predictive physics-based model.

The table to the right (adapted from Spence et al., 2004) is color-coded to show progress in the two main metric focus areas (operational and science metrics), for the different regions where space weather effects are created or manifested. Green indicates parameters for which formal metrics have been or are being evaluated. Yellow indicates parameters for which metrics are being defined or refined. This chart no longer possesses red coloring, indicating pending activity. All areas identified initially in 2004 for metric computation are currently underway. New model metric activities this year include SEP cutoffs (operational) and radiation belt energetic particle fluxes (both operational and science metrics).

In the past year, significant progress was made on defining, refining, and computing skill scores for a number of key CISM metrics, especially coronal white light structure. The results of these studies are documented in five main publications either published, in press, submitted, or in draft form.

End-to-End Validation Studies

The CISM team is undertaking an end-to-end study of several high speed solar wind streams that developed into co-rotating interacting regions during the declining phase of the last solar cycle (2006-2008). This study not only provides a comprehensive validation study of the CISM model suite but also provides a demonstration of its end-to-end capabilities. We are focusing our efforts on two Carrington Rotations, CR 2060 (Aug-Sept 2007) and CR 2068 (March-April 2008). The latter was chosen as it is a Whole Heliosphere Interval (WHI) for which a particularly complete set of observations was collected that has led to an ongoing series of coordinated observational studies. This provides a rich resource for us to compare with model results.

This end-to-end study involves a significant portion of the CISM team. A collection of 12 papers describing the CISM model suite and its capabilities will be published as a special collection in the Journal of Atmospheric and Solar Terrestrial Research.
The capabilities of modeling the space environment from the Sun to the Earth have improved dramatically since CISM was funded nine years ago. These models are now at a stage where they can simulate the formation of a specific feature or event at the Sun, follow its evolution within the heliosphere, and model its effect at Earth when it impacts the magnetosphere. This series of 12 papers will form a coherent set that investigates the source of the high speed solar wind streams, particularly those observed during Carrington Rotations 2060 and 2068, their evolution into corotating interaction regions in the heliosphere, and their subsequent impact at Earth where they generated modest geomagnetic storms. We will compare the results from various combinations of CISM models, both running the suite end-to-end starting from photospheric magnetograms, and running separable parts (e.g. CMIT) driven by their own observational inputs.

The goals of this special issue are twofold, to understand the series of physical processes that led to this series of events, and to assess the strengths and weaknesses of the various models that are used to simulate them. The collection is truly interdisciplinary in that it begins with methods of assimilating the solar magnetogram data needed to initiate models of the solar corona and ends with the effects of these high speed streams on the thermospheric temperature. At the same time these papers form a coherent set, as results from each model in the chain described in one paper are used to drive the next model in another paper. In this way the effects are modeled from the sun to the earth, giving the series a clear coherence.

The first paper in the series (Hughes and Hudson) will provide a review of what is known about CIR formation and geoeffectiveness paying particular attention to those observational features which are and which are not captured in this series of papers. As such it will provide an introduction and overview of the collection pointing out both the successes of the models and where they still need to be improved. The remaining papers in the collection will be ordered from the origins of the high speed streams at the sun, their evolution into corotating interaction regions in the heliosphere, to their observed effects in the magnetosphere, on the radiation belts and in the upper atmosphere.

The papers that will be submitted to JASTP this summer are:

1) W.J. Hughes and M.K. Hudson: Overview paper noting expected CIR features, which features the models do and don't currently capture, and pointing to the corresponding results in the various papers.

2) Nick Arge, Carl J. Henney, Kathleen Shurkin, Josef Koller, & W. Alex Toussaint, Solar wind modeling with ADAPT-WSA for Carrington rotation periods 2060 & 2068


4) V. G. Merkin, D. M. Pahud, N. Arge, W. J. Hughes, An MHD simulation of the inner heliosphere during Carrington rotations 2060 and 2068: Comparison with Messenger, ACE and STEREO spacecraft observations.

5) D. Odstrcil et al., The formation of corotating interaction regions during Carrington Rotations 2060 & 2068 as simulated by ENLIL
6) Michael L. Stevens, Jon A. Linker, Pete Riley, Why solar-heliospheric modeled magnetic fields at Earth have apparently decreased since the time of the Ulysses fast latitude scan.

7) M. Wiltberger et al., A Coupled Magnetosphere Ionosphere Thermosphere study of Carrington Rotations 2060 and 2068: a comparison of driving the magnetosphere with MAS-ENLIL with L1 observations.

8) J Lyon, R. Lopez, An LFM study of the magnetosphere responses to being driven by different SW fluctuation frequencies.


10) Mary Hudson, Thiago Brito, Scot Elkington, Brian Kress, Zhao Li, Mike Wiltberger, Radiation belt 2D and 3D simulations for two CIR-driven storms during CR2068.


2F References

18. Hayashi, K., X.P. Zhao, Y. Liu, J.T. Hoeksema and X. Sun, MHD simulation of the solar corona around August 1st using the HMI data, The First SDO Workshop, May, 2011


49. Zhao, X. P. and J. T. Hoeksema, The global character of the 2010.08.01 Earth-directed coronal mass ejection and the cause of the associated great sympathetic solar storm, Presentation at the First SDO Workshop, May 2011.
51. Zhao, X. P. J. T. Hoeksema, Y. Liu, Comparison of MHI Carrington synoptic maps between high and low spatial resolution, AGU Meeting of Americans, Iguassu Falls, Brazil, 08-13 August, 2010a.
III. Education

The primary mission of the CISM education program is to prepare the next generation of space physicists and imbue them with an understanding of the Sun and Earth as a system. Our goal is to instill in them a holistic view of the Solar Terrestrial environment that is unusual in our fragmented field. The core elements of our education program are:

1. The CISM Summer school
2. Building a graduate student community
3. Enhanced Undergraduate Research
4. Grade 6-14 education and increasing science literacy

The first three elements are highly specific to CISM and are tightly coupled with CISM’s research. The fourth element uses CISM content to engage the broader audience in formal and informal education settings, often leveraged with other efforts. Details of the CISM Education program, its objectives and assessments are given in the CISM Education Plan, which is available on our web site. During the past year we have continued to build on the highly successful aspects of our education program. Progress in the four CISM Education elements during the past year are summarized below.

Significant Accomplishments in the Last Year:

- Held another successful CISM Summer School attended by 32 participants drawn from 38 applicants. The participants included: 20 graduate students, 1 undergraduate 11 space weather professionals.
- Held the eighth graduate student retreat attended by 9 CISM graduate students from 5 institutions.
- Ongoing graduate student professional development through mentoring, multi-institutional student research and CISM graduate student gatherings at professional development meetings.
- Four graduate students completed their Ph.D. degrees bring the CISM total to 21 since the beginning of CISM
- Involved 19 undergraduates in CISM related research projects
- Involved several teachers and undergraduates in summer internships in continued support of the Space Weather Monitors program at Stanford
- New SID monitors for highschool classrooms supported by Society for Amateur Radio Astronomy
- Two CISM education related presentations at national professional conferences.
- Planning for continuation fo the summer school beyond the CISM lifetime.
Programs

The CISM Summer School:

The summer school is a two-week course in space weather and space weather models. It is intended primarily for first-year graduate students; however it is taught at a level and in a manner suitable for well-prepared upper division undergraduates, and also space weather professionals. Last summer there were 32 participants drawn from 38 applicants. The participants included: 20 graduate students, 1 undergraduate 11 Space Weather Forecaster and other space weather professionals, including 1 representative from the Airline Pilots Association. The faculty of the summer school is drawn from throughout the space weather community from both inside and outside of CISM. The faculty and students of the 2010 school are listed in Appendix F.

The basic structure of the summer school includes three series of morning lectures on the space environment (“reality”), its effects on technological systems and humans (“harsh reality”), and models used to specify or predict the space environment (“virtual reality”). In the afternoon is devoted to lab sessions where students use simulation results and data to explore the concepts discussed in the morning sessions. The pedagogy of the summer school is active and hands-on. Lectures use a “Peer-Instruction” format where during a lecture students are given a conceptual question that they must discuss with their peers and report back on. Employing another pedagogical technique, at the end of each mornings lectures students write questions on index cards that are collected; answers to the questions are provided just prior to the start of the labs. Over the last 6 years we have collected over 1000 student questions. We are currently categorizing and cataloging these questions and make them available to community. Finally, on the last day of the summer school the students engage in an event study that challenges them to integrate disparate data sets and simulations into a “concept map” that describes the event.

Summer School materials have been adopted for a variety of uses. We are also disseminating information about the summer school to the professional community. Along with presentations on the CISM Summer School at professional meetings, we have published a descriptive paper on the summer school. We have had several inquires about adopting the summer school materials and are working closely with those institutions interested in doing so. We are creating a summer school version of the CISM-DX Live disk (a bootable Knoppix disk with a version of CISM-DX, our custom designed visualization package, on it). With this disk, any PC can boot into a Linux system with CISM-DX and the summer school labs can be run.

The 2011 Summer School will be held from July 18th to the 29th in Boston. During the summer of 2012, the final CISM funded Summer School will be held at NCAR in Boulder from July 16th to the 27th. During the Fall of 2012, a team lead by Michael Wiltberger will submit a proposal for modest funding to continue the Summer School beyond 2012 in Boulder.
To take advantage of synergistic activities, the CISM education coordinator, Dr. Nicholas Gross, is working closely with the leadership of NASA’s Living With a Star - Heliophysics Summer School (HSS) to develop activities similar to the ones used for the CISM Summer School. The HSS is taking advantage of the Community Coordinate Modeling Center capabilities for the lab activities. Dr. Gross is providing support for instructional design.

Graduate Student Community

With graduate students distributed among eight CISM institutions, the center employs a variety of activities to develop a sense of community among the students. Each year we hold a Graduate Retreat and invite all CISM researchers to send their graduate students. The retreat is intended for students who are or will be engaged in CISM research and who we expect to be within CISM for a few years, completing their thesis or dissertation on a CISM topic. The 2010 graduate student retreat was held in September just prior to the CISM all-hands meeting in Boulder Colorado. 9 graduate students from five institutions participated in the retreat, which was led by J. W. Hughes with additional mentoring support from Mary Hudson and Bill Lotko. This year’s special topic was “Communicating Science to Peers”. These meetings allow the CISM graduate students to share their research and build community. The rotating program on professional development items not normally taught in a formal graduate curriculum, such as: the funding and management of research, how to prepare research proposals, ethics in science research, or publishing papers. Holding the graduate retreat just before or just after the all-hands meeting, and in the same location allows students to also attend the all-hands meeting. Students have reported that attending the all-hands meeting was very important to their understanding of how research priorities in CISM are set.

Graduate students also interact as a CISM-wide group via all-hands meetings, CISM graduate student luncheons at professional meetings, and through cross-institutional interdisciplinary research. In the past, CISM graduate student have also interacted through: Access Grid (AG) sessions, a graduate student website, and a graduate student run Wiki. These interactions provide CISM graduate students with a strong sense of community and a unique, holistic view of the Sun-Earth system. Through these close interactions the students are forging the foundation for career-long professional relationships and developing expertise that will provide a core of space weather researchers to carry forward the CISM legacy. In the last year, 4 students working on CISM related projects earned Ph.D.‘s bringing the total to 21. Nine others have earned terminal masters degrees during the life time of CISM, mainly from the Thayer Engineering School at Dartmouth and the Masters program at AAMU.

In order to gauge the value of graduate student involvement in the center, the education co-director, Dr. Nicholas Gross, conducted exit interviews with 8 students who completed a Ph.D. thesis on a CISM related topic. Based on these interviews, students identified several benefits to being involved in the center. These include:
• Being part of a program that is bigger then just their work
• Being part of a team and seeing a big team do science
• Value of enhanced mentoring
• Networking across institutions and disciplines

In order to gauge the relative value of the center to the graduate experience, Dr. Gross interviewed a non-CISM student at a CISM institution who was involved in a NASA spacecraft mission. This student’s experience was comparable with that of the CISM students though the non-CISM student did not have the same opportunity to network with other students (no other students working on the project) or the opportunity for explicit mentoring, though implicit mentoring was present. This work prompted a white paper that was submitted to the Decadal Survey on graduate mentoring.

During the life time of CISM, 21 graduate students have completed a Ph.D. thesis on a CISM related topics. The following table shows various thesis topics and the number of students who wrote in that topic.

• Radiation Belt (4)
• Ionosphere (2)
• Radiation Belt dynamics driven by Magnetosphere (3)
• MI coupling (1)
• Magnetosphere (4)
• Solar Wind - Magnetosphere Coupling (4)
• Solar Wind - Corona Coupling (2)
• Solar Corona (1)

Thus students have been involved in research in all physical domains of the center research. After graduating, students have taken first positions at a variety of institutions. Of the 20 students who have taken positions, 14 have took post-doctoral positions for their first jobs, two has taken a permanent position with an organization involved in space physics research or operations, and four have gone into industry. The table below gives more details.

• Dartmouth (5)
• AFRL (3)
• NCAR (3)
• UCLA
• NASA (2)
• CU, Boulder
• Industry (4)
• German Space Agency
Support for Undergraduate Research

Academic year research projects provide undergraduates with valuable skills and experiences within the unifying CISM context. Throughout the year CISM provides opportunities for undergraduates to share their research and engage in professional development. During the past year, 19 undergraduates, including 8 women and 5 students who belong to underrepresented minority groups, participated in CISM projects.

Undergraduate participation in CISM research provides a diverse group of students with experience and personal connections that kindle and support their interest in scientific careers in general, and in space weather specifically. Because of the distributed nature of CISM, undergraduates working on CISM projects at various institutions have diverse goals, backgrounds, and schedules. Under these circumstances we find that the Center can best support these students by providing individualized experiences for students where it is appropriate.

During the lifetime of CISM, 14 undergraduate students who have worked on CISM related projects have entered graduate programs. Of those, 12 entered departments with strong space physics research programs.

Grade 6-14 Education and Science Literacy

Class Room Materials

A center piece of the CISM Grades 6-14 formal education program is the Sudden Ionospheric Disturbance (SID) Monitor (http://solar-center.stanford.edu/SID/) developed by the Stanford Solar Group (http://solar2.stanford.edu/) under the guidance of Deborah Scherrer. The SID monitor is an inexpensive ($250) Very Low Frequency (VLF) radio receiver that is tuned to one of several VLF transmitters around the country. VLF radio signal strength is sensitive to the state of the ionosphere. Changes in the signal strength indicate changes in the ionosphere, which can be due to solar activity. This is a leveraged program with CISM providing support for the development period and is currently supporting an engineer, teachers and high school students who support the monitor program at Stanford. NASA grants provide the funds for distribution. For some locations, CISM researchers have been acting as mentors for some of the SID monitors. In addition to the 100 monitors distributed through out the US, an additional 200 have been distributed world wide through IHY programs including 50 in Africa. Each monitor can be connected to an Internet ready computer and the provided software can automatically collect data and post it in daily to a central server. Thus, students in the US can access data from around the world. Over the last two years, evaluation data has been collected on the use and effectiveness of the SID monitors. We are in the process of compiling that data and writing a report on it.

Over the last year, a new version of the SID monitor has been developed which takes better advantage of hardware already available on most computers. This version of the
monitor, dubbed “Super-SID”, only costs $50. Recently, the Society for Amateur Radio Astronomers (SARA) has taken on the construction and distribution of the monitors. The CISM team is working closely with them to train Society members to act as mentors for students using the monitors.

Informal Science Education Resources

In 2006 CISM simulation results were incorporated into a major planetarium show, “Cosmic Collisions”, produced and presented at the Hayden Planetarium at the American Natural History Museum (ANHM) in New York City. Five CISM researchers were involved in this effort including two graduate students from separate institutions who collaborated on generating the visualization. The show continues to run to millions of viewers. This visualization is now in the ANHM visualization library and they still use for a variety of purposes.

Our web based efforts continue to play a key role in our outreach program. By providing content and modest resources to existing science and space science web efforts we have been to successfully leverage the contribution we have made to reach a large and broad population. First, the UC Berkeley and Stanford education teams in partnership with the San Francisco Exploratorium have developed a Space Weather website based on CISM-related topics, imagery, and materials. It can be found at http://www.exploratorium.edu/spaceweather/ The Exploratorium space weather site is interlinked with the NCAR, Stanford, and Rice University websites. It contains background information about space weather, visualizations of space weather models, and video clips of CISM scientists explaining concepts in space weather.

The education group at NCAR, has been leading development of web-based resources on space weather for students ranging from elementary through to undergraduate students, leveraging the expertise in informal science in the “Windows to the Universe”, http://www.windows.ucar.edu/. This website exists in both English and Spanish editions. Hundreds of thousands of people visit the site every year to learn more about space weather and its impacts on the Earth. The number of pages visited and unique visitors for this website are reported on the Education Metrics in Appendix J.

Another CISM sponsored web resource is the real time space weather prediction based on a neural net model that takes the Boyle Index as input. This webpage is developed and hosted at Rice Univ. and can be seen at http://space.rice.edu/ISTP/wind.html. Based on this model, alerts are generated that can be distributed to a subscriber list. This list is not intended for operations, but is meant for education and outreach purposes. It is advertised through teaching networks and conferences.

This year, additional outreach was done in partnership with the Museum of Science, Boston. Two podcasts

http://www.mos.org/events_activities/podcasts&d=4917
http://www.mos.org/events_activities/podcasts&d=4691
and a live presentation were done at the museum about CISM science. One of the podcasts and a presentation were specifically about the transition of a CISM model to operations at SWPC.

**Education Support for other CISM components**
The CISM education program works closely with other aspects of the program, both to support the education goals, and also to further the goals of the other thrusts. For example, the Space Weather Summer School makes use of the CISM-DX visualization tools developed for the research program. This allows participants in the summer school to explore space weather phenomena as exemplified by the simulation results. Labs developed for the summer school are then used as part workshops run by the Knowledge Transfer program and as a recruitment tool for the Diversity program. The education program will continue to build closer ties with the research program, as students are trained in research and as new research materials are adopted for curricular use.

**Evaluation and Program Performance**
Where appropriate, each of the individual program elements has an evaluation component as part of that programs development. For example, the Space Weather Summer School conducts both formative and summative evaluation. In addition, for the program as a whole, we have defined and reported on metrics that are listed in Appendix J.
IV. Knowledge Transfer (KT)

In addition to the normal dissemination of research results within the scientific community (achieved through publishing papers in journals and reporting results at meetings) the CISM Knowledge Transfer plan has three distinct objectives:

1. Facilitate the transfer of validated models to an operational environment at relevant government agencies;
2. Provide models and visualization tools to the broad research community; and
3. Train and interact with government agencies, the aerospace industry, and others who must cope with space weather.

These three objectives are supported through five program elements as indicated in the CISM Knowledge Transfer Matrix that is in the CISM Strategic Plan.

The KT work is broadly distributed throughout the Center and also involves close partnerships with the Community Coordinated Modeling Center (CCMC), Space Weather Prediction Center (SWPC), and Air Force Research Laboratory (AFRL). A stage has been reached where very substantial progress is being achieved in transitioning complex, coupled models for use by the research community (through CCMC) and the operational community (through SWPC and AFRL). A list of released models is provided in Appendix G.

To provide a flavor of the model transition work, we focus below on the development of realtime forecast tools using CISM models at SWPC.

Real time specification of the magnetospheric ULF wave environment

Magnetospheric pulsations with frequencies commensurate with the drift frequency of magnetically trapped energetic particles can lead to very efficient transport and energization of relativistic electrons in the outer zone Van Allen radiation belts. In order to specify and predict the flux of energetic particles in the outer zone, we are characterizing the driving of magnetospheric ULF waves via interactions with the solar wind using the suite of models developed by the CISM efforts.

Global MHD simulations of geomagnetic storms are studied in an effort to understand and characterize ULF wave activity induced by solar wind conditions measured by our upstream monitor at L₁, ACE. For example, we have completed high-resolution runs of the March 8, 2008 geomagnetic event, and characterized the wave power in term of frequency spectrum and mode structure. Such specification of the wave power allows construction of the diffusive transport coefficients, Dₘₙ, at all the appropriate low-mode number resonant frequencies (m>24 for the resolution used in these MHD simulations) specific to a given particle energy and drift velocity. An example of this power calculation is indicated in Figure 1, where local time variations in the integrated spectral power are evident across the dayside magnetosphere. The transport coefficients generated from this analysis are being used to predictively specify of the relative importance of acceleration, transport, and loss of radiation belt electrons in the outer zone.
Figure 42. Frequency-integrated ULF wave power as a function of global position in the equatorial plane during the March 8, 2008 geomagnetic storm. An excess of low mode number power is observed in a broad range across the dayside magnetosphere, with spectral powers peaking at large radial distances and the dawn and dusk flanks as a result of shear interactions with the solar wind at the magnetopause.

Additional parametric runs using the global MHD simulations have been undertaken to characterize wave power during 'typical' solar wind conditions. We have built upon the studies performed in the first year of this effort to examine also the effects of varying solar wind pressure perturbations in global ULF power.

**Location and variation in EMIC activity**

Electromagnetic Ion Cyclotron (EMIC) waves resonantly interact with ring current and radiation belt particles in the inner magnetosphere, leading to depletions in these populations as individual particles are scattered by the waves into the Earth's atmosphere. The CISM K-T team has made efforts to characterize the spatiotemporal evolution of these waves by calculating wave growth rates based on the plasma anisotropies that lead to the wave activity. This information can be used to predict real-time loss rates of radiation belt particles, with important implications for space weather specification.

The dynamical variations in the radiation belts are the result of a complex interplay of particle acceleration, transport, and loss. Magnetospheric electromagnetic ion cyclotron (EMIC) waves have been established as a fundamental magnetospheric process underlying the acceleration and loss of relativistic electrons in the radiation belts. The goal of this effort is to investigate the spatial, temporal, and spectral characteristics of EMIC waves associated with solar wind pressure events, and to examine the resulting physical processes that lead to warm ion temperature anisotropies and the potential for EMIC wave growth in the dayside magnetosphere.
We have developed an MHD/particle method to specify electromagnetic ion-cyclotron (EMIC) wave growth in a realistic and dynamic magnetosphere. We simulate the phase space density dynamics of warm plasma particles in magnetospheric electromagnetic fields from the global Lyon-Fedder-Mobarry (LFM) MHD code and 3D test-particle trajectories. We use these results to compute temperature anisotropies and plasma densities. We then compute the convective EMIC wave growth rate using these macroscopic plasma quantities, and thus generate a spatiotemporal picture of the growth of these waves. We have used our new MHD/particle method to simulate EMIC wave growth during a compression event observed on 29 June 2007, and have compared the results with observations from ground observatories and spacecraft measurements. Results are shown in Figure 2, where the EMIC wave growth rate is plotted in the equatorial plane. Regions indicated on the color scale as having the highest wave growth rates correspond to regions where radiation belt electron and ring current ions will have the smallest lifetimes, which can be applied to real-time models of the magnetospheric energetic particle environment.

![Figure 43. Frequency-integrated EMIC convective wave growth rates, $S^*$, in the equatorial plane during the 29 June 2007 compression event. Regions indicated on the color scale as having the highest wave growth rates correspond to regions where radiation belt electron and ring current ions will have the smallest lifetimes, which can be applied to real-time models of the magnetospheric energetic particle environment.](image)

**Relationship between solar activity and space weather effects: time scales**

The CISM Knowledge Transfer efforts have included investigations of relevant time scales associated with related space weather effects, with an eye toward transfer of empirical models of the space environment to operational usefulness. For example, high-speed streams (HSS) from coronal holes provide a frequency spectrum with a main peak at approximately 27 d$^{-1}$, corresponding to the synodic solar rotation rate. The relativistic electron flux responds to high solar wind speed with a similar power spectrum. Figure 3 shows how electron flux power is distributed across L-shells for six two-year intervals throughout solar cycle SC-23. The six distributions are grouped in
pairs based on their similar shapes. The top panel shows the L-shells just above 5.0 contain the maximum power during minimum (red) and maximum (black) phases of SC-23. The middle panel shows the maximum power for the descending phase SC-22 leading into SC-23 (blue) has moved to higher L-shell, approximately L=5.5. The bottom panel illustrates a flat power distribution across L-shells for two-year intervals transitioning between the power distributions above. The relative power in these distributions indicate the highest electron flux power occurs during descending phases of the solar cycle (blue), and lowest power occurs during the early ascent phase (green).

![SAMPEX Electron Flux Power Distribution Across L-Shells 1993-2005](image)

**Figure 3:** Power Distribution Across L-shells for 1993-2005 from SAMPEX/PET/ELO 2-6 MeV electron flux measurements

Identifying and quantifying relationships and time scales in Solar-Terrestrial interactions, such as those associated with the relationship between the synodic or solar cycle periods of the sun and enhancements in the space radiation environment, will enhance operational forecasting capabilities beyond the minutes-long (~30-45) transit time from the L1, or the days-long time scales based solely on observations at the solar surface.
SWPC Real-Time Prediction of the Ambient Solar Wind Parameters

The 3-D magnetohydrodynamic numerical code ENLIL is a research tool for simulating the corotating ambient solar wind structures and the transient solar wind disturbances. The physical model is based upon an ideal magnetohydrodynamic (MHD) description while the numerical scheme is an explicit high-resolution TVD Lax-Friedrich scheme. A real-time Solar Wind Model has been implemented at NOAA/SWPC where the ENLIL application is driven by the empirical Wang-Sheeley-Arge (WSA) model. This model uses daily observations of the photospheric magnetic field (solar magnetograms) to compute a potential field source surface at 2.5 Rs, and a heliospheric current sheet model extends the magnetic structures out to 21.5 Rs, which constitutes the boundary for the MHD code. An empirical formula derives the radial solar wind speed from the radial magnetic field configuration. ENLIL uses this as the daily specification of the inner boundary (at 0.1 AU) of the computational domain which reaches out to 1.1 AU. Note that a single, corotating map is used to drive the simulation.

Figure 4. Visualization of the solar wind velocity from the experimental real-time prediction model. Results of the heliospheric computations are shown between 0.1 and 1.1 AU for a $\pm 5$ day span about the beginning of the day with the most recent solar wind source data. Date (yyyy-mm-dd hh:mm:ss UTC) at the top center corresponds to displayed results. Date (yyyy-mm-dd UTC $\pm$ $\pm$ days) at the top right gives time relative to beginning of the day with the most recent solar wind source data. Negative (positive) values are for times prior (subsequent) to that reference date. Three slices passing through Earth show the radial component of the solar wind velocity using the color scale given at the top left. The white line shows the heliospheric current sheet which represents a magnetic sector boundary. The polarity of magnetic sectors is indicated by blue or red color at boundaries of the computational region. The blue is for negative (toward the Sun) and the red is for positive (away from the Sun) polarity. The black-and-white dashed line shows the interplanetary magnetic field (IMF) line which passes through the Earth. Planets and spacecraft are denoted by symbols shown at the bottom right (Baker, D.N., et al., 2009).

Daily runs have been provided (since early 2007) with the first coupled versions of WSA+ENLIL. Dusan Odstrcil has developed a web site to display the daily results at the following NOAA/SWPC website: http://helios.swpc.noaa.gov/enlil/latest-velocity.html, specifically for the
The computations were carried out in low resolution, i.e. 4°×4° in heliographic latitude and longitude. The first daily products were in the form of the so-called spiral plots, meridional cuts at the Sun-Earth line, and 1 AU sphere, together with line plots of 5 day forecasts of the solar wind parameters. These were delivered from the latest available NSO/SOLIS magnetograms. Later in 2007, SOLIS experienced a black out period due to extended maintenance, so that it was decided to switch over to the latest available Mount Wilson magnetograms. Again, in January and February 2008, all US American solar observatories were subjected to weeklong outages due to severe winter storms passing over from the Sierras. In March 2008 it was decided to switch over to the reliable GONG magnetograms, which do not rely on a single observatory and are generated with hourly cadence. At the same time the once-daily runs were upgraded to medium resolution, i.e. 2°×2° in heliographic latitude and longitude, which allows for a much better specification of the ambient solar wind and resulting solar wind parameter forecasts. This modeling has played a key role for the MESSENGER mission at Mercury as well (Baker et al., 2009; see Fig. 1).

A new experimental product was introduced in late 2007 in the form of a comparison between the daily-generated coronal hole (CH) map that is derived from a WSA run and the SOHO/EIT image indicating the CH structures on the solar disk. This tool has been refined by Leslie Mayer and is now made available on the NOAA/SWPC website: http://helios.swpc.noaa.gov/WSA/. The purpose of this tool, shown in Figure 5, is to provide the forecaster with a quick visual representation to show the reliability of the WSA generated boundary conditions that are propagated outward by ENLIL. A reasonable agreement between the remotely observed CH structures with the model derived ones can build confidence in the trustworthiness of the 5 day prediction of the corresponding solar wind parameters, and vice versa.

Figure 5. Visualization of the coronal hole structures from the experimental real-time prediction model. The right hand image displays the SOHO/EIT remote observation for a specified date (yyyy/mm/dd hh:mm:ss UTC) of the central meridian. Black structures are indicative of coronal holes which translate into ambient solar wind structures, white regions are flares from underlying sun spots. The left hand image displays the WSA computed coronal holes in color (scale according to field strength) which is overlaid over the GONG magnetogram in gray scale upon which was
used as the input to the computation. In this magnetogram the sun spots show up as white/ black dipoles. The computed image is specified by the Carrington rotation number and the longitude of the center meridian.

Installation of ENLIL on NOAA Supercomputers

ENLIL is written in Fortran 90 and uses the MPI library for parallelization, NetCDF library for output files, and FITS library for input data. Procedures in IDL can produce “standard” visualizations of all output files. We got access to and installed ENLIL on the following two supercomputers: “Jet” at NOAA/Forecast Systems Laboratory (cluster of AMD processors with Linux operating system) and “Vapor” at NOAA/Environmental Modeling Center (system of IBM Power-6 processors with AIX operating system). We have also used “Bluefire” at NCAR (IBM architecture similar to Vapor) to speed up some parametric studies.

We performed scaling studies on the NOAA Vapor supercomputer to reveal ENLIL properties on the “target architecture” and to estimate resources needed for operational forecasting. SPWC requires forecasting the SW parameters up to 5 days ahead. Since the fastest transient heliospheric disturbances may hit Earth in 1-1.5 days, SWPC further requires initialization of 4 such runs per day.

Figure 6 shows scaling, dependency of wall-clock time on number of processors used. Note that the computational region has the same total number of numerical cells which are decomposed into spherical shells for parallel computations. Further, note that these shells require 4 “ghost” cells (2 on each shell side) for MPI communication. Thus the number of computational vs. communication cells decreases with increasing number of processors. For example, a low (medium) resolution simulation on 32 processors uses 8 (16) cells for computation vs. 4 cells for communication. And, a low (medium) resolution on 64 processors uses 4 (8) cells for computation vs. 4 cells for communication. This explains perfect (near-perfect) scaling of medium resolution simulations up to 32 (64) processors only. Note that Vapor uses 32 dual-processor computational nodes and thus there is also a performance drop in scalings from 32 to 64 processors.
Figure 6 Scaling properties of ENLIL on NOAA/EMC Vapor supercomputer. The code was executed on 2, 4, 8, 16, 32, 64, and 128 processors using three different numerical grids for the low, medium, and high resolution. Solid lines show the ideal scaling. All low and medium resolution runs simulate the background SW up to 1.7 AU for 5 days. The high-resolution runs simulate the background SW for 5 days on 64 and 128 processors only (Vapor allowed runs up to 8 wall-clock hours). Top dashed line shows projected timing for eventual fine resolution runs.

**MPI build of LFM on the NOAA/SWPC wJET computer**

An important step for CISM's geospace modeling goals with SWPC is to port the CMIT magnetosphere-ionosphere code to run on NOAA parallel processor computers. The major hurdle to be addressed in this effort is get the LFM magnetospheric component of CMIT (by far the most computationally intensive part) running in a distributed MPI mode. Development of the parallel LFM has been on IBM Power5 architecture, very different from the Intel-based LINUX cluster available at NOAA. Recent work has resulted in the LFM now running in parallel on wJET, the NOAA distributed computer. This is a significant development as wJET represents a typical LINUX cluster, a computer architecture that will be come increasingly important for cost-effective computing in the near future. Building the parallel LFM on wJET provides a solid basis for replicating this on other LINUX systems such as those at CCMC where CMIT is being ported. CMIT is currently running at about 2.5 times real-time. It is using InterComm coupling and is in a higher resolution testmode running on 32 processors.

**Development of advanced space weather visualization products**

In addition to “traditional” visualization such as classic line plots and color contour maps we have continued our efforts to develop a 3D visualization environment. Figure 7 shows an example of these efforts, in the form of a colored mesh representing global Total Electron Content (TEC). Visualizations such as these will allow a forecaster to view multiple space weather parameters concurrently.
**Figure 7.** 3D visualization of modeled ionospheric Total Electron Content (TEC). The colored mesh represents TEC above a certain threshold value and is rendered onto a globe, which also shows the night time light emitted from cities on the Earth, serving as a proxy for population density.

**Transition of Other Models to CCMC**

The transition of models to CCMC is proceeding as planned. The overall suite of CISM models is shown in Figure 8. The CISM versions of CORHEL and WSA-ENLIL have been available at CCMC for some time and many runs of these models have been made. The MPI version of LFM was transitioned to CCMC in January 2010 and is now available for Runs-on-Request, with several runs already completed. A standalone version of TIEGCM has been installed at CCMC, and issues related to display mode are currently being resolved; we expect this transition to be complete in the coming months and TIEGCM to be made available for Runs-on-Request. The coupled CMIT 2.5 model is beginning the transition process, and will benefit from experience gained in implementing the standalone TIEGCM and LFM-MIX models to the CCMC environment.
Figure 8. CISM suite status at CCMC.
V. External Partnerships

CISM has partnerships with the following organizations:

NOAA/Space Weather Prediction Center (SWPC) [formerly Space Environment Center (SEC)]: SWPC is the government agency charged with providing the civilian community with space weather information, specifications, and forecasts. CISM and SWPC have a close partnership. CISM views SWPC as a principal client or customer for space weather forecast models. Liaison between SWPC and CISM is facilitated through the CISM knowledge transfer team with substantial participation by the CISM model developers and validation team. This is discussed further in the Knowledge Transfer section of this report.

Community Coordinated Modeling Center (CCMC): The mission of CCMC is to provide space physics researchers with access to models, to provide an independent evaluation of space physics models both for research purposes and as potential forecast tools, and to facilitate the selection and ultimate transition of research models into operational forecast models. CCMC is based at NASA/Goddard and staffed through NASA, but is funded jointly by NASA, various Air Force agencies, and NSF. CCMC and CISM have a partnership in order to provide community access to numerical models developed by CISM, to collaborate in evaluation of coupling frameworks, and to provide further robustness through independent model validations. CCMC currently has versions of the Source Surface (PFSS), MAS, CORHEL, WSA, ENLIL, and LFM-MIX models available for community runs on request. The TIE-GCM, model is in-house at CCMC; it and CMIT will be made available for runs-on-request shortly.

Air Force Research Laboratory: AFRL and CISM collaborate in several areas of model development. The WSA (CISM baseline) and WSA-ENLIL model development is supported by Nick Arge, as is ongoing work toward operational transition and use of these models. Kara Perry works with radiation belt modeling using fields from CISM physics models. Keith Groves and John Retterer are supporting a collaboration in which regional scintillation modeling is driven by the CISM CMIT specification of the global ionosphere. Chin Lin and others at AFRL are performing assessments neutral density modeling with TIE-GCM under various conditions. Jack Quinn, now at AFRL, continues his role of CISM Executive Director. The AFRL Space Weather Center of Excellence is CISM’s primary interface to the DoD operational modeling community.

TeraGrid supercomputing Centers. NSF-funded supercomputer centers provide high performance computing resources for CISM model development and scientific use through the TeraGrid program. CISM is currently working with the National Center for Supercomputing Applications (NCSA), Texas Advanced Computing Center (TACC), and the National Institute for Computational Sciences (NICS).)

The Exploratorium of San Francisco: The Exploratorium is the leading science museum in the San Francisco Bay area. They have worked with CISM to make the results of CISM research available to the public in the form of simulations, animations, and interpreted data. In conjunction with CISM partners, they have developed a Space Weather website based on CISM-related topics, imagery, and materials.

In addition to these established partnerships, CISM researchers have many informal collaborations with research scientists at other government labs, research centers and universities.
VI. Diversity

DIVERSITY WITHIN CISM

The CISM diversity mission is to increase the diversity of participants in space weather research at all levels. All CISM components attempt to promote diversity and increase the involvement of women and underrepresented minorities in space science and help build a vigorous research program at minority serving institutions. The CISM Diversity Plan is available at http://www.bu.edu/cism/Publications/DiversityPlanCISM.pdf and the CISM co-director for diversity is Ramon Lopez. Our recruitment of women and minority graduate and undergraduate students has been very successful, with 38% of U.S. graduate students coming from underrepresented minorities. This is on par with the proportion of these groups in the population as a whole and far above their representation in science as a whole. Similarly, the percentage of CISM graduate students who are women (38%) is well above the level of participation of women in physics as a whole. Our numbers for diverse undergraduate participation (31% minority and 44% female) are equally impressive.

CISM sponsored a session “Exploring the Universe” at the October 2010 SACNAS meeting in Anaheim in order to recruit students and provide information about space weather to a diverse audience.

CISM has the specific diversity goal of supporting the creation and development of a graduate program in space science and a vigorous space research program within the Alabama A&M University physics department. This new program provides a route for African American students to enter a field within which they are very poorly represented, and will remain a lasting legacy of CISM. One Ph.D. student has graduated from the AAMU program, and she is now working at NASA’s Marshall Space Flight Center (MSFC). Dr. Amy Winebarger, who had been in a tenure track position at AAMU, moved to MSFC, where she retains an adjunct faculty appointment at AAMU. Dr. T.-X. Zhang, another space scientist, is now heading the CISM effort at AAMU.

A space weather weekend for students from minority-serving institutions or students attending either the SACNAS or NSHP/NSBP meeting and who are considering graduate school is held annually. The Space Weather Weekend was held at Morehouse College in March 2011 and was partially supported by the Georgia Space Grant consortium through a grant to Dr. Willie Rockward (Associate Professor of Physics at Morehouse). This grant is a three-year grant that will continue to support the Space Weather Weekend after the end of CISM.
MAJOR ACCOMPLISHMENTS DURING THE PAST TWELVE MONTHS:

- Held Space Weather Weekend for likely minority graduate student candidates.
- CISM is expanding collaboration with Morehouse College and has established a mechanism for continuing to hold the Space Weather Weekend without CISM funds.
- Continued a multi-year trend in maintaining a high level of participation by women and minority students in CISM research and educational activities.
VII. Management

A1. Organization

The CISM management structure is designed to address the challenges of running a multi-institutional center that requires close cooperation and collaboration between research groups in order to achieve its goals. The CISM management structure is shown in the organizational chart in Appendix B.

The management and administrative core is Director Jeffrey Hughes, Executive Director Jack Quinn and Assistant Director Kathryn Nottingham. Jeffrey Hughes, as the Director of CISM, is ultimately responsible for the direction and management of the Center. Jack Quinn works closely with the Director on day-to-day management functions and coordination of Center activities at the many geographically separate locations. Kathryn Nottingham is responsible for all administrative functions, including budget administration, overseeing the collection of management data and maintaining the databases required for evaluation.

The Center is divided into eight focused management areas, each led by a Co-Director. The Co_Directors, together with the Director, Executive Director, and three senior modelers (Jon Linker, John Lyon, and Frank Toffoletto) form the CISM Executive Committee, CISM's principal executive body. Michael Wiltberger has responsibility for code coupling and computational aspects of the center. Jeffrey Hughes is responsible for CISM model validation. Ramon Lopez leads our efforts in Diversity. Daniel Baker has lead responsibilities for the Knowledge Transfer component and for development of forecast models. Nicholas Gross is Education Co-Director. The research thrusts in solar/ heliospheric, magnetospheric, and ionosphere/thermosphere/ mesosphere physics and modeling are the responsibility of co-directors Janet Luhmann, Mary Hudson, and Stan Solomon. Because of the Center’s integrative nature there is extensive interaction between these areas as they address the center’s shared objectives. However this thrust division represents a logical and effective management breakdown for the key aspects of CISM’s functions.

The CISM Executive Committee confers bi-weekly by means of a telephone conference call, and meets several times a year in person, either at scientific meetings that we all attend, or in conjunction with other CISM meetings. The Executive Committee develops strategic policies including definition and prioritization of tasks and time lines, monitors progress against these goals, and monitors overall activities with respect to overarching objectives. The director, in consultation with the Executive Committee, is responsible for the allocation of resources between thrusts and tasks. This overall management plan provides the structure, depth, and breadth needed to manage our complex center. Our management team has, both individually and collectively through our working together, the experience and resolve required to effectively manage CISM.

A significant challenge to the management of CISM is that there are 12 CISM core institutions: 10 universities, a national research center, and a commercial research company, that receive NSF funds. At each CISM site, the local principal investigator is responsible for managing activities and finances at that site and for coordinating with the appropriate co-directors to ensure that local activities are aligned with the overall CISM plan. Each site has a designated administrative contact who interacts directly with Assistant Director Kathryn Nottingham on all administrative and reporting issues, with Ms Maureen Rodgers (BU Office of Sponsored Programs) regarding contractual issues, and with the BU Office of Grant and Contract Accounting regarding fiscal reporting issues.
The CISM Advisory Council provides independent guidance to the CISM director. It meets annually, in the early spring, to review the activities of CISM, and to provide guidance, advice, and oversight of Center management and all Center objectives. The Advisory Council membership is shown in Section D, below.

A2. Performance and Management Indicators

The CISM Performance Indicators are drawn from a diverse set of sources that are enumerated and referenced in the Performance Indicators descriptive document, which is maintained on the CISM web site. The Performance Indicators address the Center’s performance in five overarching areas: research, education, diversity, knowledge transfer, and function of the Center. The indicators are compiled and reported annually in various sections and appendices of this report. The entire set is extracted and maintained in separate binders that are available at the Site Visit.

The CISM Strategic and Implementation Plan was developed by the executive committee with input from the whole CISM team. The Plan defines goals and milestones for the individual thrusts within CISM and for CISM as a whole. The status of these goals and milestones, which is one of the Performance Indicators, is included as Appendix A. The director and co-directors are responsible for Center wide execution of the plan, and for engendering effective collaboration and close cooperation of the team in achieving these goals. The performance of the CISM management team, including the co-directors and local PIs, is to a large degree indicated by their ability to achieve the goals and milestones laid out in the Strategic and Implementation Plan and the other specific goals that are reflected in the Performance Indicators for the Center.

B. Progress, Problems, and Changes

CISM’s Executive Director, Jack Quinn, now works for AFRL, a close CISM partner institution. As part of his AFRL duties, Dr. Quinn is continuing to serve as Executive Director. Dr. Quinn moved with AFRL to Albuquerque, NM summer 2010. However he and Jeffrey Hughes continue to collaborate closely.

C. Communication within CISM

CISM is a collaboration of faculty, research professionals, students, and staff at 11 core institutions and several partner sites. Frequent, efficient, and productive interaction of CISM personnel is critical to achieving our research, education, diversity, and knowledge transfer goals and to our smooth operation as a Center. For this reason we have developed a comprehensive set of communication methods that consist of periodic in-person meetings supplemented with a variety of electronic communications.

All-hands Meeting: The annual CISM All-Hands Meeting, held in September each year, is a principal management tool by which CISM goals and plans are developed, refined, and adopted by the entire CISM team. The 2010 All-Hands meeting was held at the NCAR Center Green facility in Boulder on September 13-15. About 60 CISM team members attended (they are listed in Appendix E). The agenda, which is also contained in Appendix E, consisted of a series of plenary meetings together with many splinter meetings of the different groups and topical subjects within CISM. While the plenary meetings allowed for feedback and exchange within the
whole group, most of the detailed work was done in the splinter sessions. One product of the all-hands meeting is a review and status of well-developed milestones that serve as one of the principal performance indicators for all aspects of CISM.

The 2011 All-Hands Meeting will be held in Grand Teton National Park, hosted by Boston University, September 21-23.

Other Annual Meetings: The annual CISM calendar is punctuated by a series of regular meetings. These include the annual Advisory Council Meeting in February or March and the annual NSF Site Visit in May or June. In addition CISM has a large presence at Space Weather Workshop, which is organized by NOAA/SWPC, usually in April, and brings together space weather researchers, forecasters and end-users. CISM also participates in the annual SHINE, GEM, and CEDAR workshops each June or July, and at the two AGU meetings (December and May). Each of these meetings provides an opportunity for meetings of the CISM Executive Committee and/or other specialized CISM groups such as the solar, magnetospheric, or ITM teams at SHINE, GEM and CEDAR. Finally the CISM Summer School brings together many CISM participants each summer.

Electronic Communication: Physical meetings cannot be held often enough nor include all the appropriate CISM members to provide the desired level of close communication in support of the integrated activities of the Center across multiple organizations. Thus much of our communication and interaction must be done electronically.

We use three forms of electronic communication: real-time video conferencing via the AccessGrid (inSors/IOCOM), telephone conferencing, and e-mail including a large number of topical mailing lists. The executive committee and various groups within CISM have regular meetings via these means.

AccessGrid meetings are held by several groups, either regularly or as-needed, including the Magnetosphere-Ionosphere Coupling Group (led by Bill Lotko), the Solar/Heliospheric Thrust (led by Janet Luhmann), the Validation and Metrics Thrust (led by Jeffrey Hughes), the Magnetosphere Thrust (led by Mary Hudson), and CISM graduate students. During the academic year a series of CISM Science Seminars are conducted, led by Jeffrey Hughes. In addition the AccessGrid facilities are used for many ad hoc meetings by smaller groups and as a means of increasing participation in other meetings.

Telephone Conferences: Some groups within CISM make use of regular telephone conferences. These include the Executive Committee, Knowledge Transfer group and Education.
D. CISM Advisory Council

The CISM Advisory Council is chaired by Dr. Gregory Ginet; the full membership is given in the table. The Council held its 2010 meeting on March 10-11 at Boston University. The Council’s report is included in Appendix C.

<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Gregory Ginet, Chair</td>
<td>MIT Lincoln Laboratory</td>
</tr>
<tr>
<td>2. Terry Forbes</td>
<td>University of New Hampshire</td>
</tr>
<tr>
<td>3. Cherilynn Morrow</td>
<td>Georgia State University</td>
</tr>
<tr>
<td>4. Janet Kozyra</td>
<td>University of Michigan</td>
</tr>
<tr>
<td>5. Jan Sojka</td>
<td>Utah State University</td>
</tr>
<tr>
<td>6. James Stith</td>
<td>retired, American Institute of Physics</td>
</tr>
<tr>
<td>7. Jerry Brackbill</td>
<td>retired, Los Alamos Nat’l Laboratory</td>
</tr>
</tbody>
</table>

Former Advisory Council members are:
- Joe Hollweg (UNH) 2003 - 2005
- Lisa Hunter (UC Santa Cruz) 2003 – 2004
VIII. Center Wide Outputs and Issues

1A. Center Publications

* Indicates Center Member, Indicates Student


1B. Conference Proceedings

* Indicates Center Member, Indicates Student

7. Baker*, D.N. The Knowledge Transfer Program of CISM, Advisory Council Presentation, Boston University, 10 March 2010


18. **Brewer, D. R., Bruntz, and Lopez*, R.E.** Time delay between IMF Chan*ges and the response of the nightside geosynchronous magnetic field, talk, Fall 2010 Joint Meeting of the Texas Sections of the APS, AAPT, and SPS, UTSA, San Antonio, Tx., Oct. 23, 2010


42. Elkington*, S.R. Using global models to prepare for RBSP data. Presented at the 2010 GEM Summer Workshop, Snowmass, Colorado, June.


53. Garcia, K., Effects of O+ Outflow from Earth’s Ionosphere into the Magnetosphere, SSRC-Mellon Mays Summer Conference, June 2010


66. Krupar, V.; Maksimovic, M.; Santolik, O.; Cecconi, B.; Odstrcil*, D., Type III Radio Bursts Observed by STEREO and WIND: Comparison to Numerical Heliospheric Simulations, 38th COSPAR Scientific Assembly, Bremen, Germany, July 8-15, 2010


78. Lopez*, R.E., Some things physicists have learned about physics education by doing research in cognitive science, Physics Brown Bag Lunch seminar, VA Tech, Apr. 8, 2010.
86. Lopez*, R.E., The bow shock as the source of magnetospheric energy during periods of large IMF, talk, AGU Meeting of the Americas, Foz do Iguassu, Brazil, Aug. 11, 2010.


96. Lotko*, W, O J Brambles, B Zhang*, M Wiltberger*, J Lyon* What causes sawtooth oscillations in magnetospheric convection? Seminar at University of Colorado, Laboratory for Atmospheric and Space Physics, 30 Nov 2010


107. Mitchell, E.J., Discussion of By vs. Bz effects onDst, talk, 2010 GEM workshop, Snowmass, CO, June 22, 2010


109. Murphy, E., Bhattarai,S., and Lopez*, R.E., Determining the geoeffective length from LFM simulations, talk, Fall 2010 Joint Meeting of the Texas Sections of the APS, AAPT, and SPS, UTSA, San Antonio, Tx., Oct. 23, 2010

110. Odstrcil*, D. ENLIL: Recent Enhancements, CCMC 2010 Workshop, Key Largo, FL, January 25-29, 2010


112. Odstrcil*, D. Numerical simulation of ICMEs initialized by coronagraph observations, Joint Meeting of the ACE / SOHO / STEREO / WIND Spacecraft Teams, Nonantum Resort in Kennebunkport, ME, June 8-11, 2010

113. Odstrcil*, D. Present Status and Ongoing Developments of the Heliospheric Code ENLIL, American Geophysical Union, Fall Meeting 2010


116. Pembroke, A., Presentation at the AGU ESSI Focus Group: Magnetospheric Visualization: How to Extract Global Measurements for End Users, August 4, 2010

117. Pembroke, A., Tutorial and Presentation of CISM-DX Analysis tools given to CCMC staff, July 14 2010 (online presentation).


120. Pembroke, A., Space Physics Seminar at Rice University: Path, Surface, and Volume Integration for MHD models, October 28, 2010

121. Pembroke, A., Tutorial showcasing new field line tracing tools for LFM given to Ingrid Cnossen (UCAR postdoc) and Ryan Smith (Dartmouth Collge Graduate student), April 5, 2011 (online presentation):

123. Pham, K., R. Bruntz, and Lopez*, R.E., Applying Empirical Magnetopause Prediction to Results Obtained from MHD Simulations, talk, Fall 2010 Joint Meeting of the Texas Sections of the APS, AAPT, and SPS, UTSA, San Antonio, TX. Oct. 23, 2010


140. Solomon*, S. C. Search for a Thermospheric Ground State Cancelled due to Cold and Dark, Meeting of the Americas, Iguaçu, Brazil, August, 2010 (invited).


163. Wiltberger*, M., W. B. Wang*, J. G. Lyon* and V Merkin Simulations of the Earth’s Magnetosphere-Ionosphere-Thermosphere during the Whole
164. Winegarden, S., N. Gross, AGU Exploration Station -- SID demonstration of radio waves, AGU Fall Meeting, Dec 2010


## 2. Awards and Honors

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Reason for Award</th>
<th>Award Name &amp; Sponsor</th>
<th>Date</th>
<th>Award Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daniel N. Baker</td>
<td>Outstanding space weather leadership</td>
<td>James A. Van Allen Space Environments Award</td>
<td>2010</td>
<td>Scientific</td>
</tr>
<tr>
<td>Daniel N. Baker</td>
<td>Outstanding research, teaching, service</td>
<td>CU Distinguished Research Lecturer Award, Boulder Faculty Assembly</td>
<td>2010</td>
<td>Education</td>
</tr>
<tr>
<td>Arthur Richmond</td>
<td>Long-term career commitment</td>
<td>UCAR Mentoring Award</td>
<td>December 2010</td>
<td></td>
</tr>
<tr>
<td>Ashley Bianco, President of Stanford’s Online High School’s Science Club</td>
<td>Gold award at Regional Science Fair for her research project associated with the SID space weather monitor</td>
<td>Regional Science Fair</td>
<td>May 2011</td>
<td>Educational award – regional science fair</td>
</tr>
<tr>
<td>Ramon Lopez</td>
<td>Scientific accomplishment</td>
<td>2010 Distinguished Scientist, awarded by the Society for the Advancement of Chicanos and Native Americans in Science (SACNAS)</td>
<td>Presented on 10/30/2010</td>
<td>Scientific</td>
</tr>
<tr>
<td>Robert Allen</td>
<td>Dept. Service</td>
<td>Keith W. Tompkins Scholarship, UTA Physics Department</td>
<td>04/02/2010</td>
<td>Education</td>
</tr>
<tr>
<td>Shree Bhatarrai</td>
<td>Outstanding Physics Major</td>
<td>Outstanding Physics Major, UTA Physics Department</td>
<td>04/02/2010</td>
<td>Scientific</td>
</tr>
<tr>
<td>Micah Weberg</td>
<td>Undergraduate research</td>
<td>R. Jack Marquis Scholarship, UTA Physics Department</td>
<td>04/02/2010</td>
<td>Scientific</td>
</tr>
<tr>
<td>Bethany Hiller</td>
<td>Academic performance</td>
<td>James Horowitz Scholarship, UTA Physics Department</td>
<td>03/21/2011</td>
<td>Scientific</td>
</tr>
<tr>
<td>Binzheng Zhang</td>
<td>Advanced study at NCAR/HAO</td>
<td>Advanced Study Program, NCAR</td>
<td>12/27/2010</td>
<td>Other - Award and support to visit NCAR for advanced studies</td>
</tr>
</tbody>
</table>
### 3. Graduates

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Degree(s)</th>
<th>Placement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manny Presicci</td>
<td>Ph.D.</td>
<td>LASP</td>
</tr>
<tr>
<td>Nathan L. Farr</td>
<td>Ph.D.</td>
<td>Raytheon</td>
</tr>
<tr>
<td>James P. McCollough</td>
<td>Ph.D.</td>
<td>Air Force Research Laboratory</td>
</tr>
<tr>
<td>Elizabeth Mitchell</td>
<td>Ph.D.</td>
<td>NASA/GSFC</td>
</tr>
<tr>
<td>Micah Weberg</td>
<td>B.S.</td>
<td>Grad Student U. of Michigan</td>
</tr>
<tr>
<td>Dustin Brewer</td>
<td>B.S.</td>
<td>Grad Student Columbia University</td>
</tr>
<tr>
<td>Crystal Red Eagle</td>
<td>B.S.</td>
<td>Study abroad UK, intending grad school in Astronomy</td>
</tr>
<tr>
<td>Phyllis Whittlesey</td>
<td>B.S.</td>
<td>Working, applying to grad school in solar and space physics</td>
</tr>
<tr>
<td>Yonggang Hu</td>
<td>Ph.D.</td>
<td>Numerix, NY</td>
</tr>
<tr>
<td>Sarah McGregor</td>
<td>Ph.D.</td>
<td>Dartmouth College</td>
</tr>
</tbody>
</table>
### Appendix A: CISM Year 6-10 Goals and Milestones
(established October 2007) Status as of April, 2011

#### Annual Milestones:

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Yr-6</th>
<th>Yr-7</th>
<th>Yr-8</th>
<th>Yr-9</th>
<th>Yr-10</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hold all-hands CISM meeting in early Fall.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Sep 17 - 19, 2007&lt;br&gt;Sep 15 - 17, 2008&lt;br&gt;Sep 14 - 16, 2009&lt;br&gt;Sep 13 – 15, 2010&lt;br&gt;(Sep 22 – 23, 2011)</td>
</tr>
<tr>
<td>Hold Summer School for at least 25 students, of which at least 8 are women or underrepresented minorities and 3 are from non-graduate school settings.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Jul 23 – Aug 3, 2007&lt;br&gt;Jul 21 – Aug 1, 2008&lt;br&gt;Jul 20 – 31, 2009&lt;br&gt;Jul 19 – 20, 2010&lt;br&gt;(Jul 18 - 29, 2011)</td>
</tr>
<tr>
<td>Hold annual meeting for CISM graduate students.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Sep 14-17, 2007&lt;br&gt;Sep 12-14, 2008&lt;br&gt;Sep 11-13, 2009&lt;br&gt;Sep 10-12, 2010</td>
</tr>
<tr>
<td>Provide research opportunities for at least 10 undergrads of diverse backgrounds.</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Year 6 Milestones (July 2008):

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze CORHEL 4.0, incorporating MPI MAS and (domain decomposition) ENLIL.</td>
<td>X</td>
</tr>
<tr>
<td>Freeze LTR 2.0: MPI LFM, TIE-GCM, RCM coupled geospace model.</td>
<td>X</td>
</tr>
<tr>
<td>LFM-MIX-RCM paper in final stages of preparation for submission to JGR. This paper documents the capabilities of the frozen version of LTR. CMIT hooks are in place, but not extensively tested.</td>
<td></td>
</tr>
<tr>
<td>Provide community access to COHEL 3.4 (coupled MAS, ENLIL, CONE models).</td>
<td>X</td>
</tr>
<tr>
<td>Perform initial validations of SEPMOD runs with cone model.</td>
<td>X</td>
</tr>
<tr>
<td>Submitted to JASR Space Weather Modeling special issue.</td>
<td></td>
</tr>
<tr>
<td>Identify and develop test forecast products for CMIT at SEC. [SEC is now SWPC]</td>
<td>X</td>
</tr>
<tr>
<td>Interactive ground delta-B display with arbitrary point forecast and comparison with magnetometer chains. CMIT 2.5 (with MPI-LFM) installed on SWPC wJET cluster. Testing and event analyses proceeding in coordination with SWPC personnel.</td>
<td></td>
</tr>
<tr>
<td>Report on validations of WSA-ENLIL running as realtime solar wind forecast model at SEC.</td>
<td>X  On-going</td>
</tr>
<tr>
<td>WSA-ENLIL running daily since March 2008; displays used in SWPC (formerly SEC) morning forecaster briefing. Forecaster and CISM assessments of realtime performance continuing. Model transitioning to formal NCEP operations Fall 2011.</td>
<td></td>
</tr>
<tr>
<td>Hold community modeling workshop.</td>
<td>X</td>
</tr>
<tr>
<td>Community workshop held June 22 with NSF sponsorship in conjuction with CEDAR, GEM, SHINE.</td>
<td></td>
</tr>
</tbody>
</table>
### Year 7 Milestones (July 2009):

<table>
<thead>
<tr>
<th>Task</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Provide Summer School labs and supporting materials for community use.</td>
<td>X</td>
</tr>
<tr>
<td>Web access provided. Announced and described in: Gross et al., EOS, V90, 2, p13, 2009.</td>
<td></td>
</tr>
<tr>
<td>Freeze CORHEL 5.0, adding “thermodynamic” MAS.</td>
<td></td>
</tr>
<tr>
<td>Also providing a significant improvement to the user interaction at CCMC. This is still under development, anticipate operational at the CCMC by end of 2011.</td>
<td></td>
</tr>
<tr>
<td>Provide community access to CMIT 2.5 (coupled MPI LFM, TIE-GCM)</td>
<td>X</td>
</tr>
<tr>
<td>Available through CCMC runs-on-request.</td>
<td></td>
</tr>
<tr>
<td>RADBELT and SEP Cutoff codes running in LTR fields with SEPMOD input.</td>
<td></td>
</tr>
<tr>
<td>Pending LTR. Codes running in LFM fields as interim measure.</td>
<td></td>
</tr>
<tr>
<td>Freeze LTR with capability for initialization using a data-assimilated ionosphere, solar forcing, and asymmetric RCM.</td>
<td></td>
</tr>
<tr>
<td>Solar forcing implemented in TIE-GCM (CMIT 2.5). Asymmetric RCM in development. Initial tests performed with data assimilated ionosphere in TING, but not yet implemented in TIE-GCM. Implemented interpolation codes for MPI-LFM output file.</td>
<td></td>
</tr>
<tr>
<td>Complete realtime test system for CMIT at SEC.</td>
<td>On-going</td>
</tr>
<tr>
<td>Systems for realtime processing of input Solar wind data and output displays/products are in place. Begun implementation of realtime operation of CMIT installation on local machines with transition to SWPC machines to follow.</td>
<td></td>
</tr>
<tr>
<td><strong>Year 8 Milestones (July 2010):</strong></td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>Freeze SEPMOD 2.0, adding x-ray based flare source option.</td>
<td>Flare option programmed. Testing and normalization will follow addition of coronal field to SEPMOD.</td>
</tr>
<tr>
<td>Freeze RABELELT and SEP Cutoff codes for LTR fields.</td>
<td>Pending LTR.</td>
</tr>
<tr>
<td>Freeze LTR version with TIME-GCM, multi-fluid LFM.</td>
<td>MF-MPI-LFM development progressing with completion expected 2011.</td>
</tr>
<tr>
<td>Identify institution(s) and structure for post-STC “integrator” functions.</td>
<td></td>
</tr>
</tbody>
</table>
### Year 9 Milestones (July 2011):

<table>
<thead>
<tr>
<th>Task</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete development of time-dependently driven MAS; ready for CORHEL implementation.</td>
<td>Time-dependent MAS is capable of accepting map sequences, but not useful unless the input data has smoothly assimilated magnetograms. Anticipate performing tests of time-dependent MAS in the coming year.</td>
</tr>
<tr>
<td>Freeze LTR adding high resolution TIME-GCM and inductive coupler for MI gap region.</td>
<td>Development work on Inductive coupler with MIX underway. Investigating impact on model results.</td>
</tr>
</tbody>
</table>

### Year 10 Milestones (July 2012):

<table>
<thead>
<tr>
<th>Task</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freeze CORHEL 7.0, adding thermodynamic MAS driven by flux-evolution model</td>
<td></td>
</tr>
<tr>
<td>Graduate first Ph.D. student from new AAMU program.</td>
<td>X</td>
</tr>
<tr>
<td>Complete transition of model repository and “integrator” functions.</td>
<td></td>
</tr>
<tr>
<td>Comprehensive validation/metrics report.</td>
<td></td>
</tr>
</tbody>
</table>
Appendix B: Organizational Chart
Appendix C: Advisory Council Report

Center for Integrated Space Weather Modeling

Advisory Council Summary

20 Apr 2011

The Advisory Council (AC) to the Center for Integrated Space Weather Modeling (CISM) met at Boston University on 8-9 Mar 2011. Present were Gregory Ginet (Chair), Terry Forbes, Cherilynn Morrow, Jan Sojka, James Stith, Jeremiah Brackbill and Janet Kozyra.

It has been the privilege of the AC to be a part of the CISM team over the years and provide what is hoped to have been useful guidance. Progress has been substantial in many areas: model-coupling, transition to operations, promotion of diversity and enhancing graduate and undergraduate education. For the final push, at least under the CISM flag, the AC urges the team to continue the focus on the integrated, sun-to-thermosphere model and produce end-to-end simulations with sufficient fidelity to allow meaningful comparisons to data. As a contribution to the effort the AC offers the comments below in the spirit of independent and constructive analysis.

General

Continue the focus on coupling. From the beginning the AC has emphasized that the strength of CISM should be in developing and demonstrating the capability of coupled models. There has been success in this arena with the recent set of CIR studies being a good example. As CISM enters its final phase, the emphasis on studies with coupled models should not flag but rather accelerate. There are exciting discoveries to be made running the full CMIT with the RCM, LFM, MIX, TIE-GCM and RADBELT models driven both by CORHEL (the full forecast suite) and L1 data (the short term forecast suite). All the pieces are there, but need continued commitment and imagination to put them together in ways that will generate meaningful results for scientists and space weather forecasters.

A conference or workshop on the challenges of building coupled space-weather models is sorely needed and CISM should take the lead in organizing it. This would not be a “CISM results only” meeting but rather a gathering of all the model developers with a mandate to get into the details associated with all the sun-to-thermosphere coupled forecasting models. There are a host of issues in coupling phenomena with widely varying time and space scales (e.g. the LFM-RCM coupling or the Bz generation in the
corona/heliosphere) and various groups have tried different techniques which seem to be producing different results. Or are they? Substantial progress could be made if the various groups aired their techniques, trials and tribulations. Though there is no guarantee of success, the time has come to try.

Research

Comprehensive validation studies of WSA-Enlil and MAS-Enlil performance for co-rotating interaction regions (CIRs) should continue with the short term goals of (a) understanding the reason behind the Wilcox magnetogram “best” results and (b) deriving a physics-based estimate of the solar radial magnetic field used in Enlil. These studies represent a major contribution to improving the accuracy of space weather forecasting given that WSA-Enlil is one of the work-horse models at the NOAA Space Weather Prediction Center (SWPC). Compared to the other magnetograms, the Wilcox magnetogram greatly underestimated the strength of the Sun's south polar field. Apparently this underestimate caused a significant tilt in the heliospheric current sheet that lead to an improvement in the simulation results, more or less by accident. If this explanation is correct, than the underestimation of the south polar field in the Wilcox magnetogram must be compensating for an error in the tilt of the current sheet predicted by the simulations. More effort is needed to determine whether in fact the one case studied is just a fluke or not. It was also pointed out during this year's council meeting that the current implementation of Enlil at SWPC requires the solar radial magnetic field to be input manually. A manual specification runs the risk the values for the radial field may be used which are not consistent with the modeling of lower corona using MAS or WSA. This problem should be rectified before the end of the CISM program.

A summary of the status and potential utility of the simulated coronal emission maps would be of benefit. One of the accomplishments of the CISM program has been the work done on the simulation solar emissions during coronal mass ejections, particularly with respect to the 2005 event that was examined in-depth. There was no discussion in this year's meeting of the current state of simulating solar emissions with the presumed reason being finite resources and higher priorities. Nevertheless, the emission work represents a significant CISM investment with a large potential for facilitating model-to-data comparisons and providing new avenues of initialization.

A more complete validation of the solar particle event (SPE) forecasting model developed by CISM should be performed. Forecasting SPEs is a major operational priority and CISM has made some significant achievements in the modeling of shock accelerated particles. The CISM SPE model should be thoroughly validated by comparing to data from a large number of events (several were presented at previous AC meetings) in order to determine the valid
parameter regimes for operational use, illustrate the model and data input limitations, delineate where coupling to other models occurs or needs to occur, and establish the optimal research path forward.

**New results from the coupled RCM-LFM are intriguing but need to be validated by further analysis with increased numerical resolution and comparison to specific event data.** The stable operation of the coupled LFM-RCM is welcome news and an important and advance. Model runs now generate filamentary structures conjectured to be caused by the convection of low entropy plasma from reconnection sites in the magnetotail to the inner magnetosphere where interchange instabilities drive flow. However, despite some theoretical support for this interpretation and the observation of similar features in plasmasphere images from the IMAGE satellite, there is concern that with increased resolution the structures will occur on an increasingly finer scale. The combination of contemporary numerical algorithms that are designed to limit dissipation to the smallest resolved scales, and physical processes that depend on dispersive waves can conspire to prevent convergence. For example, shocks are a few grid cells wide, no matter how fine the grid. If runs on increasingly finer scales do not produce increasingly finer structures, all is well. If they do, it may be necessary to consider modifications to the models to include viscosity or other transport terms to model the unresolved physical length scales. Direct comparison to data for specific events is challenging due to the low data rate but the CISM team is encouraged to find some method for meaningful validation. It is success in this endeavor which will ultimately prove the code worthy.

**Exercising the electron radiation belt model for the two CIRs occurring during the Whole Heliospheric Interval (WHI) of the International Heliospheric Year (IHY) and comparing with data should be a high priority.** The AC realizes this is underway but wants to emphasize the importance of demonstrating that the machinery of RADBELT coupled to the CMIT fields can produce the observed energetic electron populations. MeV electrons produced by CIRs are one of the big space weather hazards to satellites and successful forecasting for not only GEO but in the inner magnetosphere and LEO as well would be a major CISM accomplishment.

**The ionosphere-thermosphere, which is the last component of the end-to-end CISM modeling links, is ready to be comprehensively tested.** A first version of CMIT is now available at the CCMC and consists of an L1 specification into a coupled LFM-MIX-TIEGCM. This version needs to be extensively studied to understand the role played by MIX and the “p” function interface for the equatorial and high latitude electric fields. In doing these tests, it will be important to have included the most recent TIEGCM lower boundary updates (eddy diffusion coefficient dependencies). These tests need to validate the ionospheric response to solar minimum and solar maximum conditions and for CME/CIR geomagnetic disturbances storms. This validation will provide a basis for CISM claims that an L1 solar wind specification does, in fact, generate via LFM-MIX-
TIEGCM coupling ionospheric responses that are consistent with observations. Note that prior TIEGCM studies demonstrate already how the ionospheric simulations respond to climatological drivers driven by proxy indices. Hence, these could be viewed as a data set for comparison.

The MIX-LFM team should introduce an O\textsuperscript{+} enhanced outflow into the magnetosphere. Work done by the CISM team in this area has been discussed at previous AC reviews and any parameterization developed to replace the Strangeway empirical function is likely to generate more self-consistent O\textsuperscript{+} outflow. Studies here would be to evaluate how a more realistic ionospheric outflow affects the saw-tooth substorm results seen in the LFM simulations presented as well as impact the LFM-RCM coupling.

Every effort should be made to test the new version of CMIT in which LFM-RCM-MIX-TIEGCM are coupled. This set of runs will not only provide a new set of constraints for the RCM coupling, but also, if the history of LFM-RCM coupling is any guide, potentially very exciting and unexpected results. To some level of CISM value, a demonstration of this latter outcome provides clear evidence that without the CISM STC, science would not have progressed to this level. The ionosphere is a crucial link because of the wealth of observations available to validate the simulations.

**Knowledge Transfer**

The partnership between CISM and NOAA/SWPC continues to be remarkably productive and the team is encouraged to pursue the transition of CMIT with full vigor. CISM has listened well to the operational community, focused R&D in the correct directions and worked out a realistic transition path for the next several years. With WSA-ENLIL-CONE more-or-less complete, attention now turns to transitioning CMIT for dB/dt forecasting – NOAA’s first large scale, physics-based, magnetosphere-ionosphere coupled model. The CISM team should robustly support the transition in the remaining CISM years and, hopefully, secure support from NOAA and/or other operational agencies to continue the CMIT and Energetic Particle Transport Model transition once the current CISM program has ended. Additional support is amply justified by the high-priority needs of the operational community met by the chosen models and the outstanding track record of the partnership.

Limitations of the original metrics proposed by CISM and others to evaluate the performance of space weather forecasting models have become apparent. Examples include the validation of the heliospheric CIR models where the simple difference of predicted to observed arrival time does not capture the true operational utility of knowing something is coming and the use of single point satellite measurements which observe a forecasted magnetospheric feature but perhaps at a somewhat different location. Where
appropriate in the course of validation CISM should create better metrics, demonstrate their utility and propose them as new community standards.

The AC applauds Predictive Science’s pro-active collaborative development of the CORHEL interface at CCMC. With CCMC becoming the repository of the CISM models for the scientific community it is important that they be relatively easy to use over the web and yet still deliver the full range of model capabilities. It is recommended that other members of the CISM team follow Predictive Science’s lead and work closely with the CCMC staff to develop web interfaces which maximize the utility of the models and ultimately facilitate their acceptance as standards within the community.

Management

As CISM winds down it will be a challenge keeping the team focused as new opportunities are necessarily pursued. Nevertheless, to enhance the CISM legacy and help maintain focus the AC recommends that CISM produce a book, or at least a dedicated journal issue, summarizing the hard-won knowledge and lessons learned over the course of the effort. The theme, not surprisingly, should be on the algorithms, results and issues associated with the development of a sun-to-thermosphere space weather forecast model. A book format might allow for a greater flexibility in connecting the usually disparate domains with a common theme in contrast to the piecemeal nature of journal articles.

In addition to the science-oriented coupled model workshop mentioned previously, a meeting between the various large-scale coupled space weather modeling groups (to include the CISM, CESM and OpenGGCM teams) and decision makers from both operational and research agencies is warranted. With an understanding among large-scale space weather model developers having been reached concerning the importance of standing together, the case for continued support model development and transition should be strongly made to the operational and funding agency decision makers. CISM has convincingly demonstrated that collaborative teams of researchers working with operators can effectively transition large scale physics-based models into operations. A clear path based on user needs has been defined and the momentum gained during CISM should not be lost. An appropriate forum for the presentation could be the Executive Committee of the National Space Weather Program which, though keeping a relatively low-profile in recent years, has the mandate to bring together the necessary agencies in the context of developing and maintaining the nation’s space weather forecasting capabilities.

Education and Diversity
The Education and Diversity components of CISM have become especially positive forces at the undergraduate and graduate levels. The CISM Education leader is highly qualified and experienced. He is sensitive to educational needs, diversity issues, and the need for a scholarly, evaluative approach to the Center’s education and diversity endeavors. He is lead author or co-author on several publications related to the CISM education & diversity program. The education leader appears to have been well supported by the Center’s director, a vital ingredient for a successful program.

It is particularly notable that the Education co-Director has become nationally visible in heliophysics education circles, including co-facilitation of the nationally renowned CISM summer school, and election by his peers to serve as chair of the AGU SPA Education and Public Outreach (E/PO) committee. He has also been selected to serve on the Education and Workforce working group associated with the 2011 NRC Decadal Survey in Solar and Space Physics. The E/PO co-Director is strongly encouraged to bring CISM wisdom and data to these valuable roles.

These professional distinctions make the CISM Education and Diversity programs well poised to leave a legacy of national import and influence. However, the realization of this potential in this final year of operation will require a strategic focus on evaluation, dissemination, and strategies for sustainability. It must become clear which education program elements can be sustained outside the formal existence of the Center and which ones cannot be. Of those that cannot be sustained, which ones may at least be worthy of documentation and dissemination in the literature?

The CISM Education and Diversity program will be assessed vis-a-vis the areas listed below. The ensuing sub-sections describe specific strengths, weaknesses, and recommendations in each of these areas:

- Scientist Engagement in E/PO
- Partnerships in E/PO
- Integration of Research and Education
- Needs Awareness & Action in E/PO
- Evaluation
- Sustainability

**Scientist Engagement in Education and Public Outreach**

**Strengths:** The Center Director is supportive of the Education and Diversity programs, makes first-person contributions via the CISM summer school, and is encouraging of other CISM scientists to do the same.

**Weaknesses:** Little is known about the specific contributions of other CISM scientists to Education and Diversity (except Lopez’ efforts on diversity) as this
has not been explicitly reported to CISM advisors. Furthermore, contributions of the Education co-Director known by members of the CISM advisory committee were not included in the report to the Committee.

Recommendations: Conduct a poll of the CISM team and assemble a matrix of substantive ways in which CISM-supported scientists have contributed to the Education and Diversity efforts of CISM. This would make a nice item for your final report, and potentially for publication.

Partnerships in Education and Public Outreach

Strengths (Partnerships in E/PO):

1. The new partnership with the Boston Museum of Science program has long-lived potential to put space physics and space weather in the public eye.

2. It is noteworthy that the partnership with NCAR will be supporting the sustainability of the CISM Summer School.

3. The establishment of dissemination partners for the CISM Summer School curricular materials (e.g. REU program and AF workshops) is commendable.

4. New externally funded partnership between Morehouse and UT Arlington based on CISM’s Space Weather Weekend model for undergraduates.

Weaknesses (Partnerships in E/PO):

1. There is a lack of clarity about how the CISM Summer School will complement and co-exist with other summer schools such as the Heliophysics summer school funded by NASA’s Living With a Star program. In addition, how will the NCAR-based implementation adapt to or compensate for the advantages of conducting the summer school in the academic environment of Boston University?

2. No apparent strategy for sustaining the AAMU partnership and legacy since Amy Winebarger left for NASA MSFC.

3. Partnerships should amplify impact and leverage resources, not drain the program of resources. For example, it remains unclear what value has accrued from CISM’s annual outlay of $75K to the Windows to the Universe website, which added up over all the CISM years is a very noteworthy amount for an E/PO effort. The CISM team has not reported adequately on the added value of funds disseminated to Windows and to the Stanford’s SID program. Both of these programs are independently praiseworthy, but too little is known about how CISM has added value to their efforts.

Recommendations (Partnerships in E/PO):
1. Strengthen the partnership between the Boston University space physics program and the Boston Museum of Science so that it lives on beyond the life of CISM.

2. Clarify to the community the complementary nature and scheduling of the CISM Summer School, the LWS Heliophysics Summer School, and other summer schools. Articulate and address pros and cons of the Summer School’s shift from BU to a non-academic lab like NCAR.

3. Write up and disseminate the Space Weather Weekend model more broadly to see if there is potential for additional partnerships like the Morehouse-UT Arlington connection. Make an attempt to quantify in measurable rather than “feel good terms” the impact of the program.

4. Clarify for the final report to NSF what Windows to the Universe and the Stanford SID program were able to do that they would not otherwise have done without CISM support. For Windows, this should go beyond web statistics and a small, un-linked CISM logo on the home page. Consider tasking these partners with evaluation related deliverables in the final year of operation.

5. Investigate how best to leave the legacy of the space weather web presence at the Exploratorium – also a trusted an oft-used website by educators all over the world.

6. The CISM PIs should give some serious consideration to its legacy at AAMU and how best to achieve it. The collaboration with AAMU has been a novel approach to increasing the diversity within space science and may well serve as a model for future efforts.

**Integration of Research and Education**

**Strengths (Integration of Research and Education):**

1. Spending two CISM advisory board slots on securing expertise about: 1) education programs embedded in scientific research environments; and 2) diversity is evidence of a high degree of commitment on the part of the Center for creating a successful and influential education and diversity program.

2. CISM’s education leader is a co-Director for the Center. This action has generally supported programmatic integration of research and education, and has led to fruitful contact and communication that nourishes both research and education activities.

3. Educational access to the data and human resources of the CISM research community is laudable, particularly when it comes to the CISM summer school.
4. Integrating graduate students into the Center’s All Hands meetings may well have been one of the biggest contributors to the formation of CISM graduate students. Such meetings conceivably provide windows through which graduate students can view the field at large in a more intimate way than at professional society meetings. They may come to know many of the key scientists around the nation, gain a more systemic perspective of the field and how their own work fits in, witness how team science is really accomplished, and experience a sense of belonging to a project that is larger than their own work and the work of their institutions.

5. Undergraduate research opportunities with CISM are evidently quite productive with 13 undergraduates entering space physics graduate programs.

Weaknesses (Integration of Research and Education):

None perceived, except perhaps for a somewhat inadequate degree of authority held by the education co-Director regarding budgetary outlays to CISM’s partners for K-12 education purposes, and regarding the associated accountability of those partners.

Recommendations (Integration of Research and Education):

1. Use CISM’s educational mediums (e.g. CISM Summer School) to experiment with revealing the successes and challenges of the systemic, Sun-to-Mesosphere model that CISM has labored to produce. There is enormous educational potential in “taking these gloves off”, even if CISM scientists are as yet unprepared to “take off the gloves” before their research peers.

2. Document CISM grad students who “tell the CISM story” from their perspective.

3. Analyze and disseminate underrepresented student participation in CISM research publications. A possible question is “Does this activity influence continued participation in CISM or other STEM fields?”

4. Consider creating a Facebook or other social networking site that would allow follow-up with the community of CISM undergraduate and graduate researchers.

5. Generate an E/PO and/or media-style story of how the physics-based models are making the transition to an operational forecasting environment. Consider talking with the editors of Physics Today or Science or another suitable publication about publishing an overview article on the lessons learned and success of CISM activities.
6. The Center Director is strongly encouraged to support the Education co-Director in holding the CISM K-12 partners accountable for results and value added based on CISM funding they have received (see above: Recommendation #4 under Partnerships in E/PO.)

**Needs Awareness in E/PO**

**Strengths (Needs Awareness):**

1. Evidence that the CISM Education program is aware of and addressing important educational needs is strong, particularly with undergraduate and graduate programming. There is especially notable attunement to the need for engaging women and other underrepresented minorities in STEM fields, including participation in conferences that are havens for a diverse mix of undergraduate researchers (e.g. SACNAS, NSHP, NSBP).

2. The Summer School foci on inquiry-based activities, collaborative learning, and systemic understanding is highly commendable and in step with educational needs and opportunities.

**Weaknesses (Needs Awareness):**

It is very difficult to discern from advisory meeting presentations how or if the SID program and Windows to the Universe are consistent with local, state, national, or international standards, and how CISM has made a difference to these programs efforts to contribute to educational needs.

**Recommendations (Needs Awareness):**

1. Articulate the educational needs being addressed by K-12 and informal education partners.

2. Consider how CISM’s experience might inform a recommendation to the broader community for more routine curricular or extra-curricular exposure of undergraduate and graduate students to systems science thinking.

3. Consider how CISM Education could contribute to disseminating and illuminating the education recommendations of the Decadal Survey.

**Evaluation**

**Strengths (Evaluation):**

The exit interviews for graduate students and tracking where they go after PhD is highly commendable.

**Weaknesses (Evaluation):**
1. The evaluation effort and focus is not as strong as it needs to be in this final year. There is no external evaluator for the program.

2. Comparing number of PhD’s in the CISM pipeline to number of PhD’s produced.

3. Lack of evident evaluation data in response to funding of Windows and SID partners.

Recommendations (Evaluation):

1. Sustain contact with undergraduate and graduate students and potential for later follow-up with them through the formation of a Facebook group (mentioned previously).

2. Do a final report or publication on lessons learned vis-à-vis the CISM graduate school.

3. Do a summative evaluation study on CISM summer school past participants to examine the role the summer school may have played or is playing in their current professional lives.

4. Make an attempt to quantify in measurable rather than “feel good terms” the impact of the Space Weather Weekend program (mentioned previously).

5. Analyze underrepresented student participation in CISM research publications (mentioned previously)

6. Task funded partners (e.g. Windows and SID) to provide clear evaluative evidence of the value added of CISM funding (mentioned previously).

Sustainability

Strengths (Sustainability):

It is commendable that CISM education has many examples of partnerships for sustainability and legacy building (e.g. with NCAR to support the legacy of the CISM Summer School, with REU and AF workshops to support ongoing use of CISM Summer School curricular materials, and between Morehouse and UT Arlington to help sustain CISM’s Space Weather Weekend model for undergraduates.

Weaknesses (Sustainability):
1. Lack of adequate understanding about closure with the Exploratorium, Windows, and SID.

2. No obvious next position in space physics education for the Education co-Director so that the community will not lose the talents, expertise, and experience he has gained through service as CISM’s education leader.

Recommendations (Sustainability):

1. Consider convening CISM student reunions at professional society meetings.


3. Consider the CISM Education leader with the same sense of respect and urgency as a favored graduate student who needs to be placed into their next position.

4. Leave a legacy of CISM education & diversity models in the literature.
Appendix D: Media Publicity

1. The NSF press release picked up by the following website:
   - Coalition for Space Exploration
   - E! Science News
   - Nano Patents and Innovations
   - News Wise
   - Night Sky Live
   - NPR On line
   - On Orbit
   - PhysOrg.com
   - R&D Mag
   - Red Orbit
   - Science Daily
   - Science360
   - Softpedia
   - TG Daily
   - The Register, UK
   - Times of India
   - Watts Up With That?

2. Boston University College of Arts and Sciences Press Release

3. US News Science
First large-scale, physics-based space weather model transitions into operation

Published: Thursday, January 27, 2011 - 12:29

Related images

Desan Odstrcil, George Mason University

The first large-scale, physics-based space weather prediction model is transitioning from research into operation. Scientists affiliated with the National Science Foundation (NSF) Center for Integrated Space Weather Modeling (CISM) and the National Weather Service reported the news today at the annual American Meteorological Society (AMS) meeting in Seattle, Wash.

The model will provide forecasters with a one-to-five day advance warning of high-speed streams of solar plasma and Earth-directed coronal mass ejections (CMEs).

These streams from the Sun may severely disrupt or damage space- and ground-based communications systems, and pose hazards to satellite operations.

CISM is an NSF Science and Technology Center (STC) made up of 11 member institutions. Established in 2002, CISM researchers address the emerging systems science of Sun-to-Earth space weather.

The research-to-operations transition has been enabled by an unprecedented partnership between the Boston University-led CISM and the National Oceanic and Atmospheric Administration (NOAA)’s Space Weather Prediction Center.

“It’s very exciting to pioneer a path from research to operations in space weather,” says scientist Jeffrey Hughes of Boston University, CISM’s director. “The science is having a real impact on the practical problem of predicting when ‘solar storms’ will affect us here on Earth.”

The development comes in response to the growing critical need to protect the global communications infrastructure and other sensitive technologies from severe space weather disruptions.

This transition culminates several years of close cooperation between CISM and its partner organizations to integrate, improve and validate a model for operational forecast use.

“This milestone represents important scientific progress, and underscores the effectiveness of NSF’s Science and Technology Centers in applying research results to real-world problems,” says Robert Robinson of NSF’s Division of Atmospheric and Geospace Sciences, which funds CISM.

CISM team members worked on-site with scientists and forecasters at NOAA’s Space Weather Prediction Center to improve models and visualizations.

Having key team members co-located during the critical phase of development enabled an ongoing discussion between forecasters and scientists that enhanced the development of the model, says Hughes, and ultimately led to NOAA’s decision to bring it into operation as the first large-scale physics-based space weather model.

CISM’s research and education activities center on developing and validating physics-based numerical simulation models that describe the space environment from the Sun to the Earth.

The models have important applications in understanding the complex space environment, developing space weather specifications and forecasts, and designing advanced tools for teaching, Hughes says.

CISM partners include the U.S. Air Force Research Laboratory, NASA’s Community Coordinated Modeling Center, and the NOAA Space Weather Prediction Center.

The lead model developers for the work are CISM team members Desan Odstrcil of George Mason University and Nick Arge of the Air Force Research Lab.

Source: National Science Foundation
New Space Weather Forecasting Model Going Operational With National Weather Service

Newswire — Through an unprecedented research-operations partnership, the Boston University-based Center for Integrated Space Weather Modeling (CISM) and the National Oceanic and Atmospheric Administration (NOAA) Space Weather Prediction Center are transitioning the first large-scale, physics-based space weather prediction model from research into operations. National Weather Service (NWS) scientists affiliated with CISM reported the news today at the annual American Meteorological Society (AMS) meeting in Seattle, Wash. CISM is a National Science Foundation (NSF) Science and Technology Center.

This model will provide forecasters with a one-to-four day advance warning of high-speed streams of solar plasma and Earth-directed coronal mass ejections (CMEs). These streams from the Sun can severely disrupt or damage space- and ground-based communications systems and pose hazards to satellite operations.

"It's very exciting to pioneer a path from research to operations in space weather," says Jeffrey Hughes, CISM's director and professor of astronomy at Boston University. "The science is having an impact on the practical problem of predicting when 'solar storms' will affect us here on Earth."

The development comes in response to the growing critical need to protect the global communications infrastructure and other sensitive technologies from severe space weather disruption. This transition culminates several years of close cooperation between CISM and its partner organizations to integrate, improve, and systematically validate the model for operational forecast use.

"This milestone is important scientific progress and underscores the effectiveness of NSF's Science and Technology Centers in applying research results in real-world problems," says Robert Robinson at NSF's Division of Atmospheric and Geospace Sciences, which funds CISM.

CISM team members worked side-by-side with scientists and forecasters at NOAA's Space Weather Prediction Center to improve the models and visualizations. Having key team members co-located during this critical phase of development enabled an ongoing discussion between forecasters and scientists that enhanced the development of the model, and ultimately led to NOAA's decision to bring it into operations as the first large-scale physics-based space weather model.

Headquartered at Boston University, CISM is an NSF Science and Technology Center (STC) made up of 11 member institutions. Established in 2000, CISM researchers address the emerging system-science of Sun-to-Earth space weather. CISM's research and education activities center on developing and validating coupled physics-based numerical simulation models that describe the space environment from the Sun to the Earth. These models have important applications in understanding the complex space environment, space weather specifications and forecasts, and advanced training for teaching.

CISM partners include the U.S. Air Force Research Laboratory, NASA's Community Coordinated Modeling Center, and the NOAA Space Weather Prediction Center. The lead model developers for this work are CISM team members Susan Ostdiek of George Mason University and Nick Anger of the Air Force Research Lab.

Founded in 1839, Boston University is an internationally recognized private research university with more than 30,000 students participating in undergraduate, graduate, and professional programs. As Boston University's largest academic division, the College and Graduate School of Arts & Sciences is the heart of the BU experience with an intensive global reach that contributes to the University's reputation for excellence in teaching and research.

Link to view/download graphics: http://www.bu.edu/news/newswire/releases/cism/
By Marlene Cimons, National Science Foundation

Just before dawn on September 2, 1859, the skies above Earth erupted into a brilliant light display of red, green and purple auroras, accompanied by a world-wide breakdown in communication systems. Telegraph operations were shut down. The discharges from sparks shocked telegraph operators, and telegraph papers caught fire.

The so-called Carrington Event, named after the British astronomer who identified it, was the result of a magnetic explosion on the sun, more commonly known as a solar flare, believed to be the biggest solar storm in history. If an event of that magnitude happened today, it could prove disastrous, wiping out electric power, disrupting spacecraft, aviation, and GPS-based positioning industries, and costing in the trillions.

“That was only 150 years ago. Could it happen again? We don’t know,” says Craig Foltz, of the National Science Foundation’s (NSF) division of astronomical sciences, and program director for the National Solar Observatory. “Remember that our system was very simple then. When you think about the vulnerability of our very complex communications systems today, the impact of an event like that could be substantial.”

Space weather originates with the sun. At least four solar phenomena, not one of which is well understood, release matter from the sun into the solar system and together are the starting point for understanding the processes by which space weather develops and affects near-earth space: coronal mass ejections, solar flares, coronal holes and solar prominences.

In recent years, scientists have become increasingly involved in studying all the pieces of the space weather puzzle, using several different but complementary approaches to improve their understanding of what is happening on the sun and in the atmosphere—and when. These include the construction of a new high-powered telescope that will tell researchers more about the impact of magnetic fields on the sun, and new mathematical models—or computer calculations—that will speed up and make more accurate predictions of space weather events.

The Carrington Event was probably the greatest space weather occurrence ever recorded, but it was by no means the only one—about 500 magnetic storms occur during a typical 11-year solar cycle. In March 1989, for example, a solar storm caused the entire Quebec power grid to collapse in less than two minutes, affecting six million people in the middle of a Canadian winter. A 2003 Halloween storm prompted a massive blackout in the Northeast, and extensive satellite problems, including the loss of the $450 million Midori-2 research satellite.
“The driver for space weather is the sun,” says Dr. Stephen L. Keil, director of the National Solar Observatory. “The sun has a continuously changing magnetic field due to convective turbulence. When it reaches a certain state, the field has a lot of excess energy. When that happens, you get the field erupting, an explosion on the surface of the sun. It accelerates particles and ejects mass and magnetic field during the flare. When they reach Earth, they can affect Earth’s magnetic field—space systems, satellites, GPS, Direct TV, military satellites, etc.”

Coronal mass ejections, which may or may not have accompanying flares, also cause space weather and geomagnetic disturbances, and they also accelerate energetic particles that can damage space systems. High speed solar wind streams also can cause geomagnetic disturbances.

All of these phenomena involve rapid changes in the solar magnetic field, which can have a significant impact on life on Earth. Experts believe that society is ill prepared to cope with such severe solar disturbances, or predict them, without more knowledge of their causes.

Researchers are working to change this. The Boston University-based Center for Integrated Space Weather Modeling, for example, with the National Oceanic and Atmospheric Administration Space Weather Prediction Center, recently announced a new large-scale physics based space weather prediction model, or computer calculation program, designed to provide forecasters with a one-to-four day advance warning of high-speed streams of solar plasma and Earth-directed coronal mass ejections. “This will tell us what solar wind will be near Earth in the coming days,” says Jeffrey Hughes, director of the Center for Integrated Space Weather Modeling. “That will enable the protection of some of these sensitive devices, if we know what’s coming.”

The space weather modeling center includes research groups at eight universities and several government and private non-profit research organizations and commercial firms. These include Alabama A&M University, Rice University, Dartmouth College, Stanford University, University of California at Berkeley, University of Colorado at Boulder, the University of Maryland, College Park, and the University of Texas at Arlington. Its goal is to draft a comprehensive physics-based numerical simulation model that describes the space environment from the sun to the earth. Scientists also are constructing a 4-meter Advanced Technology Solar Telescope (ATST), a tool for magnetic remote sensing that will help scientists learn how magnetic fields affect the physical properties of the sun. It has been described as the largest leap in ground-based solar capabilities since Galileo’s telescope. It will be built atop Haleakala, in Maui, Hawaii, and will not be operational for several years.

NSF supports the Center for Integrated Space Weather Modeling with $38 million in funding over ten years. NSF also has funded the telescope project with a $298 million cooperative support agreement to the Association of Universities for Research in Astronomy, of which $146 million is part of the American Recovery and Reinvestment Act of 2009.

For the mathematical modeling, researchers rely on observations made by about a half-dozen existing telescopes to provide data for the new mathematical modeling system developed by the center, and now in use by the National Weather Service. The program
runs every six hours, four times a day, with updated information on magnetic fields every time.

“We start with the magnetic field over the surface of the sun based on observations made by various solar telescopes, and the input goes into the model,” Hughes explains. “One program works out the magnetic field in the sun’s atmosphere, while a second program picks up from there and calculates the speed and density and magnetic field of the solar wind. Taken together, this tells us what to expect. This is the first model. It will be improved over time.”

Of the new telescope under construction, Hughes says “we complement each other in a number of ways. They’re doing observations, and we’re doing the modeling from those observations. The goal is to use the best of observations with the modeling to understand how the sun works. This understanding comes from a combination of state-of-the-art observations and state-of-the-art modeling.”

In the meantime, however, “one of the reasons we are so bad at this is because we don’t understand what destabilizes the sun’s magnetic field,” Keil says. “Right now, we can’t see most of the magnetic field. We are only measuring between 15-20 percent of the flux coming out of the sun. We can’t see most of the magnetic elements because the telescopes are too small.

“If we knew a storm was coming, we could do things like turn off the electronics on our satellites so they are not affected,” Keil adds. “Our current ability to predict when a solar flare is going to occur is similar to where weather forecasters were at the turn of the previous century in predicting rain storms.”

Scientists expect the new telescope to provide the capacity that currently is missing. Furthermore, the ATST will enable scientists to study irradiance changes that affect climate and basic plasma physics, and use “the sun as an astrophysics lab,” Keil says. Foltz agrees. “We know a lot about the sun, but we don’t yet understand the interactions that lead to small and large scale solar magnetism,” he says. “The fundamental physics of solar activity is not well understood. We don’t understand what causes space weather.”

To be sure, “the telescope won’t protect us from these problems,” Foltz says. “But it will help us understand the root causes, and that’s a step to being able to predict them.”

The research investment in both the telescope and the center ultimately could prevent an expensive societal catastrophe. In a report released last year, the National Academy of Sciences’ National Research Council estimated that a Carrington Event today could wreak between two and four trillion dollars in damages during the first year alone, Foltz says.

“Solar activity can be very extreme, and we are far more vulnerable to it now than we’ve ever been because we are so reliant on technology,” Foltz says. A major space weather event “could take the power grid down for much of the United States,” he says. A 1997 solar storm knocked the television satellite Telstar 40, owned by AT&T, out of order, Keil says. “The next year, Galaxy IV satellite was damaged by a magnetic storm. The satellite was operating ATM machines and aviation tracking systems,” he says. “A solar storm ruined the Japanese satellite Asko, which fell down into the Pacific Ocean,
and sank. Magnetic storms affect cellular communication too. They cause damage to the Internet, and automatic systems, and they disturb high-frequency radio communication.” Moreover, such storms can disrupt spacecraft, as well as aircraft that fly Polar routes, causing them to cancel flights, or fly at lower altitudes, using more fuel, a more expensive alternative. While still under debate, the radiation also may pose a potential health danger to pilots.

“Major storms can affect GPS, making the GPS satellite look like it’s someplace that it’s not—the errors can be pretty substantial,” Keil says. “You can miss where you are by several miles. If you are a second lieutenant out in the field, you really don’t want to be off by that much.”

At some point, the models under development might be able to predict the arrival of such solar particles, Hughes says. “There are many other pieces of the space weather puzzle we don’t have yet, but we are working on building them,” he says.
4. Space Weather Quarterly


Space Weather Model Moves Into Prime Time

Colin Schultz
Published 9 March 2011.


When category 5 Tropical Cyclone Yasi struck the northeastern coast of Australia in early February, it left hundreds of thousands of people without power but none dead or seriously injured, possibly thanks to the detailed forecasting efforts that warned Australians, tens of thousands of whom then sought emergency shelter. But as society increases its dependence on space-based technology, it may be vulnerable to space weather that forecasters cannot predict with current capabilities.

“We’ve recognized terrestrial weather as a hazard for millennia,” said Jeffrey Hughes, director of the Center for Integrated Space Weather Modeling (CiSWM). “Space weather,” on the other hand, “has only been recognized as a hazard relatively recently.”

When a coronal mass ejection (CME), the space weather equivalent of a hurricane, strikes Earth’s magnetosphere, it can knock out satellites, overload the electrical grid, and endanger space-walking astronauts. Forecasters’ ability to predict the effects a CME might have on Earth pales against their ability to predict terrestrial storms. Hughes hopes space weather forecasting might be on track to catch up, starting with the implementation of the first physics-based space weather model, which will go into operational use in fall 2011 and will be run out of NOAA’s Space Weather Prediction Center (SWPC) in Boulder, Colo.

Vic Pizzo, a product evaluator at SWPC, is in charge of moving the model, Wang-Sheeley-Arge (WSA)–Enlil, from development and research into operations. He says the model could bring quantitative analysis to a field dominated by history- and experience-based predictions. “Our forecasters would just watch pictures of the Sun,” said Pizzo. If they saw what appeared to be a CME heading toward the Earth, they would “make a wild guess, basically, about when it’s going to get here and how bad it’s going to be.”

The model deals only with CMEs and not with other sources of space weather, and it will not be able to predict exactly what the effects might be when one hits Earth. However, while current forecasting techniques provide a 1- or 2-day window within which a CME is expected to hit, it is hoped that the operational use of the WSA-Enlil will make it possible to narrow the window to between 6 and 8 hours.

Pizzo notes that adapting a numerical model for daily use will require the model to sacrifice some physical details. The SWPC is “not interested in having the latest, greatest research code. They need something that will be robust,” said Dusan Odstrcil, one of the lead developers of the model and a researcher at George Mason University.

Researchers tend to build incredibly detailed models that include physical processes that are not well understood, said Pizzo. More detailed physics increases the time it takes to
run the model and can allow more opportunities for error; according to Pizzo, added
detail has not yet led to sufficient gains in accuracy for forecasting. In comparison, the
WSA-Enlil model is almost bare bones. The operational model comprises two parts: an
automatically updating measurement of the ambient solar wind and a simplified
numerical description of CMEs that the forecasters can decide to run if they think a CME
might be headed toward Earth. (For more details, see V. Pizzo et al., Wang-Sheeley-
Arge–Enlil cone model transitions to operations, *Space Weather, 9*, S03004,

According to Pizzo, what the model lacks in detail it makes up for in dependability. The
system can pull from two sources of data each for both the ambient solar wind and CME
detections. The operational model also has multiple checks to avoid errors. Furthermore,
all of the data flows from the various detectors into SWPC automatically. On the basis of
preliminary testing by the forecasting group at SWPC, Pizzo said that if all the detectors
are up and running and the data are flowing properly, “it can actually work really well.”

Odstrcil and Pizzo variously described parts of the model as “simple,” “crude,” and “good
enough,” but they suggest that any flaws are pointers for improvement, not a
condemnation. According to CISM director Hughes, this effort to transition a simple
model to operations for space weather prediction is not so different from early attempts
at understanding terrestrial weather. “When [terrestrial] weather researchers started to
use models in the mid-1950s, they did a worse job than the experienced forecasters,”
said Hughes. “It really was more or less a steady slope of improvements over the last 50
years to get up to their current reliability.”

This realization was part of the impetus for CISM and NOAA coming together over the
past few years to discuss the viability of using WSA-Enlil as an operational model, said
Hughes. The two organizations, along with groups from the Department of Defense and
NASA, were integral in building, polishing, and validating the model.

According to Hughes, it is important for the space weather community to start using
numerical models for operational space weather prediction. “Until they have a model—
any model—they don’t really have their foot on the ladder yet,” said Hughes. “Let’s get
our foot on the ladder, then we can start climbing.”

*Colin Schultz* is a staff writer for the American Geophysical Union. *E-mail:*
cschultz@agu.org
## Appendix E: All Hands Meeting

**NCAR, Boulder, Colorado**  
**September 13-15, 2010**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Nick Arge, AFRL</td>
</tr>
<tr>
<td>2.</td>
<td>Dan Baker, University of Colorado</td>
</tr>
<tr>
<td>3.</td>
<td>Chris Balch, NOAA</td>
</tr>
<tr>
<td>4.</td>
<td>Shree Bhattacharai, University Texas, Arlington</td>
</tr>
<tr>
<td>5.</td>
<td>Lauren Blum, University of Colorado</td>
</tr>
<tr>
<td>6.</td>
<td>Robert Bruntz, University of Texas</td>
</tr>
<tr>
<td>7.</td>
<td>Joan Burkepile, NCAR</td>
</tr>
<tr>
<td>8.</td>
<td>Alan Burns, NCAR</td>
</tr>
<tr>
<td>9.</td>
<td>Richard Denton, Dartmouth College</td>
</tr>
<tr>
<td>10.</td>
<td>Giuliana de Toma, NCAR</td>
</tr>
<tr>
<td>11.</td>
<td>Scot Elkington, University of Colorado</td>
</tr>
<tr>
<td>12.</td>
<td>Yuhong Fang, NCAR</td>
</tr>
<tr>
<td>13.</td>
<td>Ben Foster, NCAR</td>
</tr>
<tr>
<td>14.</td>
<td>Katie Garcia, Boston University</td>
</tr>
<tr>
<td>15.</td>
<td>Nicholas Gross, Boston University</td>
</tr>
<tr>
<td>16.</td>
<td>Mary Hudson, Dartmouth College</td>
</tr>
<tr>
<td>17.</td>
<td>Jeffrey Hughes, Boston University</td>
</tr>
<tr>
<td>18.</td>
<td>Roberta Johnson</td>
</tr>
<tr>
<td>19.</td>
<td>Brian Kress, Dartmouth College</td>
</tr>
<tr>
<td>20.</td>
<td>Christina Lee, University of California</td>
</tr>
<tr>
<td>21.</td>
<td>Jiuhou Lei, University of Colorado</td>
</tr>
<tr>
<td>22.</td>
<td>Yan Li, University of California</td>
</tr>
<tr>
<td>23.</td>
<td>Zhao Li, Dartmouth College</td>
</tr>
<tr>
<td>24.</td>
<td>Jon Linker, PSI</td>
</tr>
<tr>
<td>25.</td>
<td>Hanli Liu, NCAR</td>
</tr>
<tr>
<td>26.</td>
<td>Ramon Lopez, University of Texas</td>
</tr>
<tr>
<td>27.</td>
<td>Bill Lotko, Dartmouth College</td>
</tr>
<tr>
<td>28.</td>
<td>Xiaoli Luan, NCAR</td>
</tr>
<tr>
<td>29.</td>
<td>Janet Luhmann, University of California</td>
</tr>
<tr>
<td>30.</td>
<td>John Lyon, Dartmouth College</td>
</tr>
<tr>
<td>31.</td>
<td>Astrid Maute, NCAR</td>
</tr>
<tr>
<td>32.</td>
<td>Slava Merkin, Boston University</td>
</tr>
<tr>
<td>33.</td>
<td>Terry Onsager, NOAA</td>
</tr>
<tr>
<td>34.</td>
<td>Dusan Odstrcil, University of Colorado</td>
</tr>
<tr>
<td>35.</td>
<td>Danielle Pahud, Boston University</td>
</tr>
<tr>
<td>36.</td>
<td>Asher Pembroke, Rice University</td>
</tr>
<tr>
<td>37.</td>
<td>Kara Perry, AFRL</td>
</tr>
<tr>
<td>38.</td>
<td>Kevin Pham, University Texas, Arlington</td>
</tr>
<tr>
<td>39.</td>
<td>Vic Pizzo, NOAA</td>
</tr>
<tr>
<td>40.</td>
<td>Liying Qian, NCAR</td>
</tr>
<tr>
<td>41.</td>
<td>Jack Quinn, AFRL</td>
</tr>
<tr>
<td>42.</td>
<td>Art Richmond, NCAR</td>
</tr>
<tr>
<td>43.</td>
<td>Pete Riley, PSI</td>
</tr>
<tr>
<td>44.</td>
<td>Randy Russell, UCAR/E&amp;O</td>
</tr>
<tr>
<td>45.</td>
<td>Stanislav Sazykin, Rice University</td>
</tr>
<tr>
<td>46.</td>
<td>Don Schmit, NCAR</td>
</tr>
<tr>
<td>47.</td>
<td>Peter Schmitt, NCAR</td>
</tr>
<tr>
<td>48.</td>
<td>Howard Singer, NOAA</td>
</tr>
<tr>
<td>49.</td>
<td>Stan Solomon, NCAR</td>
</tr>
<tr>
<td>50.</td>
<td>Michael Stevens, Boston University</td>
</tr>
<tr>
<td>51.</td>
<td>Alan Sussman, University of Maryland</td>
</tr>
<tr>
<td>52.</td>
<td>Michael Thompson, NCAR</td>
</tr>
<tr>
<td>53.</td>
<td>Frank Toffoletto, Rice University</td>
</tr>
<tr>
<td>54.</td>
<td>Rodney Viereck, NOAA</td>
</tr>
<tr>
<td>55.</td>
<td>Wenbin Wang, NCAR</td>
</tr>
<tr>
<td>56.</td>
<td>Erik Wilson, Boston University</td>
</tr>
<tr>
<td>57.</td>
<td>Mike Wiltberger, NCAR</td>
</tr>
<tr>
<td>58.</td>
<td>Sheng Xi, Dartmouth College</td>
</tr>
<tr>
<td>59.</td>
<td>Benzheng Zhang, Dartmouth College</td>
</tr>
</tbody>
</table>
# CISM All-Hands Meeting, 2010
## NCAR/HAO Center Green

<table>
<thead>
<tr>
<th>MON, Sep 13</th>
<th>TUE, Sep 14</th>
<th>WED, Sep 15</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Center Auditorium</strong></td>
<td><strong>Center Auditorium</strong></td>
<td><strong>SPLINTERS</strong></td>
</tr>
<tr>
<td><strong>8:30</strong> Intro &amp; Welcome – <strong>HAO Welcome</strong> Michael Thompson</td>
<td><strong>8:30</strong> Model Mechanics &amp; Infrastructure (Wiltberger coordinator)</td>
<td><strong>8:30</strong> 1) Characterization of interplanetary shocks <strong>South Auditorium</strong></td>
</tr>
<tr>
<td>8:45 <strong>CIR Overviews:</strong></td>
<td><strong>Model Mechanics &amp; Infrastructure</strong></td>
<td>2) Plasmasphere modeling progress <strong>CG 3131</strong></td>
</tr>
<tr>
<td>9:00 Solar &amp; SW – Riley</td>
<td>* Rice computing resources</td>
<td></td>
</tr>
<tr>
<td>9:30 Discussion – All</td>
<td>* LTR coupling</td>
<td></td>
</tr>
<tr>
<td>9:55 <strong>BREAK</strong></td>
<td>10:00 <strong>BREAK</strong></td>
<td></td>
</tr>
<tr>
<td>10:10 Geospace – Wiltberger</td>
<td>10:15 <strong>Panel &amp; Discussion</strong></td>
<td>10:15 WSA-ENLIL Transition <strong>Upate – Pizzo</strong></td>
</tr>
<tr>
<td>10:40 Discussion – All</td>
<td>Solar Cycle Status &amp; Understanding Panelists TBD</td>
<td>10:45 Splinter reports</td>
</tr>
<tr>
<td>11:05 Iono/Thermo response – Wang</td>
<td>(Luhmann, Solomon coordinators)</td>
<td></td>
</tr>
<tr>
<td>11:35 Discussion – All</td>
<td>12:00 <strong>LUNCH – cafeteria or offsite</strong></td>
<td></td>
</tr>
<tr>
<td><strong>12:00</strong> <strong>LUNCH – cafeteria or offsite</strong></td>
<td><strong>12:00</strong> <strong>LUNCH – cafeteria or offsite</strong></td>
<td>12:00 <strong>ADJOURN</strong></td>
</tr>
<tr>
<td>1:30 <strong>SPLINTERS – CIR Modeling</strong></td>
<td><strong>SPLINTERS</strong></td>
<td></td>
</tr>
<tr>
<td>1) Geospace <strong>CG 3131</strong></td>
<td>1) Solar-Helio – TBD <strong>CG 3131</strong></td>
<td></td>
</tr>
<tr>
<td>2) Solar-Helio <strong>South Auditorium</strong></td>
<td>2) Geospace – TBD <strong>South Auditorium</strong></td>
<td></td>
</tr>
<tr>
<td>3:00 <strong>BREAK</strong></td>
<td>3:00 <strong>BREAK</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Center Auditorium</strong></td>
<td><strong>Center Auditorium</strong></td>
<td><strong>Center Auditorium</strong></td>
</tr>
<tr>
<td><strong>3:20</strong> <strong>Full Team Workshop:</strong> Solar wind Bz modeling (Luhmann coordinator)</td>
<td><strong>3:20</strong> <strong>Projects &amp; Plans</strong></td>
<td><strong>5:00</strong> Ethics training session <strong>CG 2126</strong></td>
</tr>
<tr>
<td>5:30 <strong>CISM Reception</strong> <strong>CG Atrium</strong></td>
<td>- CIR study publications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- other TBD</td>
<td></td>
</tr>
</tbody>
</table>

149
Appendix F: CISM Summer School 2010

Faculty Profiles

Alan Burns is a scientist at the High Altitude Observatory (HAO) at the National Center for Atmospheric Research. He is expert in ionosphere/thermosphere simulations.

Michael Golightly is currently at the University of New Hampshire where he is the deputy project scientist for the CRaTER experiment on the Lunar Reconnaissance Orbiter. He was previously with the human space flight program at NASA/Johnson Space Center, where he had responsibility for Astronaut Safety.

Nicholas Gross is the CISM Co-Director for Education. A physicist, he is an expert in physics education and curriculum development.

Jeffrey Hughes is a professor of astronomy at Boston University. He is an expert in magnetospheric physics, and is director of CISM.

Delores Knipp is professor emerita of physics at the Air Force Academy where she taught a course on space weather. She is now a visiting scientist at the NOAA Space Weather Prediction Center. She is an expert on magnetosphere-ionosphere coupling and magnetic storms.

Sarah McGregor is a Ph.D. candidate at Boston University. Her research involves extensive coronal magnetic field modeling using the Wang Sheely Arge Model as well as solar wind modelling with Enlil. She is a CISM summer school alumna.

Kara Perry is a research scientist at Boston College. She works closely with Air Force Research Laboratory scientists on the radiation belts and their space weather effects. She is a graduate of the first CISM Summer School in 2001.

Antti Pulkkinen is with the Coordinated Community Modeling Center at NASA/Goddard Space Flight Center. He is an expert in modelling geomagnetically induced currents.

John Retterer is a physicist with the Air Force Research Laboratory. He is an ionospheric physicist expert in modelling ionospheric scintillations.

Lawrence Robertson is the Technical Lead in the Space Situational Awareness Group of the Air Force Research Laboratory at Kirkland Air Force Base. He is attending the summer school as a student.

Nathan Schwadron is a professor of astronomy at Boston University. An expert in solar and heliospheric physics, he leads the IBEX (Interstellar Boundary Explorer) mission science team.

Stan Solomon is a scientist at the High Altitude Observatory (HAO) at the National Center for Atmospheric Research. He is an expert in ionosphere and thermosphere physics.

Howard Singer is Chief Scientist at NOAA’s Space Weather Prediction Center (SWPC). He is a magnetospheric physicist interested in dynamics and ULF waves. He is also a BU alumnus and a former research faculty member.

Michael Wiltberger is a scientist at the High Altitude Observatory (HAO) at the National Center for Atmospheric Research. He is expert in MHD simulations of space plasmas and is CISM co-director for code coupling.
# Student Information 2010

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Brett Anderson</td>
<td>Dartmouth College</td>
</tr>
<tr>
<td>2. Christopher Benton</td>
<td>University of Bath, England</td>
</tr>
<tr>
<td>3. Yun-Ju Chen</td>
<td>Grad Inst. Of Space Science</td>
</tr>
<tr>
<td>4. Chris Chronopoulos</td>
<td>University of Colorado</td>
</tr>
<tr>
<td>5. Timothy Duly</td>
<td>University of Illinois</td>
</tr>
<tr>
<td>6. Ehab Hassan</td>
<td>University of Texas, Austin</td>
</tr>
<tr>
<td>7. Donald Petrush</td>
<td>Air Force Research Laboratory</td>
</tr>
<tr>
<td>8. Chih-Te Hsu</td>
<td>Grad Inst. Of Space Science</td>
</tr>
<tr>
<td>9. Yanshi Huang</td>
<td>University of Texas, Arlington</td>
</tr>
<tr>
<td>10. Uday Kanwar</td>
<td>University of Illinois, Urbana</td>
</tr>
<tr>
<td>11. Christopher Keating</td>
<td>United States Naval Academy</td>
</tr>
<tr>
<td>12. Joe Kinrade</td>
<td>University of Bath, England</td>
</tr>
<tr>
<td>13. Kathy Landis</td>
<td>Northrop Corporation</td>
</tr>
<tr>
<td>14. Kathleen Malone</td>
<td>American Airlines</td>
</tr>
<tr>
<td>15. Robert McIntosh</td>
<td>University of Texas, Dallas</td>
</tr>
<tr>
<td>16. Jennifer Meehan</td>
<td>Hampton College</td>
</tr>
<tr>
<td>17. Warren Miller</td>
<td>Space Weather Prediction Center</td>
</tr>
<tr>
<td>18. Dat Nguyen</td>
<td>Augsburg College</td>
</tr>
<tr>
<td>19. Kevin Pham</td>
<td>University of Texas, Arlington</td>
</tr>
<tr>
<td>20. Sadha Pillay</td>
<td>University of Kwazulu Natal, South Africa</td>
</tr>
<tr>
<td>21. Lawrence Robertson</td>
<td>United States Air Force</td>
</tr>
<tr>
<td>22. Neel Savani</td>
<td>Imperial College, England</td>
</tr>
<tr>
<td>23. Quintin Schiller</td>
<td>University of Colorado</td>
</tr>
<tr>
<td>24. Ilgin Seker</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>25. Xiangwei Tang</td>
<td>University of Minnesota</td>
</tr>
<tr>
<td>26. Bruce Tepke</td>
<td>West Virginia University</td>
</tr>
<tr>
<td>27. David Voss</td>
<td>Air Force Research Laboratory</td>
</tr>
<tr>
<td>28. Ndiwa Wachina</td>
<td>International Air Transport Association, Canada</td>
</tr>
<tr>
<td>29. Shuo Wu</td>
<td>Dartmouth College</td>
</tr>
<tr>
<td>30. Sheng Xi</td>
<td>Dartmouth College</td>
</tr>
<tr>
<td>31. Karl Yando</td>
<td>Dartmouth College</td>
</tr>
<tr>
<td>32. Ben Zhu</td>
<td>Dartmouth College</td>
</tr>
</tbody>
</table>
Appendix G: Released Models

CISM Released Models
Status as of Apr, 2011

Coordinated Community Modeling Center
MAS
   Solar Corona 1-30 solar radii
ENLIL
   Heliosphere beyond 30 solar radii
CORHEL
   Coupled MAS-ENLIL model.
PFSS
   Solar coronal magnetic field from magnetograms
WSA
   Wang-Sheeley-Arne coronal and solar wind model
WSA-ENLIL
   CCMC Assessing realtime runs in collaboration with SWPC
Cone
   Included in CORHEL 3.4 and later, and in WSA-ENLIL
LFM-MIX
   MPI LFM and Magnetosphere-Ionosphere Coupler Solver, with CISM coupling technologies.
TIE-GCM
   Thermosphere-Ionosphere General Circulation Model. Source code released and publicly available from NCAR/HAO.
CMIT
   Coupled magnetosphere (LFM) – thermosphere-ionosphere (TIE-GCM)

NOAA Space Weather Prediction Center
Daily average Ap
   SWPC testbed in April, 2004; running in Development Environment.
Ap Forecast 3-Hr
   Running in SWPC Development Environment
MeV electron flux
   SWPC testbed in April, 2004; running in Development Environment
WSA Forecast Model
   Running in real-time in SWPC Development Environment. (CISM baseline model)
WSA-ENLIL Solar Wind Forecast Model
   Daily runs with forecaster displays since Spring 2008. Installed & in test at NWS/NCEP.
WSA-ENLIL-Cone
   Running SWPC, installed at NWS/NCEP for transition to formal operational status Fall 2011.
CMIT
   CMIT 2.5 (MPI LFM, MIX, TIE-GCM) running on NOAA/SWPC wJET supercomputer.

Other releases
CISM_DX 0.5.9 analysis and visualization suite for Linux & Mac OS.
   Released for public use and continuing community development.

There is a lag of approximately one year between the date of a publication and the appearance in print of the first citations, due to the time required for a citing publication to be written, reviewed, and published. We therefore report here citations to-date for publications in 2003 – 2009. Each annual report will add citations for one additional year of publications (e.g., first reporting citations for 2009 in next year’s report) and update citations of previously reported citation years.

The citations reported here are only for publications that explicitly acknowledge CISM support. Publications of CISM-related work, and publications that do not explicitly acknowledge CISM, are not included.

To date, there are 1817 citations of CISM publications from 2003-2009. (Last year’s number was 1197.) The top-cited publications as of April, 2010 are:

<table>
<thead>
<tr>
<th>2010 Citations</th>
<th>Citation Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Page</td>
<td>Author(s)</td>
</tr>
<tr>
<td>------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>Reference</td>
</tr>
<tr>
<td>---</td>
<td>-----------</td>
</tr>
</tbody>
</table>

* Center personnel.
# Appendix I: Statistics of Outside Participants

## CISM Summer School:

<table>
<thead>
<tr>
<th>Year/# Students</th>
<th># of Applications</th>
<th>Male</th>
<th>Female</th>
<th>Students</th>
<th>Non-Students</th>
<th>Hispanic/Latino</th>
<th>Race</th>
<th>U.S. Citizens</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003: 31 Students</td>
<td>43</td>
<td>24</td>
<td>7</td>
<td>25</td>
<td>6</td>
<td>1</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2004: 32 Students</td>
<td>41</td>
<td>23</td>
<td>9</td>
<td>23</td>
<td>9</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>2005: 36 Students</td>
<td>47</td>
<td>20</td>
<td>16</td>
<td>22</td>
<td>14</td>
<td>5</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>2006: 32 Students</td>
<td>41</td>
<td>24</td>
<td>8</td>
<td>27</td>
<td>5</td>
<td>1</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2007: 31 Students</td>
<td>40</td>
<td>19</td>
<td>12</td>
<td>24</td>
<td>7</td>
<td>1</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>2008: 28 Students</td>
<td>56</td>
<td>20</td>
<td>8</td>
<td>21</td>
<td>7</td>
<td>0</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2009: 34 Students</td>
<td>50</td>
<td>20</td>
<td>14</td>
<td>21</td>
<td>13</td>
<td>0</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>2010: 32 Students</td>
<td>38</td>
<td>25</td>
<td>7</td>
<td>21</td>
<td>11</td>
<td>0</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>Year/# Students</td>
<td>Male</td>
<td>Female</td>
<td>Students</td>
<td>Non-Students</td>
<td>Hispanic/Latino</td>
<td>Race of Students</td>
<td>U.S. Citizens</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>------</td>
<td>--------</td>
<td>----------</td>
<td>--------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>2004: 10 Participants</td>
<td>4</td>
<td>6</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>0 7 0 2</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2005: 10 Participants</td>
<td>6</td>
<td>4</td>
<td>9</td>
<td>1</td>
<td>3</td>
<td>0 4 0 5</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>2006: 9 Participants</td>
<td>6</td>
<td>3</td>
<td>9</td>
<td>0</td>
<td>4</td>
<td>0 5 0 4</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2007: 9 Participants</td>
<td>7</td>
<td>2</td>
<td>9</td>
<td>0</td>
<td>4</td>
<td>0 5 0 4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2008: 9 Participants</td>
<td>7</td>
<td>2</td>
<td>9</td>
<td>0</td>
<td>4</td>
<td>0 5 0 4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2009: 9 Participants</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>0</td>
<td>1</td>
<td>0 7 1 0</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>2010: 9 Participants</td>
<td>4</td>
<td>5</td>
<td>9</td>
<td>0</td>
<td>8</td>
<td>0 2 1 6</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>2011: 8 Participants</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td></td>
</tr>
</tbody>
</table>
Appendix J: Education Assessments

**Outcome 1:** A thriving, diverse community of graduate students actively engaged in CISM research and related activities

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of graduate students engaged in CISM research each year.</td>
<td>20 each year, including 8 women and 4 underrepresented</td>
<td>18 students including 6 women and 3 underrepresented US citizens</td>
</tr>
<tr>
<td>Number of CISM PhDs.</td>
<td>5 after five years; 25 after 10 years, including 12 women and 5 underrepresented</td>
<td>Interim progress: 21 after 9 years 6 woman</td>
</tr>
<tr>
<td>Number of graduate student first-author presentations at professional scientific meetings related to CISM research.</td>
<td>12 per year</td>
<td>23 first author presentations 27 co-author presentations</td>
</tr>
<tr>
<td>Number of graduate student first-author papers in scientific journals.</td>
<td>5 per year</td>
<td>13 first author paper 5 co-author papers</td>
</tr>
<tr>
<td>Graduate student enrollment in Summer School.</td>
<td>24 each year</td>
<td>20 graduate students of 32 attendees</td>
</tr>
<tr>
<td>Formative evaluations of Summer School.</td>
<td>an average of “4” on a five-point Likert scale</td>
<td>4.36 average daily evaluation</td>
</tr>
<tr>
<td>Summative evaluations by graduate students of the Summer School contribution to professional development.</td>
<td>“4” on a 5-point scale</td>
<td>2009: 4.38 Average Evaluation</td>
</tr>
</tbody>
</table>
**Outcome 2:** A thriving, diverse community of undergraduate students actively engaged in CISM research and related activities

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of undergraduates engaged in CISM research each year.</td>
<td>20, including 10 women and 5 underrepresented</td>
<td>19, including 8 women and 5 underrepresented U.S.</td>
</tr>
<tr>
<td>Number of CISM undergraduates entering graduate school in Space Weather related programs.</td>
<td>3 each year.</td>
<td>1</td>
</tr>
<tr>
<td>Number of undergraduate co-authored presentations at professional scientific meetings related to CISM research.</td>
<td>5 per year</td>
<td>7 undergraduate first author presentations 4 co-authored presentations</td>
</tr>
<tr>
<td>Number of undergraduate co-authored papers in scientific journals.</td>
<td>5 per year</td>
<td>2 co-authored papers</td>
</tr>
</tbody>
</table>

**Outcome 3:** Both CISM and non-CISM students interacting with peers and working scientists thorough CISM provided means

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of student first-author presentations with co-authors from other institutions at professional conferences.</td>
<td>8 each year</td>
<td>5 first author presentations 12 co-author presentations 6 first author paper 6 co-authored papers</td>
</tr>
<tr>
<td>Number of students representing different institutions attending the CISM all-hands meeting.</td>
<td>12 students representing 6 institutions each year</td>
<td>10 graduate students representing 6 institutions</td>
</tr>
<tr>
<td>Students from most CISM institutions participating in regular CISM AG sessions</td>
<td>students from 6 institutions participating</td>
<td>No Graduate AG meetings held this year</td>
</tr>
<tr>
<td>Number of students attending the graduate retreat.</td>
<td>12</td>
<td>9 students from 5 Institutions</td>
</tr>
</tbody>
</table>
### Outcome 4: Teachers using CISM materials in their classes. Teaching professionals participating in CISM sponsored activities. Members of the general public participating in CISM sponsored programs and accessing CISM provided materials.

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teachers trained in use of CISM curriculum modules (such as the Space Weather Monitor System) at middle school, high school and community college level.</td>
<td>20 teachers trained per year.</td>
<td>Module is in the summative evaluation stage.</td>
</tr>
<tr>
<td>Space Weather Monitor suitable for widespread classroom use developed and tested with teacher interns and students by end of year 3.</td>
<td></td>
<td>Done.</td>
</tr>
<tr>
<td>100 Space Weather Monitor systems (SIDs) and 15 research-quality monitors (AWESOME) distributed, with at least 80% incorporated into classroom curriculum or activities, by end of year 5.</td>
<td>Initial Distribution Completed</td>
<td>Distribution of new monitors is done with the cooperation of the Society of Amateur Radio Astronomers (SARA)</td>
</tr>
<tr>
<td>Presentations and workshops on CISM science, classroom relevance, and pedagogical approaches at professional meetings for educators and scientists.</td>
<td>10 per year</td>
<td>8 Workshops serving 350 teachers</td>
</tr>
<tr>
<td>Teachers report using CISM curriculum modules in the classroom.</td>
<td>25% of previous year’s cohort after 5th year</td>
<td>None Reported</td>
</tr>
<tr>
<td>CISM content accessed by the public via the web or in person.</td>
<td>1 million visitors per year after 5th year</td>
<td>Tracking for past year: Windows to the Universe: Not available at the time of compilation Exploritorium CISM Site: no explicit tracking data Haydan Planetarium: No explicit tracking data</td>
</tr>
</tbody>
</table>
Appendix K. Diversity Assessments

**Objective 1:** Recruit undergraduates from groups who are underrepresented in science to attend graduate school in space science at CISM institutions

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
</table>
| Number of minority and female graduate students engaged in CISM research each year. | 30 % of US total are women  
20% of US total are minority | Current number is 38% (3/8)  
Current number is 38% (3/8) |
| Formative evaluation of the 2010 Space Weather Weekend | Overall score of “4” on a 5-point Likert scale.  
1/3 of participants indicate likelihood of applying to CISM graduate schools | Both objectives met |
| Summative evaluation of the Space Weather Weekend | Over the 6 years, 7 students will begin study at CISM (or other space physics) graduate schools | From 2005 – 2010, 2 students have joined CISM, two have applied to other Space Physics programs, and four others (from the 2009 and 2010 Space Weather Weekend) have stated that they now want to do graduate study in space physics. |
| Number of women and minority students involved in CISM undergraduate research | 40 % of US total are women  
25% of US total are minority | Current number is 44% (7/16)  
Current number is 31% (5/16) |
| Number of minority students involved in CISM undergraduate research who go to CISM (or other space weather related) graduate schools | 7 students over 5 years | 8 CISM minority undergraduate researchers since 2002 have begun graduate work in space science. |
**Objective 2:** Work with existing programs that aim to improve diversity in science

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inventory of Diversity programs at CISM campuses</td>
<td>CISM creates inventory of programs and find mechanisms by which CISM can contribute</td>
<td>Inventory done. Undergraduate research programs identified as high leverage activity as CISM campuses.</td>
</tr>
</tbody>
</table>

**Objective 3:** Ensure that participants in Center activities and programs represent a diverse population

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
</table>
| Number of minority and female graduate students engaged in CISM research each year. | 30% of US total are women  
20% of US total are minority  | Current number is 38% (3/8)                                           |
| Number of minority and female participants at the CISM summer school.      | 1/3 of US participants are women and/or minorities                    | 24% in 2003 (5/21)  
41% in 2004 (9/22)  
52% in 2005 (12/23)  
37% in 2006 (7/19)  
33% in 2007 (4/12)  
29% in 2008 (5/17)  
??% in 2009 (?/15) |}

| Number of women and minority students involved in CISM undergraduate research | 40% of US total are women  
25% of US total are minority  | Current number is 44% (7/16)                                           |
| Grade 6-14 programs target women and minorities                            | 30% of teachers involved CISM professional development represent diverse populations | TBD |
**Objective 4:** Support the establishment of a viable space science program at Alabama A&M University, which is a leading producer African-American physics degrees

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Degree programs at AAMU.</td>
<td>Establish new B.S. and M.S. space science degrees at AAMU</td>
<td>New M.S. space science concentration for the Physics degree now in place at AAMU. Two M.S. degrees awarded so far. First Ph.D. degree awarded in 2009.</td>
</tr>
<tr>
<td>New tenure-track positions at AAMU in space science; CISM-sponsored faculty gets tenure</td>
<td>Hire a tenure-track space physicist with partial CISM support and provide support network</td>
<td>Dr. Tian - Xi Zhang is on the tenure track at AAMU</td>
</tr>
</tbody>
</table>

**Objective 5:** Integrate the new AAMU program into the research and education programs of the Center

<table>
<thead>
<tr>
<th>Assessment</th>
<th>Goal</th>
<th>Year-9 Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CISM-wide participation in a mentoring/support role for AAMU</td>
<td>At least 3 CISM institutions are actively engaged in joint research/mentoring with AAMU</td>
<td>Boston, NCAR, and PSI are working with AAMU students.</td>
</tr>
<tr>
<td>Provide CISM-sponsored colloquia with outside speakers at AAMU</td>
<td>AAMU will participate regularly in Access Grid Session. 2 CISM colloquium visitors/yr</td>
<td>AAMU attends scheduled AG sessions. One CISM visit to AAMU last year</td>
</tr>
</tbody>
</table>