

***ASSESSMENT OF THE  
LIVING WITH A STAR (LWS) TARGETED  
RESEARCH AND TECHNOLOGY (TR&T)  
PROGRAM WITH DISCUSSION OF POSSIBLE  
FUTURE DIRECTIONS  
AND PROGRAM ELEMENTS***

***NASA LWS TR&T 2012 STEERING COMMITTEE***

***JULY 2014***

NASA Living With a Star (LWS) Targeted Research and Technology (TR&T)  
2012 Steering Committee

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## 1. Introduction

The 2012 LWS TR&T Steering Committee was asked by NASA HQ LWS Scientists to carry out an assessment of the TR&T program which by now had been in place for ~10 years. The assessment was to produce an informal working document for use by NASA HQ LWS scientists in helping to recommend future directions for the program, and to suggest possible changes or addition of program elements to facilitate reaching future goals. The assessment was to:

- describe the strategic goals of the program
- describe progress achieved in the past 10 years
- assess the importance of TR&T program elements to achieving progress
- identify future directions for the program
- suggest modifications or new program elements to assist in achieving the goals.

The full charge to the Steering Committee is attached in Appendix A.

The Steering Committee split into four subgroups to assess different portions of the TR&T program:

- Subgroup 1: Variable solar particulate and radiative environment
- Subgroup 2: Solar radiative and particulate contribution to global and regional climate
- Subgroup 3: Forecast/specify magnetospheric radiation and plasma environment
- Subgroup 4: Upper atmosphere and ionospheric response to solar electromagnetic radiation and coupling to adjacent regions

The subgroups were provided a summary of Focus Science Team (FST) and Strategic Capability (SC) selections under the program (see Appendix B). In addition a survey was conducted by polling all PIs who had received grants under the program, and results were used by the Subgroups and are summarized in Appendix C.

Each subgroup report drew on the experience of Steering Committee members, most of whom had participated in or led FSTs or SC teams; they also contacted other LWS PIs in order to broaden the inputs to the report. In assessing progress in the field, the committee made extensive use of the NAS/NRC Decadal Survey, “Solar and Space Physics: A Science for a Technological Society” (ISBN 978-0-309-16428-3) which was released during the Steering Committee’s assessment study. The Decadal Survey, with its peer-reviewed assessment of progress in the field based on inputs from a large community, was a timely and definitive description of the field and recent progress which the Steering Committee adopted as the basis for assessing scientific progress.

Each subgroup’s report, or draft report, is attached below in Appendices D-G, and they contain summaries of each group’s response to the tasks in the charge. Below is a top-level summary of these reports, with further details to be found in the appendices.

## 2. Summary of Strategic Goals

The NASA LWS TR&T web page summarizes the top level objectives of the program:

*The goal of the Living With a Star (LWS) Program is to develop the scientific understanding needed for the United States to effectively address those aspects of the connected Sun-Earth system that may affect life and society. The LWS Targeted Research and Technology (TR&T) program element solicits proposals leading to a physics-based understanding of the integral system linking the Sun to the Earth both directly and via the heliosphere, magnetosphere, and ionosphere. The program's objectives can be achieved by data analysis, theory and modeling, and the development of tools and methods (e.g., software).*

Over the years of the program, the Steering Committees have formulated lower level goals for the program, and for the assessment study the Steering Committee chose the formulation made by the 2007 TR&T Committee Report (Tamas Gombosi, Chair):

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

These four strategic goals were assigned to the four subgroups.

Lower level objectives and priorities have been identified for each of the four strategic goals and some of these are described in the Subgroup reports in the appendices. It should be kept in mind that while reaching the Strategic Goals requires a broad program including new spacecraft missions, the TR&T program contributions are achieved by the use of existing data, development of theories and models, and tools for community use.

### 3. Progress Achieved by the TR&T Program Over the Past 10 Years

The TR&T program elements are:

- *Strategic Capabilities*: developed models and tools needed for predictive work; 2-3 such programs were selected beginning in 2005; these programs typically run for 5 years
- *Focus Science Topics (FSTs)*: 4-5 topics were pursued each year beginning in 2004, with each topic consisting of 4-5 individual grants that addressed aspects of the topic. Over the 9 years of the program this corresponds to over 150 PI grants with typical duration of 3 years.
- *Sun-Climate*: addresses solely climate investigations related to the question of solar forcing, with ~5 selections per year beginning in 2009, and typical durations of 3 years. Topics in this area are reviewed along with the FSTs.
- *Tools and Methods*: encourage development of tools or data sets that are of broad use to the community, and which are to be delivered to one of the community repositories (CCMC, VxO, solarsoft). For 2004-2009 about 8 such efforts were selected each year.
- *Heliophysics Summer School*: this yearly program focuses on space weather with a goal of introducing young researchers to the field and also leading to the development of classroom and textbook materials.
- *Postdoc program*: the LWS Jack Eddy postdoctoral 2-year fellowships match recent PhDs with senior LWS scientists, with 4-5 awardees each year starting in 2010.

Below we list some selected highlights of progress achieved in the subgroup areas over the past 10 years. Each subgroup's high level goal has been divided into several subject areas. Due to the very large amount of research involved, these selections should be considered as illustrative only. Further details and many more specifics are in the subgroup reports in the appendices.

#### ***Subgroup 1: Solar particulate and radiative environment:***

- 1) solar wind: establishing key property of slow wind is ion composition and temporal variability, and critical role of pseudostreamers in the origin of the slow wind; theoretical progress in Alfvénic wave heating of solar wind, and greatly improved numerical 3D models of solar wind; discovery of magnetic reconnection in the heliosphere
- 2) CME-ICME connection: large improvement in CME and shock arrival forecasting, reducing Earth-arrival uncertainties from ~12hr to ~3hr.
- 3) solar energetic particles: establishing role of preceding CMEs in large SEP events that produce ground level enhancements at Earth; discovering that

remnant suprathermals from SEP events form an important part of the seed population for CME-shock acceleration events; showing that 10-20% of CME kinetic energy goes into the energetic particles

4) coronal and interplanetary shocks: identifying key roles of seed particles, self-excited waves, and magnetic field geometry in the effectiveness of interplanetary shock acceleration of energetic particles; illuminating the role of CMEs below  $\sim 5R_s$  creating current sheets where reconnection drives particle acceleration.

5) solar UV and X-radiation: determining of the relationship between solar spectral irradiance and unsigned magnetic flux, and simulations suggesting that coronal heating may be linked to impulsive non-thermal sources possibly close to the Sun's surface.

***Subgroup 2: Solar contribution to global and regional climate:***

1) Understanding of solar spectral irradiance on daily to millennial time scales: discovery of hot plasma ejection from nanoflares; deriving relationship between SSI and total magnetic flux; improved models of solar variability;

2) Impacts of solar spectral irradiance on the high terrestrial atmosphere: development of improved physics-based thermosphere-ionosphere models that accurately calculate the response to solar EUV variations, including effects of magnetic activity and IMF orientation; identifying secular changes in greenhouse gas concentrations through their effects on satellite drag

3) Understanding of SEP/GCR variability: identification of the global solar magnetic field as a key element in the modulation of galactic cosmic rays (GCRs), with important implications on climatological times scales where large changes in magnetic field would lead to greatly enhanced or decreased GCR intensities at Earth

4) Impacts of energetic precipitating particles (EPPs) on the terrestrial atmosphere: determination of the role of precipitating low, medium, and high-energy particles on the atmospheric production of hydrogen and nitrogen oxides which can catalytically cause ozone loss; inclusion of EPPs into whole atmosphere models.

5) Information flow from climate-related and geomagnetic research into Heliophysics: improvements in Global Climate Models by inclusion of SSI variations over solar cycle scales

- 6) Information flow from astrophysics into Heliophysics: improved understanding of the relation between cosmogenic radionuclides (e.g. C14) and solar magnetic activity.

***Subgroup 3: Forecast/predict magnetospheric radiation and plasma environment***

- 1) Global dynamics, controlled by changes in the north-south component of the interplanetary magnetic field (IMF): The global dynamics of the magnetosphere is dominantly controlled by the north-south component of the interplanetary magnetic field (IMF), which is variable in space and time, and drives global circulation in the magnetosphere. Changes in the IMF and solar wind dynamic pressure produce storms and substorms, auroral brightenings, and local as well as global convection patterns in the magnetosphere as well as the ionosphere. Sophisticated global imaging, supported by global simulations, have identified heretofore invisible plasma populations of the magnetosphere, the drastic changes in the configuration of the plasmasphere and the ionospheric density enhancements under the influence of powerful storms.
- 2) Wave-particle interactions in the radiation belts: Wave-particle interactions have been established as the principal drivers of particle energy gain and loss in the radiation belts. Greater understanding of the theory of plasma micro-instabilities, simulations, and spacecraft observations demonstrate that the local acceleration of radiation belt electrons due to wave-particle interactions can dominate that due to diffusive radial transport.
- 3) Role of ionosphere-magnetosphere coupling on ionospheric outflows: There have been major advancements in the understanding of conditions leading to the flux of ionospheric plasma to high altitudes and into the magnetosphere. Intense ionospheric ion outflows occur due to a combination of local heating by waves and external forcing. Outflows merge with plasmas of solar wind origin in the plasma sheet, creating a multi-species plasma that alters the dynamics of magnetic reconnection. Multi-fluid global simulations confirmed the major role ionospheric outflow plays in the creation of sawtooth intervals.
- 4) Major new understanding of collisionless magnetic reconnection in the context of the Earth's magnetospheric plasma environment: *In situ* probing by multiple satellites and sophisticated computer simulations have elucidated collisionless mechanisms and triggers of fast reconnection (mediated by the Hall current and electron pressure tensor in a generalized Ohm's law), particle energization and production of fast and bursty bulk flows. These studies have pointed to the necessity of integrating kinetic effects in global MHD codes.

***Subgroup 4: Upper atmosphere and ionosphere response to solar radiation and coupling:***

- 1) Ionosphere: discovery and improved understanding of storm-time enhancements of total electron content (TEC) in the dayside ionosphere, and their relationship to subauroral electric fields; discovery of importance of tides and planetary waves driving ionospheric variability; ability to simulate GICs and effects on electric power lines.
- 2) Thermosphere: Impacts of solar spectral irradiance on the high terrestrial atmosphere: development of improved physics-based thermosphere-ionosphere models that accurately calculate the response to solar EUV variations, including effects of magnetic activity and IMF orientation; satellite drag studies established that the semiannual thermospheric density variation was found to be extremely variable but could be modeled in empirical models using UV solar indices, and using  $k_{zz}$  in first-principles models; density estimates from the GRACE accelerometers were established to be in excellent agreement with limb remote-sensing data, and could be well simulated by the TIME-GCM model.
- 3) Coupling with the magnetosphere and lower plasmasphere: breakthrough understanding in sawtooth mode magnetospheric oscillations emerged from multifluid simulations of the solar wind-magnetosphere-ionosphere interaction; determination of the principal drivers of ionospheric outflows including the role of Alfvén waves
- 4) Coupling with the lower atmosphere: established the importance of tides and planetary waves on ionospheric variability; identification of the role of planetary and gravity waves in temperature anomalies from the stratosphere to lower thermosphere; discovery that Sudden Stratospheric Warming events have a strong ionospheric signature; development of whole-atmosphere models that couple atmospheric layers from the troposphere to the thermosphere-ionosphere.
- 5) Forecasting/nowcasting: general circulation models are being improved by coupling to lower atmosphere and magnetosphere; high fidelity high latitude inputs improved fidelity of thermospheric simulations; Assimilation is burgeoning and expected to improve ionospheric specification.

#### 4. Role of Structure of the TR&T program:

*The Focused Science Topics (FSTs)* are the most novel aspect of the TR&T program in that groups of investigators propose to carry out research on aspects of a larger problem, but are also required to meet once or twice a year as a team and encouraged to work collaboratively. One of the PIs is selected by NASA HQ as the team leader. Table 1 summarizes responses of the 39 PIs who responded to the TR&T feedback web-based questionnaire (see Appendix C),

Table 1 -- PI assessments of Focus Science Teams

Question	Yes	Limited	No	No answer
1) Did the FST team activity enhance your ability to meet the objectives of your individual proposal?	79%	8	4	3
2) Did the FST team concept aid in the creation of an interdisciplinary science community that would not otherwise have reason to collaborate?	74%	3	7	5
3) Did the FST lead to advancement of science beyond what was in the individual proposals?	67%	15	15	3

The above table shows the positive assessment of the FST implementation by survey responders. In particular, groups from other disciplines often learned from each other regarding observational data or modeling techniques. More detailed examples are in the appendices. However, free-form comments from the responders made it clear that not all teams were equally successful in achieving a synergistic interaction of the members. Some attributed this to the subject matter, as well as other factors such as leadership.

Some specific suggestions are in Appendix C, and these were considered by the Steering Committee groups in making their recommendations.

*Strategic Capabilities:* these teams developed models for delivery to the CCMC or other repository, and were highly successful in developing the proposed products. The goal of this activity - to have these products become useful tools to the broader community - has not been fully realized, nor has validation of the models been entirely satisfactory in many cases.

Tools and methods: these investigations were limited in scope due to their size and so produced valuable results but not on the scale of the FSTs and SCs. So they are not assessed here.

Heliospheric summer school and postdoc program: the summer school has been vital in producing textbooks and teaching material and in training the next-generation research community. Since they address the science goals of the program only over the long term, they were not reviewed by the Steering Committee.

## 5. Future Directions of the TR&T Program

The Steering Committee reports outlined possible areas for future emphasis in the TR&T program, but given the dynamic progress being made in the field they recognize that other topics will emerge in the coming years that cannot be foreseen at this time. A summary of some of the areas for future work is provided below, with more details in the subgroup reports in the appendices.

### ***Subgroup 1: Solar particulate and radiative environment:***

- Heating and mass acceleration of the quasi-steady corona and winds
- explosive acceleration of CME plasma and magnetic field
- shock formation and propagation
- particle acceleration at shocks
- fast magnetic reconnection in flares and its various channels of energy release, especially into energetic particles

### ***Subgroup 2: Solar contribution to global and regional climate:***

- establish reliable SSI record
- understand atmospheric impacts of SI variations
- understand radionuclide and sunspot records over centuries to millennia and calibrate with SSI
- chemistry and dynamics of middle and upper atmosphere
- develop a predictive solar dynamo model

### ***Subgroup 3: Forecast/predict magnetospheric radiation and plasma environment***

- Carry out integrated studies of the coupling and feedback between the magnetosphere-thermosphere-ionosphere system under variable solar wind conditions
- Advance physical understanding of the magnetosphere and its coupling to the ionosphere and thermosphere by comparing models against observations from different planetary magnetospheres
- Synthesis of global and particle models in predicting the production, energization and loss of energetic particles in the magnetosphere
- Establish how fast reconnection and secondary instabilities are triggered in the plasma environment of the magnetosphere and how they drive mass, momentum, and energy transport

### ***Subgroup 4: upper atmosphere and ionosphere response to solar radiation and coupling:***

- Simulate geospace response as an integrated system
- Understand global neutral wind dynamics, its variability and effects
- Gravity waves transport energy and momentum from the troposphere into the thermosphere and ionosphere. The characteristics and climatology of these

waves in the upper atmosphere are essentially unknown. New measurement techniques and models are starting to be developed that could shed light in this area.

- Understand and predict ground induced currents, geoelectric fields, and their impacts on the power grid infrastructure. Lack of data has hampered this domain of study, although new measurement techniques and modeling capabilities are starting to be developed.
- Upper atmosphere response to solar variability
- Integration of IT models with magnetosphere models
- Influence of upward coupling vs. in situ forcing by solar and particle inputs
- Variability of topside ionosphere

## 6. Suggested Program Elements and Implementation Changes

The Steering Committee began development of concepts for changes to improve the TR&T program or to better assess the progress it is making. A full discussion of the suggestions did not take place due to lack of time, however, a preliminary discussion revealed that many of the ideas were supported by most committee members. Due to this same lack of time, the suggestions below were not refined by the committee but are listed here as potential ideas that could point to useful areas for NASA HQ to consider.

### The Focused Science Topics (FSTs)

- *add* a new type of investigation, the **Targeted Science Teams (TSTs)** which will be like FST except that the TSTs will form *prior* to selection under a single PI. The advantages of this approach are obvious and address some of the major community concerns with regard to the teaming aspects of the present FST program. First, in order to be selected, the TST will necessarily have all the expertise required to attack the specified Science Target rather than rely on random chance to form a complete Team. Second, the Team Leader, the PI, will again be pre-selected and will necessarily be a likely, effective leader in order for the proposal to be selected rather than again rely on “the luck of the draw”. A key aspect of the TST program is that the expertise required for a particular Target will be specified in advance by the TR&T program as part of the Target description. One of the main criteria for evaluating TST proposals will be the extent to which individual members of the Team satisfy the expertise requirement. This will encourage the TSTs to be strongly interdisciplinary and to involve the best people in the field, rather than simply co-located groups. The funding and duration for each TST should be roughly equal to that of the present FST teams. Note, however, that we do NOT recommend allowing both FST and TST proposals for the same Topic, since one group of proposers will not be funded. The TR&T Steering Committee should recommend and NASA HQ should pre-select which Topics will be competed as FSTs or TSTs exclusively.
- as an alternate to the TSTs, increase the supplemental funding to \$50k/year rather than the current ~\$20k/yr, and have the PI deliver a specific plan to NASA HQ and provide a plan so that the work of the team is delivered to the community such as through the CCMC, linking up to an SC group, or partnering with a Space Weather organization.
- maintain the current 4-year baseline expectation for FST grants.
- The Sun-Climate group felt that the TSTs were an appropriate model for research in that area, but that the FSTs were not since the range of expertise required made it unlikely that successful teams could be formed through separate proposals.

Strategic Capabilities:

The next stage for SCs is the expansion of applications to a broader range of physical problems, the validation of models, and the expansion of deliverables from strategic capabilities, which will lead to deepened benefits for the LWS community.

- Metrics and model validation represent two key elements upon which the success of models depends. The comprehensive, systematic quantitative comparison of model output with observations is required for identifying and documenting model strengths and weaknesses. Representative examples of validation efforts include case studies: for example, comparison with in situ observations during real events would be valuable for exploring the range of model validity. Additional uses include statistical approaches to compare model parameters deduced from both spacecraft observation and modeled by the LFM code. Spence et al. (J. Atm. ST Phys, 66, 1499, 2004) document important examples of model metrics and validation.
- The developed models that describe components of space weather are still in their infancy. The basic modules can be coupled to each other, which will culminate in even more powerful tools.
- The use of the CCMC is critical for running and maintaining models and thereby expanding accessibility of space weather tools. Efforts involving model validation (developing skill scores) and the coupling of models to describe interconnected phenomena should be developed in partnership with the CCMC. Ultimately, the CCMC benefits from and serves the space science community by developing greater accessibility and utility of the complex research tools it houses.

Tools and methods and Heliospheric summer school and postdoc program: were deemed valuable and successful in the committee discussions, but there were no specific recommendations in this area.

Other investigation ideas: one member of the committee suggested the addition of a new type of investigation, the **Innovative Independent Investigation (IIIs)** that would help counteract the inertia being built into the TR&T system with 3-4 year grants. The IIIs would be more risky ideas that would have one year with about 2 months FTE to show progress to then unlock 3 more years of funding at standard rate. There was no opportunity for the Steering Committee to discuss this concept, although one member pointed out that the NSF has a similar program.

*Sun-Climate programmatic:* the Sun-Climate group identified several program or interagency issues that are described in more detail in section 4 of Appendix D. The issues were:

- assess the impact of the division of responsibilities at NASA HQ between Heliophysics and Earth Science in order to minimize the negative effects of division of responsibilities between the two groups
- partner with NOAA and NSF to establish the variability in regional climates and correlation with SSI records
- partner with NSF and the NASA SMD Astrophysics Division to develop a predictive solar dynamo model

*Better mechanisms of feedback from the community to the program*

One of the great strengths of the LWS TR&T program is the communication between the program scientists and the heliophysics science community, mediated in part by members of the Steering Community who represent the community, as well as direct input every year from the community to the process of selection of FSTs, Strategic Capabilities, and Tools and Methods. An area of possible improvement is the monitoring of FSTs and Tools and Methods during their period of funding (especially at the three-year mark for FSTs), and an evaluation of how successful the FSTs are in realizing their science theme objectives. To a significant extent, this process can be improved by adding at least one program scientist to the LWS TR&T roster at NASA, one who can alleviate the existing workload of the two program scientists responsible for this program and assist in closer monitoring of the accomplishments of the awards.

**APPENDIX A -- CHARGE TO STEERING COMMITTEE**

Charge to LWS Steering Committee for  
LWS TR&T Steering Committee program assessment.

References: SC telecon 2/17; email inputs from committee members; Steering Committee discussions 4/10-11/2012.

The assessment will organize the evaluation based on the 4 strategic goals given in the 2007 TR&T committee report (Gombosi, chair; see page 2); these were:

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

For additional details on priorities associated with the Strategic Goals, see pp 3-5 below.

In these basic areas the assessment should

- Describe the strategic goal in sufficient detail for a non-expert to understand why it is important. What are the relevant phenomena, what are the important physical processes, what are the major impacts on life and society, and what would be required to mitigate these impacts? ~ 1 page
- Describe what progress has been achieved by the TR&T Program over the past 10 years in achieving the strategic goal. What new science understanding has been delivered, what progress toward physics-based forecasting/nowcasting has been achieved, (ask other agencies and other NASA scientists for input), what infrastructure/resources have been developed for further work toward the goal? The answers to each of the questions will have varying degrees of contributions from each element of the TR&T program. ~ 5 – 10 pages
- Assess how important was the special structure of the TR&T to achieving the progress. For example, setting a certain science goal will clearly lead to advances in understanding in that area, but did the FST Team structure help much (TM, DP, CStC, questionnaire, include lessons learned) ? Since all of the four goals are interdisciplinary, in nature, it would be useful to comment on whether the TRT&T has

helped the community to carry out interdisciplinary work. This section could be a single writeup for all four questions. ~ 2 pages

- Identify where the LWS program should be headed in the next 10 years based possibly on (a) problems not addressed previously, (b) areas where future progress is critical and achievable, (c) other...; contrast this if applicable to the original goals. ~ 1 page
- address as appropriate how these goals will be implemented in terms of LWS TR&T program elements, e.g., focused science topics, strategic capabilities, tools and independent science, LWS postdocs, cross disciplinary infrastructure, next generation, other...? ~ 1 page

The SC and liaison scientists will divide into 4 groups to assess the 4 strategic goals -- members may serve on more than one group.

Topics and groups

1. Variable solar particulate and radiative environment	2. Solar radiative and particulate contribution to global and regional climate	3. Forecast/specify magnetospheric radiation and plasma environment	4. Upper atmosphere and ionospheric response to solar electromagnetic radiation and solar wind, and coupling to adjacent regions
Abbett * Antiochos Eparvier Kasper Mason Riley Schwadron St.Cyr	Bogdan Mannucci * Schrijver Spence Viareck	* Bhattacharjee Gombosi Goodrich Kuznetsova Mauk Onsager Sibeck	* Crowley Eparvier Kamalabadi Kerr Kuznetsova Mannucci Pesnell

IDENTIFIED PRIORITIES FROM 2003 STDT REPORT SECTIONS 2 AND 3 GROUPED UNDER 2007 REPORT STRATEGIC GOALS:

Strategic Goals Below are from 2007 Report (Gombosi, chair, see p 2); objectives and priorities are from the 2003 report (Antiochos, chair, sections 2 and 3).

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

*Objective:* Develop the capability to forecast and predict the intensity of energetic particles accelerated by CME-driven shock disturbances in the solar wind.

*Priorities:*

- Understand and model the shock acceleration and heliospheric transport of energetic particles.
- Create models of CME-driven shock disturbances that include realistic CME and ambient solar wind initial conditions.
- Develop and progressively improve the specification of the ambient coronal and solar wind plasma and magnetic field.

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

*Objective:* Identify and quantify the changes in Earth's near-surface temperature and other climate parameters attributable to solar variability from both direct and indirect solar energy forcings.

*Priorities:*

- Develop a robust observational and mechanistic description of climate change associated with solar variability.
- Incorporate candidate solar driver processes into available climate and coupled stratosphere/climate models.
- Clarify the interpretation of solar proxy data.
- Improve models of solar irradiance, including coupling to the solar dynamo, for long-term studies and more reliable long-term predictions.
- Quantify the influence of solar-driven stratospheric ozone variations on climate change.

*Objective:* Identify and quantify the changes in ozone distribution attributable to variations in the solar output of electromagnetic radiation and energetic particles.

*Priorities:*

- Develop the ability to separate atmospheric processes, such as volcanic eruptions and man-made influences, from solar cycle-driven changes in stratospheric ozone.
- Quantify the effects of solar-driven changes in the thermosphere and mesosphere on the stratosphere.
- Incorporate effects of solar variability in coupled upper atmosphere/lower atmosphere models.

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

*Objective 1:* Develop accurate specification models of the Earth's radiation environment from tens of eV to GeV energies on timescales from seconds to decades.

*Objective 2:* Create scientific understanding needed to model the physical processes responsible for the acceleration, transport and loss of radiation belt particles throughout the magnetosphere.

*Priorities:*

- Create accurate empirical radiation-belt specification models.
- Create new understanding and physics-based models of particle injection, acceleration, transport and loss that include the solar wind-magnetosphere interaction.
- Create next-generation magnetospheric electric and magnetic field models that include the inner magnetosphere.

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

*Objective:* Predict the effects of space weather on the global behavior of ionospheric density in the altitude range from 100 to 1000 km.

*Priorities:*

- Develop a dynamic thermosphere-ionosphere model.
- Develop the capability to specify low and mid-latitude electric fields.

*Objective 1:* Determine the effects of long and short-term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe these effects with accuracy better than 5%.

*Objective 2:* Understand and predict satellite drag variations during geomagnetic storms and during the solar activity cycle.

July 7, 2014

*Priorities:*

- Develop accurate empirical neutral wind models.
- Develop more advanced thermosphere density and composition models

**APPENDIX B -- HQ SUMMARY OF FSTs AND STRATEGIC CAPABILITY  
TEAMS**



# LWS Focus Topics



2004	2005	2006	2007	2008	2009	2010*
Solar origins of the plasma and magnetic flux of observed ICMEs	Shock acceleration of SEPs by interplanetary CMEs	Predict emergence of solar active regions before visible	Magnetic Connection of Photosphere and Low Corona	Properties of the Solar Dynamo that affect Irradiance and Active Regions	Behavior of the Plasmasphere and its Influence on the Iono-/Magnetosphere	Low- To Mid-Latitude Ionospheric Irregularities and Turbulence
Topology and impact of the magnetic field through the photosphere, corona and heliosp.	Mechanism for solar wind heating and acceleration	Understand how flares accelerate particles near the Sun and contribution to large SEP events	Modulation of Galactic Cosmic Rays,... due to Long-term Solar Activity	Use Inner Heliosphere Obs. to Better Constrain CME and SEP Models	Origin and Nature of the Slow Solar Wind, and its effect on Helio Structures, and SEP Transport	Incorporating Plasma Waves in Models of the Radiation Belts and Ring Current
Origin of solar-energetic particles at the sun and inner heliosphere	Solar wind plasma entry and transport in the magnetosphere	Plasma redistribution during storms in the ITM system	Daily Variability in the Thermosphere and Ionosphere	Integrate Non-MHD/Kinetic Effects into Global Models	Predict the Onset and Space Weather Impacts of Fast CMEs/Eruptive Flares	Factors that Control the Highly Variable Intensity and Evolution of Solar Particle Events
Formation and loss of new radiation belts in the slot region .....	Storm effects on global electrodynamics of the middle & low latitude ionosphere	Middle and low latitude sources, effects, and dist of large electron density gradients	Combined Modeling of Loss, Accel, and Transport of Mag Electrons, Protons	ITM Comp. and Temp due to Solar XUV and Energetic Particle Variation	Plasma-Neutral Gas Coupling	Jets in the Solar Atmosphere and their Effects in the Heliosphere
Thermosphere composition and due to Solar and high Lat forcing	Abundance of greenhouse gases and dynamics of Upper Atmsph	Solar origins of irradiance variations	Prediction of the Interplanetary Magnetic Field Vector Bz at L1		The Sun-Climate Strategic Theme	Science Analysis for the Solar Dynamics Observatory (SDO)
Global, regional climate sensitivity to solar forcing			Extreme Space Weather Events in the Solar Sys/			The Sun-Climate Strategic Theme

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# LWS Focus Topics



2004	2005	2006	2007	2008	2009	2010*
Solar origins of the plasma and magnetic flux of observed ICMEs	Shock acceleration of SEPs by interplanetary CMEs	Predict emergence of solar active regions before visible	Magnetic Connection of Photosphere and Low Corona	Properties of the Solar Dynamo that affect Irradiance and Active Regions	Behavior of the Plasmasphere and its influence on the Iono-/Magnetosphere	Low- To Mid-Latitude Ionospheric Irregularities and Turbulence
Topology and impact of the magnetic field through the photosphere, corona and heliosp.	Mechanism for solar wind heating and acceleration	Understand how flares accelerate particles near the Sun and contribution to large SEP events	Modulation of Galactic Cosmic Rays,... due to Long-term Solar Activity	Use Inner Heliosphere Obs. to Better Constrain CME and SEP Models	Origin and Nature of the Slow Solar Wind, and its effect on Helio Structures, and SEP Transport	Incorporating Plasma Waves in Models of the Radiation Belts and Ring Current
Origin of solar-energetic particles at the sun and inner heliosphere	Solar wind plasma entry and transport in the magnetosphere	Plasma redistribution during storms in the ITM system	Daily Variability in the Thermosphere and Ionosphere	Integrate Non-MHD/Kinetic Effects into Global Models	Predict the Onset and Space Weather Impacts of Fast CMEs/Eruptive Flares	Factors that Control the Highly Variable Intensity and Evolution of Solar Particle Events
Formation and loss of new radiation belts in the slot region .....	Storm effects on global electrodynamics of the middle and low latitude ionosphere	Middle and low latitude sources, effects, and distribution of large electron density gradients	Combined Modelling of Loss, Accel, and Transport of Magnetospheric Electrons, Protons	Response of ITM Comp and Temp due to Solar XUV and Energetic Particle Variation	Plasma-Neutral Gas Coupling	Jets in the Solar Atmosphere and their Effects in the Heliosphere
Thermosphere composition and due to Solar and high Lat forcing	Abundance of greenhouse gases and dynamics of Upper Atmsph	Solar origins of irradiance variations	Prediction of the Interplanetary Magnetic Field Vector Bz at L1		The Sun-Climate Strategic Theme	Science Analysis for the Solar Dynamics Observatory (SDO)
Global, regional climate sensitivity to solar forcing			Extreme Space Weather Events in the Solar Sys/			The Sun-Climate Strategic Theme

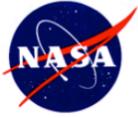
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# LWS Focus Topics (Updated)



2006	2007	2008	2009	2010	2011
Predict emergence of solar active regions before visible	Magnetic Connection of <b>Photosphere and Low Corona</b>	Properties of the <b>Solar Dynamo</b> that affect Irradiance and Active Regions	Behavior of the <b>Plasmasphere</b> and its Influence on the <b>iono-/Magnetosphere</b>	<b>Jets in the Solar Atmosphere</b> and their Effects in the <b>Heliosphere</b>	Interaction between the magnetotail and the inner magnetosphere and the impact of that interaction on the radiation belt environment
Understand how <b>flares</b> accelerate particles near the Sun and contribution to large <b>SEP events</b>	Modulation of Galactic Cosmic Rays, ... due to <b>Long-term Solar Activity</b>	Use Inner Heliosphere Obs. to Better Constrain CME and SEP Models	Origin and Nature of the Slow Solar Wind, and its effect on Helio Structures, and SEP Transport	Factors that Control the Highly Variable Intensity and Evolution of <b>Solar Particle Events</b>	Atmosphere-Ionosphere Coupling During Stratospheric Sudden Warmings
Plasma redistribution during storms in the <b>ITM</b> system	Daily Variability in the Thermosphere and Ionosphere	Integrate Non-MHD/Kinetic Effects into Global Models	Predict the Onset and Space Weather Impacts of Fast CMEs/Eruptive Flares	Incorporating Plasma Waves in Models of the <b>Radiation Belts</b> and Ring Current	Flare Dynamics in the Lower Solar Atmosphere
Middle and low latitude sources, effects, and distribution of large electron density gradients	Combined Modelling of Loss, Acceleration, and Transport of Magnetospheric Electrons, Protons	Response of ITM Composition and Temperature due to Solar XUV and Energetic Particle Variation	<b>Plasma-Neutral Gas Coupling</b>	Low-To Mid-Latitude <b>Ionospheric Irregularities and Turbulence</b>	
<b>Solar origins of irradiance variations</b>	Prediction of the Interplanetary Magnetic Field Vector Bz at L1		<b>The Sun-Climate Strategic Theme</b>	<b>The Sun-Climate Strategic Theme</b>  Steering C	<b>The Sun-Climate Strategic Theme</b>



# LWS Strategic Capabilities



2005	2006	2008
<p><b>Earth – Moon – Mars Radiation Model</b>                      PI: Nathan Schwadron (now UNH)</p> <p>A comprehensive model capable of predicting radiation exposure anywhere on the surface or in the atmosphere of Earth, on the Moon, on Mars, and in interplanetary space between Earth and Mars. The model will provide deliverables of use to mission planners and space system designers for space exploration missions.</p>		<p><b>Physical modeling of the radiative Sun-Earth connection</b>                      PI: John Fontenla/University of Colorado</p> <p>Capability Description: A model of the solar spectral irradiance and its variability from 1 to 2500 nm based on solar imagery and/or wavelength proxies, to inform and provide inputs to climate studies</p>
<p><b>Time-Dependent 3D Model for the Corona and Ambient Solar Wind</b>                      PI: Tamas Gombosi / University of Michigan</p> <p>3D time-dependent model that provides the structure and properties of the slowly varying corona and the ambient solar wind.</p> <p>A 3D quantitative description of the structure and properties of the large scale corona and heliosphere at any given instant in time.</p>	<p><b>3D Model of an Active Region Coronal Magnetic Field</b>                      PI: Peter Macneice (now GSFC)</p> <p>A quantitative 3D model for the slowly evolving magnetic field of a complex active region. This topic was chosen to reflect the fact that in the next five years we will have high resolution, high cadence solar observations from unique vantage points in the heliosphere such as STEREO, Solar-B, and SDO for assimilation into models. As observations from other new missions become available we will be concentrating on those strategic areas.</p>	<p><b>Integrated Model of the Atmosphere-Ionosphere System</b>                      PI: Rolando Garcia/NCAR</p> <p>Develop an integrated model of atmospheric dynamics, composition, chemistry, radiation, and plasma properties, from the Earth's surface to the top of the thermosphere/ionosphere.</p>
<p><b>A Comprehensive Magnetosphere-Ionosphere Model</b>                      PI: Aaron Ridley / University of Michigan</p> <p>A comprehensive, coupled, quantitative 3D model that predicts plasma and magnetic field conditions for both inner and outer magnetosphere, including the plasmasphere, ring current, and radiation belts, and the ionosphere, including polar regions.</p>		<p style="text-align: right;"><b>Steering Committee Meeting 2010</b></p>

**APPENDIX C -- COMMUNITY SURVEY OF TR&T PIs**

(organized by Chris StCyr)

# TR&T Feedback

- **Four questions developed; website activated**
  - **Website solicited free-form responses**
- **Email from Sandra Bembry on May 16, 2012, sent to 152 TR&T awardees**
- **39 responses by July 24, 2012 [39/152 = 26%]**
  - 28 identified
  - 11 anonymous
- **Discipline**
  - 13 Geospace
  - 18 Solar-Helio
  - 8 blank

# TR&T Feedback

- **Questions**
  - **[Q1] In your opinion, did the FST team activity enhance your ability to meet the objectives of your individual proposal?**
  - **[Q2] In your opinion, did the FST team concept aid in the creation of an interdisciplinary science community that would not otherwise have reason to collaborate?**
  - **[Q3] In your opinion, did the FST team lead to advancement of science beyond what was in the individual proposals?**

	<b>[Q1]</b>		<b>[Q2]</b>		<b>[Q3]</b>	
Yes/Probably	31	79%	29	74%	26	67%
Limited/Partial/Maybe	3	8%	1	3%	6	15%
No/Don't Know	4	10%	7	18%	6	15%
Blank/No Comment	1	3%	2	5%	1	3%
<b>Total</b>	<b>39</b>		<b>39</b>		<b>39</b>	

# TR&T Feedback

- **Question 4 -- Any additional comments on the FST team concept? Please include suggestions, if any, on how implementation of the FST concept could be improved.**
  - **Overwhelmingly constructive suggestions -- Very little negative input**
  - **Repeated Themes [39 responses]:**
    - **Collaboration as a positive [13] [2]**
    - **Re-propose (re-align) on new joint topic [6]**
    - **Importance of Team Leader [4]**
    - **Duration 4 years versus 3 years [2]**
    - **Travel burden [2]**

# TR&T Feedback

- ...Consider having a "quiet Year 1" in which selected proposals receive a few \$K of travel money and perhaps a small amount of salary effort. They spend the first year figuring out what they will do as a Team in Years 2-4.
- ...collaborative-proposals that are submitted to a single topic -- these represent something between individual awards and strategic capability...kind of a mini-strategic-capability, depending on how many proposers pre-coordinated before submitting. That actually increases the likelihood that at least some of the awardees will work together as a "team".
- It would be better to let people constitute their own interdisciplinary teams and let them propose for a whole focus group
- ...if the team leader agrees that this is a better use of the researchers time, then the researcher should be allowed to change the official statement of work for the grant...
- If the FST team (during their team work activity) come up with a well advanced and potential joint work objective, which may not be included in any of the individual proposals, it would be nice if the LWS design a program that can provide additional support for such joint work as it substantially advance the science
- ...very important that after the selection the FST teams organize a meeting and prepare a joint proposal for coordinated research (based on the individual proposals), and then report on the progress in the annual FST reports. I think that this will substantially improve the effectiveness of the FST concept
- ...subsequent to selection, request them to work collaboratively. Perhaps an alternative approach could be tested where subsequent to selection, all the teams under one theme are asked to re-align their proposal into one integrated proposal (before individual funding is released) in a way such that a more grass-root level collaboration is ensured from day one. This could be achieved e.g., through a team meeting even before work begins on the proposal.

**APPENDIX D -- SUBGROUP 1: SOLAR PARTICULATE AND RADIATIVE ENVIRONMENT**

## Assessment of the Progress of the LWS Targeted Research and Technology (TR&T) Program on Achieving Strategic Goal 1:

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

**W. Abbett (UCB)**  
**S. Antiochos (GSFC, Goal 1 Study Lead)**  
**J. Kasper (CFA)**  
**G. Mason (APL)**  
**P. Riley (PSI)**  
**N. Schwadron (UNH)**  
**C. St.Cyr (GSFC)**

### 1. Introduction

Unlike the atmosphere that we live in, which is so dense that matter and radiation are tightly coupled, the highly tenuous space environment of the Earth, the planets, and the solar system consists of a collection of distinct but co-spatial and only weakly interacting streams of matter and radiation. Predicting the space environment, therefore, requires understanding the origins of each of these particulate and radiative streams, which is usually, but not always at the Sun, and understanding their propagation to Earth and throughout the heliosphere.

Due to its intrinsic multi-component nature, this space environment exhibits spatial and temporal variations at all scales, but for understanding and predicting the important space weather effects only a limited number of components and their characteristic scales dominate. The largest scale variations result from the solar rotation  $\sim 27$  days, and the global distribution of magnetic flux on the Sun's disk. These give rise to three primary components of our space environment:

- **The fast solar wind**
- **The slow solar wind**
- **The solar UV – X-Ray luminosity**

The three phenomena listed above can be considered as defining the background plasma, magnetic field, and radiation environment through which disturbances propagate. The most important disturbances are due to the giant magnetic explosions at the Sun known as coronal mass ejections (CME) / solar flares. These events are the largest releases of energy in the solar system and drive three major transient components of our space environment, listed below, with time scales  $\sim 10$  hours to days at Earth:

- **Interplanetary CMEs/magnetic clouds**
- **Gradual Solar Energetic Particle (SEP) Events**
- **Flare UV – X-Ray radiation**

On even shorter time scales ~ *an hour or less*, large amplitude waves are driven by the interactions of the CME, fast and slow wind components, and bursts of high-energy radiation are driven by the impulsive particle acceleration during solar flares. These give rise to the fastest transient components of our space environment:

- **Interplanetary shocks**
- **Impulsive SEP events**
- **Flare hard X-ray bursts**

The nine space-environment components listed above and divided according to their characteristic time scales lead to most of the important space weather phenomena at Earth and in the heliosphere. One point that should be clarified is that the characteristic times given above are definitely not the only time scales inherent to each phenomenon. Even the fast wind, which is the most steady of the nine phenomena, exhibits structure at all scales due to the presence of turbulence in the wind.

In order to predict these nine space environment phenomena, we must be able to observe their origins. This is the goal of the LWS missions such as SDO and Solar Probe Plus. But, in addition, we must be able to model them accurately, which requires a deep understanding of the physical processes underlying the phenomena. Of course, each phenomenon generally involves a long chain of physical processes, but many of the processes, such as the generation of optically-thin radiation from a thermal plasma or the production of X-Rays by Bremsstrahlung from a particle beam, are quite well understood.

Among the physical processes that we do not yet understand, five stand out as the major obstacles to accurate first-principles modeling of the space environment phenomena above:

- **Heating and mass acceleration of the quasi-steady corona and winds**
- **Explosive acceleration of CME plasma and magnetic field**
- **Shock formation and propagation**
- **Particle acceleration at shocks**
- **Fast magnetic reconnection in flares and its various channels of energy release, especially into energetic particles**

## 2. Decadal Progress toward Goal 1

### 2.1 Focus Science Topic (FST) investment in Goal 1

The TR&T Program has done a thorough job over the past decade in devoting resources to the space environment phenomena and processes discussed above. All of the phenomena have been included as important research subjects of one or more Focus Science Topic (FST) Team, and all, but one of the phenomena have been the actual Focus of, at least, one FST. Although the FSTs are generally defined according to space environment phenomena, every FST has at its core, the study of one or more of the physical processes listed above. Progress on any of the FSTs is not possible without progress on understanding the underlying physical processes.

We list below the correspondence between FSTs and space environment phenomenon.

- Fast wind –** Focus: *Mechanism for solar wind ... 2004*  
Also: *Topology and impact of the magnetic field ... 2004*
- Slow wind –** Focus: *Origin and nature of the slow solar wind ... 2009*  
Also: *Topology and impact of the magnetic field ... 2004*
- UV – X-Ray –** Focus: *Solar origins of irradiance variations ... 2006*  
Also: *Jets in the solar atmosphere ... 2010*  
*Predict emergence of active regions ... 2006*
- ICMEs –** Focus: *Solar origins of the plasma and flux of ICMEs ... 2004*  
Focus: *Predict the onset and space weather impact ... 2009*  
Also: *Use inner helio obs. to better constrain ... 2008*  
*Magnetic connection of photosphere and low corona 2007*
- Gradual SEPs –** Focus: *Shock accelerations of SEPs ... 2005*  
Focus: *Understand how flares accelerate particles ... 2006*  
Also: *Origin of energetic particles at the Sun ... 2004*  
*Factors that control the highly variable ... 2010*  
*Use inner helio obs. to better constrain ... 2008*
- Flare UV – X-Ray –** Focus: *Flare dynamics in the lower ... 2011*
- Interplanetary shocks –** Also: *Predict the onset and space weather impact ... 2009*
- Impulsive SEPs –** Also: *Origin and nature of the slow solar wind ... 2009*  
Also: *Origin of energetic particles at the Sun ... 2004*
- Flare hard X-Ray –** Focus: *Flare dynamics in the lower ... 2011*

In addition to FSTs that address one or more of the nine space environment phenomena, three FSTs have addressed important aspects of space weather prediction and modeling that cut across many phenomena:

*Prediction of interplanetary Bz at L 2007*

*Extreme space weather events ... 2007*

*Integrate kinetic effects into global models 2008*

As emphasized above, progress on any of the topics of these FSTs inherently requires progress on understanding the five physical processes. In fact, some FSTs, such as the “*Origin and nature of the slow solar wind ... 2009*”, involves study of all five processes. Furthermore, these five processes are critical not just to the FSTs dealing with Goal 1, but to all the FSTs dealing with all four strategic goals of the TR&T Program. Consequently, we structure the discussion in this chapter in terms of the relevant phenomena rather than the processes.

## **2.2 Strategic Capability (SC) investment in Goal 1**

The FSTs are expressly designed to deliver the understanding required for accomplishing Goal 1, but to achieve true success; the TR&T must also deliver the required modeling. This is the purpose of the Strategic Capability (SC) element of the TR&T.

As with the FSTs, the TR&T Program has devoted substantial resources in the SC element to modeling the space environment phenomena above. Most of the effort has been concentrated on the first three long-time-scale phenomena, because these define the background that is required for modeling all space weather phenomena. Accurate modeling of ICME geoeffectiveness, for example, necessarily requires accurate models for the wind through which the ICME propagates.

We list below the correspondence between SCs and the space environment phenomena:

**Both fast and slow winds** – 3D heliosphere model (two separate SCs) 2005

**Both gradual and impulsive SEPs** – earth-moon-mars radiation model 2005

**UV-X-Ray luminosity** – Active region magnetic field model (addresses key requirement for modeling phenomenon) 2006

## **2.3 Other TR&T investments in Goal 1**

In addition to the FSTs and SCs, the TR&T Program includes other elements that either directly or tangentially have produced advances in achieving Goal 1. These include the *Independent Investigations* and the *Tools and Methods* elements of the Program. Both these elements have funded individual PI studies that focused directly on one or more of the

phenomena of Goal 1. Since these investigations are so limited in scope due to their size, they have tended to produce incremental (but valuable) advances similar to those delivered by the non-TR&T programs, such as the SR&T and GI. The truly unique and distinguishing features of the TR&T are the FSTs and SCs. Therefore, we will not consider the impact of the *Independent Investigations* and *Tools and Methods* elements in this Assessment.

The other element of the TR&T that has had important impact on Goal 1 is the *Infrastructure Building* element. This element includes a variety of programs, such as support for focused meetings and workshops, the Heliophysics Summer School and textbooks, and the LWS Postdoctoral Fellow program. As its name implies, this element generally does not support directly science advances toward Goal 1, but the element is essential for developing the science personnel that will eventually achieve Goal 1. In particular, the Heliophysics Summer School and textbooks have proved vital to training a next-generation research community that has the knowledge and skills to attack successfully the required system science. Since the Infrastructure Building element does cut across all the LWS Goals, we will not discuss this element further in this chapter, except to encourage strongly its continued support.

### 3. Status and Progress in achieving Goal 1

In this Section we describe the progress during the last decade in understanding each of the phenomena relevant to Goal 1. Note that much of the discussion is based on the recent NRC Decadal Survey, which performed the authoritative study of the progress in Heliophysics during the previous decade.

Given their very close physical connection we have grouped both the slow and fast solar winds into one Section, the impulsive and gradual SEPs into another, and the coronal and flare UV – X-ray emission into a third. Furthermore, we do not include a separate Section on flare hard X-ray emission, because this form of radiation is not believed to have important space weather consequences directly. The actual energy in hard X-ray emission,  $> 30$  keV, is small compared to that in other forms of flare energy. However, this emission is extremely important for understanding electron acceleration in flares, which then leads to the flare UV - X-ray radiation, and for understanding flare SEP production. Both these latter forms of flare energy are discussed in depth.

#### 3.1 Progress on Understanding the Solar Wind

Developing robust models for how the heliospheric magnetic field and plasma connect to the Sun's corona and photosphere is a central requirement for achieving the LWS Goal 1 above. For much of the heliosphere, this connection appears to be clearly established. It is now generally accepted that so-called coronal holes, which appear dark in X-rays and are predominantly unipolar at the photosphere, are the sources of quasi-steady wind that exhibits a fairly constant velocity and plasma composition, and is generally fast ( $> 500$  km/s). However, the connection to the Sun of the slow ( $< 500$  km/s) non-steady wind is far from understood and has long been a major problem in Heliophysics. The slow wind is especially important to LWS, because it is frequently found near the ecliptic plane and, therefore, is the wind that encompasses the Earth and other planets.

The past decade has seen great progress in understanding both the properties of the slow wind and its sources at the Sun. This progress has been due to advances in observations and measurements from NASA missions and to theory and modeling, which in large part has been supported by the TR&T program.

From in situ composition measurements, it has now been firmly established that the physical properties distinguishing the slow wind from the fast are not wind speed, but ionic composition and temporal variability. The slow wind exhibits an elemental composition and a charge state composition that is clearly different than those of the fast. Furthermore, the temporal variability of the composition is distinctly different than that of the fast. This work benefitted greatly from the 2004 FST on the “Topology and impact of the magnetic field ...”

From remote sensing observations it has also been firmly established that so-called pseudostreamers are playing a critical role in the origins of the slow wind. These structures were originally discovered by Skylab, and at that time were termed “plasma sheets”, but their

significance was not recognized until recently. In coronagraph images, pseudostreamers appear similar to the usual streamers that extend out to form the heliospheric current sheet, except that the field does not change sign across a pseudostreamer, and the field becomes open at lower radii than is usual for streamers. This work also benefitted from the 2004 FST, and substantial progress on understanding exactly how pseudostreamers lead to the slow wind is being made in the 2009 FST on the slow wind.

On the theoretical front, the observations have inspired detailed work on how Alfvén wave heating and acceleration in flux tubes with varying geometry can produce non-steady slow wind, similar to what is observed. This work is now being pursued in the 2009 FST. Furthermore, the data, especially the compositions results have led to a new theory for the source of the slow wind, the so-called S-Web model. In fact, this model was strongly influenced by a desire to understand the basic features and predictions of the Fisk model of large-scale reconfiguration of the coronal magnetic field through "interchange reconnection," and was developed directly as a result of the 2004 FST. The S-Web is now being studied by the 2009 FST as well as by the community, in general.

A further advance that may not have occurred without the strong team component of the 2009 FST concerns the interaction between the MHD modeling and SEP components of the team. In particular, the team realized that a number of unresolved properties related to energetic particles observed at Earth and the STEREO spacecraft could be explained by the topological nature of the heliospheric magnetic field and its connection to the solar corona. For example, how could an apparently isolated flare lead to such a wide longitudinal distribution of energetic particles in interplanetary space? It turns out that one of the key features of the "S-Web" model is that widely separated locations in the heliosphere can map back to nearly adjacent regions in the solar corona.

In addition to the work on the sources of the slow wind, there have been substantial advances on understanding the fundamental heating and acceleration of the quasi-steady fast wind, in large part due to the work of the 2004 FST on the mechanisms for solar wind acceleration. A consensus has developed among solar wind theorists that the basic process involves a non-linear cascade of Alfvén wave energy flowing up from below, but the basic dissipation process is still under debate.

The numerical models for the quasi-steady solar wind have also made enormous progress in accuracy and sophistication during the past decade, due primarily to the two 2005 SCs on the 3D Corona – Wind model. Two 3D MHD models have been delivered to the CCMC and are now being used widely to calculate the 3D structure of the full heliosphere. These models are especially important to missions such as STEREO and MESSENGER and all the MARS missions that are making observations far from the Sun – Earth line.

In addition to progress on the origins of the fast and slow winds, there have been major advances during the previous decade on the properties of the wind in the heliosphere. As described in the SH Panel Report of the 2012 Heliophysics Decadal Survey, an unexpected

discovery has been the observation of ubiquitous reconnection events in the solar wind, often on a very large scale of  $\sim 1$  million kilometers. These reconnection events are observed to possess the characteristic outflows of plasma and magnetic field that are expected for quasi-steady reconnection, as in the well-known Petschek model, but for some reason, they do not appear to be effective at accelerating non-thermal particles. It seems unlikely, therefore, that the heliospheric reconnection events have important space weather consequences and so they have not been the focus of an FST. They may, however, prove to be very useful for investigating the basic properties of fast reconnection, which is one of the key processes, listed above.

Another important discovery in the solar wind has been the observation of clearly defined upper and lower boundaries on the temperature anisotropy of heliospheric protons and other ions. These boundary curves provide unique insights on the kinetic processes that heat solar wind ions and that determine their distribution functions. There is growing consensus that the anisotropy is controlled by wave-particle interactions. In the MHD approach, anisotropy can give rise to the mirror and firehose instabilities. Kinetic effects due to ion Larmor radius effects modify these MHD instabilities into the kinetic mirror and oblique firehose instabilities. The work of the 2008 FST on integrating kinetic effects into global models has been definitive in concluding that the anisotropy bounds are due to the kinetic mirror and oblique firehose instabilities.

In summary, progress on understanding the origins and propagation of the solar wind has been substantial during the past decade and has benefitted enormously from the FST and SC programs.

### **3.2 Progress on Understanding the CME – ICME Connection**

In the past decade there has been great progress in observing and modeling CMEs, shocks, and SEPs from solar eruptions. SOHO/STEREO/SDO observations of the initiation, propagation, and subsequent evolution of CMEs into interplanetary space have provided the means by which to compare theory and modeling advances. Uncertainties in forecasting CME Earth-arrival times have been reduced from  $\pm 12$  hours to  $\pm 3$  hours by using STEREO observations more than 1 day in advance.

The success of simulations in reproducing many of these observations testifies to the maturity of scientific understanding of these space weather events. However, even though it is now possible to predict where on the Sun a CME will originate, it is not yet possible to predict its timing, speed, energy, or momentum, nor is there a good scientific understanding of how a CME converts so much of its energy into particle radiation. In the words of the Decadal Survey: These issues present us with a third challenge: SH3. Determine how magnetic energy is stored and explosively released and how the resultant disturbances propagate through the heliosphere.

A number of LWS TR&T FST's have attacked various aspects of these specific problems. The combination of observations and modeling have led to significant improvements in predicting the arrival time of interplanetary shocks and CMEs at Earth, but the ability to predict other geo-effective properties (particularly, the direction and magnitude of  $B_z$ ) remains a challenge. Validation for inner heliosphere models, SEP generation and transport mechanisms, as well as new strategies for observations are needed to take advantage of the novel space assets that will be available later this decade with LWS-funded Solar Orbiter and Solar Probe Plus.

#### RELEVANT FST's

2004: Solar origins of plasma and magnetic flux in an ICME

2007: Prediction of the Interplanetary Magnetic Field Vector  $B_z$  at L1

2008: Use Inner Heliospheric Observations to Better Constrain Coronal Mass Ejection (CME) and Solar Energetic Particle (SEP) Event Models

2009: Predict the Onset and Space Weather Impacts of Fast CMEs/Eruptive Flares

### 3.3 Progress in Understanding Solar Energetic Particles

New observations of solar energetic particles (SEPs) yielded a number of surprises. Solar-cycle 23 produced sixteen ground-level events in ground-based neutron monitors, which allowed us to establish that most large SEP events have a recent, preceding CME from the same active region. This indicates that the most intense events may involve the acceleration of particles in one or more flares that produce a seed population of energetic ions that can then reach very high energy through classical "diffusive shock acceleration" at the CME driven shock. The measured enrichments by ACE of  $^3\text{He}$  and Fe in many large SEP events are consistent with this picture. Continuing observations from STEREO, ACE and other platforms as well as upcoming Solar Orbiter and Solar Probe Plus missions will provide key measurements in the source regions of these events and their spatial extent and evolution so that the complex dynamics of SEP acceleration and transport to the geospace environment can be unraveled. (Decadal Study page 2-7)

The most common SEP events, with 104 events/year near solar maximum, are small "impulsive" events associated with coronal jets that are enriched in  $^3\text{He}$  and heavy ions up to  $Z \approx 80$  by amounts that depend on mass:charge ratios. ACE and SOHO observations indicate substantially higher Fe charge states than ambient values, most likely because of electron stripping during acceleration in the low corona.  $^3\text{He}$  and Fe are also enriched in many large SEP events; this indicates that remnant suprathermal particles from previous impulsive flares are an important source of seed particles for CME-shock acceleration. (Decadal study page 10-18)

Several LWS FSTs were targeted to study the mechanisms responsible for these newly observed SEP features. One compared simulation results obtained from coupling two distinct SEP models with the MHD CME model outputs with SEP particle time-intensity profiles and energy spectra observed at ACE. The results were promising and reasonable for understanding the physics of shock acceleration in the inner heliosphere. Another compared the energy content of the SEPs with the energy content of the associated CMEs and found that

the acceleration efficiency was could reach surprisingly high values of 10-20%. Another team studied the mixing of particles accelerated in flare loops with the population seed in interplanetary space and showed that the often observed enrichment of Fe in SEP onsets was most usually due to interplanetary transport effects. The widely varying intensity of SEPs associated with interplanetary shocks was found to be often related to prior passage of CMEs which had the effect of raising interplanetary turbulence levels and seed populations. While no teams focused on impulsive events by themselves, they frequent occurrence was used to trace active region sources of solar wind observed at 1 AU.

2004	Mihir Desai	Solar-energetic particles origin at the sun and inner heliosphere
2005	Martin Lee	Shock acceleration of SEPs by interplanetary CMEs
2006	Glenn Mason	Flares Particle Acceleration Near the Sun and Contribution to Large SEP Events
2008	O.C. St. Cyr	Use Inner Heliospheric Observations to Better Constrain Coronal Mass Ejection (CME) and Solar Energetic Particle (SEP) Event Models
2009	Thomas Zurbrucken	Origin and Nature of the Slow Solar Wind, Associated Interplanetary Structures, and SEP Transport
2010	Nat Gopalswamy	Factors that Control the Highly Variable Intensity and Evolution of Solar Particle Events

### 3.4 Progress in Understanding Shocks in the Corona and Interplanetary Medium

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

Understanding large solar energetic particle (SEP) events is central to space weather and space climate. Large SEP events observed at Earth are accelerated near the Sun and in the heliosphere by shocks associated with interplanetary CMEs (ICMEs). However, direct comparisons between observations, models, and theories have been scarce. The FSTs have culminated into studies of shock acceleration of energetic-particles, their propagation, and the evolution of CMEs in the heliosphere. One of the critical aspects developed in these studies is

the importance of self-consistent wave generation upstream of CME-driven shocks, which is critical for preventing energetic particles from leaving the acceleration region near the shock. Indeed, the conditions of generating strong wave enhancements may be one of the most critical factors that differentiates large, prompt SEP events from lower energy, less dangerous events.

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

The acceleration profiles of CMEs below  $\sim 5 R_s$  are found to be closely synchronized with flare-Hard-X-ray energy releases. CME expansion creates a flare current sheet, where reconnection drives particle acceleration. The shocks produced by fast CMEs can now be identified in coronagraph images and other remote observations.

Solar-cycle 23 produced  $\sim 100$  large SEP events, including the largest Ground-Level Event (observed by neutron monitors) since 1956. SEP composition and spectral variations depend on ionic charge/mass ratios, likely due to interactions with excited waves and variable shock geometry.

The most common SEP events are small Impulsive events, associated with coronal jets that are enriched in  $^3\text{He}$  and heavy ions up to  $Z \approx 80$  by amounts dependent on mass-to-charge ratios.  $^3\text{He}$  and Fe are also enriched in many large SEP events, indicating remnant suprathermal-particles from previous impulsive flares are an important source of seed particles for CME-shock acceleration.

In reviewing the FSTs since 2004, there are several that address the *effects* of Shocks in the corona and interplanetary medium:

- [Solar-energetic particles origin at the sun and inner heliosphere](#) (2004; Team Lead: Mihir Desai; Members: Jozsef Kota, Gang Li, Yuri Litvinenko, Igor Sokolov, and Allan Tylka)
- [Shock acceleration of SEPs by interplanetary CMEs](#) (2005; Team Lead: Marty Lee; Members: Christina Cohen, Jakobus Le Roux, Richard Mewaldt, Ilia Roussev, Tycho von Rosenvinge, Angelos Vourlidas)

- Use Inner Heliospheric Observations to Better Constrain Coronal Mass Ejection (CME) and Solar Energetic Particle (SEP) Event Models (2008; Team Lead: Chris St Cyr; Team: Chee Ng, Curt de Koning, Neil Shelley, Jakobus le Roux, Ward Manchester)
- Predict the Onset and Space Weather Impacts of Fast CMEs/Eruptive Flares (2009; Team Lead: Mark Linton; Members: Zoran Mikic, Peter Schuck, Alysha Reinhard)
- Factors that Control the Highly Variable Intensity and Evolution of Solar Particle Events (2010; Team Lead: Nat Gopalswamy; Members: Len Fisk, David Lario, Marty Lee, Richard Mewaldt, Tycho von Roseninge)

### 3.4.1 Open Questions

Key questions remain about the how variable conditions and shocks near the Sun lead to variability in SEPs. *Why does SEP acceleration-efficiency vary so greatly from event-to-event, and how do preceding CMEs apparently improve acceleration efficiency?*

Observational studies show that ~10% of the CME kinetic energy often goes into accelerated particles. Uncertainties arise from limited knowledge of CME geometries and single-point sampling of particle intensities. *Multi-point observations of SEP events may indicate broad longitudinal SEP distributions that may be related to shock formation and structure.*

Observations indicate that the flare energy-release/particle-acceleration region is located high above the flare X-ray loops. The acceleration of fast CMEs is synchronized to the flare energy release, suggesting that magnetic reconnection in the current sheet behind the CME both generates the flare and accelerates the CME. The CME-driven shock then accelerates SEPs. However, because of uncertainties concerning the coronal environment, it is unclear where a shock forms. The Alfvén speed and fast magnetosonic speed is very high low in the corona and complex due to its dependence on coronal field and plasma structure. Further, it is unclear how compressions low in the corona instead of shocks contribute to particle acceleration.

### 3.5 Progress in Understanding Solar UV – X-Ray Radiation

Integral to achieving Goals 1 are the FSTs dedicated to understanding the variance and physical origins of the Sun's UV and X-ray emission over a broad range of spatial and temporal scales. This includes understanding both localized UV and X-ray emission during flares as well as global irradiance variations associated with active region magnetic fields. The following five FSTs funded over the past decade that are relevant to Goal 1 include (in chronological order): (1) "The Solar Origins of Irradiance Variations (2006)," (2) "Predict Emergence of Solar Active Regions Before they are Visible (2006)," (3) Exploring the Magnetic Connection Between the Photosphere and Corona (2007), (4) "Measuring the Properties of the Solar Dynamo that Affect Solar Irradiance and Active Region Generation (2008)," (5) "Jets in the Solar Atmosphere and their Effects in the Heliosphere (2010)," and most recently (6) "Flare Dynamics in the Lower Solar Atmosphere."

Our objective here is not to perform an exhaustive review of the scientific results to date of each of the teams dedicated to the above FSTs. Instead, we will assess how the team concept

itself has contributed to the success of two representative groups who have made contributions to the science relevant to Goals 1 and 2. Here, we choose to focus on two teams formed prior to 2008, since the collaborative research of teams associated with more recent FSTs may still be ongoing and cannot be fully evaluated until the projects are complete.

Of direct relevance to Goal 1 is the 2006 team dedicated to the FST "Solar Origins of Irradiance Variations." The team made substantial progress toward the FST goal of understanding physical mechanisms that cause variations in solar UV, EUV, and soft X-ray emission. They used models of varying degrees of sophistication to synthesize radiative output of the chromosphere, transition region, and corona over a variety of spatial scales. These theoretical investigations were carried out in conjunction with observational studies to advance our understanding of the nature of the heating, and its dependence on observable quantities (such as total unsigned magnetic flux at the solar photosphere). Collaboration between research groups produced new physics-based models of active regions and the global transition region and corona, and new semi-empirical models of the chromosphere and transition region. Significant scientific results published by the team include: (1) A determination of the relationship between solar spectral irradiance and total unsigned magnetic flux, and (2) A comparison of numerical simulations with imaging and spectral data that suggests coronal heating may be linked to highly impulsive, non-thermal sources (possibly concentrated close to the Sun's visible surface). The latter results in particular can be considered a product of the TR&T team concept. Collaborations between groups facilitated new scientific interactions between observers and different modeling groups. In this case, the team concept encouraged researchers to use distinctly different types of numerical models to address a single, focused scientific problem.

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

#### 4. Recommendations for the Future of the TR&T Implementation

##### 4.1 Proposal for TR&T Targeted Science Teams

During the past ten years the TR&T FST and SC programs have brought about a revolution in both LWS science and infrastructure. As a result of the TR&T, many of the most basic science issues important to LWS have been identified and addressed. Our understanding of a number of LWS science problems has advanced to the point that the remaining issues are ripe for a concerted team effort, where the attributes of the required team can be clearly defined. Furthermore, collaborations between traditionally different subdisciplines have been fostered to the point that we now have a robust interdisciplinary community, which is capable of supporting such pre-defined science teams. Consequently it is now timely to attack some of the TR&T science targets with pre-defined dedicated Teams.

The difference between these Targeted Science Teams TSTs, and the traditional FSTs is that the TSTs will form *prior* to selection under a single PI, and submit a single TST proposal that attacks the TR&T target. The advantages of this approach are obvious and address some of the major community concerns with regard to the teaming aspects of the present FST program. First, in order to be selected, the TST will necessarily have all the expertise required to attack the specified Science Target rather than rely on random chance to form a complete Team. Second, the Team Leader, the PI, will again be pre-selected and will necessarily be a likely, effective leader in order for the proposal to be selected rather than again rely on “the luck of the draw”.

A key aspect of the TST program is that the expertise required for a particular Target will be specified in advance by the TR&T program as part of the Target description. One of the main criteria for evaluating TST proposals will be the extent to which individual members of the Team satisfy the expertise requirement. This will encourage the TSTs to be strongly interdisciplinary and to involve the best people in the field, rather than simply co-located groups.

The funding and duration for each TST should be roughly equal to that of the present FST teams. We recommend that the TST program be run in parallel with the present FST program, with approximately two TST and two FST Topics per selection round. One possibility would be to specify several TST Topics in a proposal round, say 4, and then have the review panels decide which two should be pursued based on the submitted team proposals. Note, however, that we do NOT recommend allowing both FST and TST proposals for the same Topic. The TR&T Steering Committee should recommend and NASA HQ should pre-select which Topics will be competed as FSTs or TSTs exclusively.

##### 4.2 Proposal for Strategic Capability Validation, the Development of Coupled Models, Integrated LWS Data Products, and CCMC Partnerships

The strategic capabilities have been highly successful in the development of complex models for a host of phenomena in Heliophysics. The investments by LWS have resulted in powerful tools that are used in a wide-variety of physical problems. The challenge at this stage is in the expansion of applications to a broader range of physical problems, the validation of models, and the expansion of deliverables from strategic capabilities with deepened benefits for the LWS community. Here we list a number of examples of the types of developments we foresee:

1. Metrics and model validation represent two key elements upon which the success of models depends. The routine calculation of important operationally- and scientifically-motivated metrics permits us to objectively measure and track the ability of complex models to predict essential space weather quantities. Rationale for metrics selection need to be developed along with a list specific metrics, baseline models, first-generation physics models, and the data sets needed to compute skill scores. Metrics provide a means for the objective assessment of long-term model improvement and model validation. The comprehensive, systematic quantitative comparison of model output with observations is required for identifying and documenting model strengths and weaknesses. Representative examples of validation efforts include case studies comparison with in situ observations during real events would be valuable for exploring the range of model validity. Additional uses include statistical approaches to compare model parameters deduced from both spacecraft observation and modeled by the LFM code. Spence et al. (2004)<sup>1</sup> document important examples of model metrics and validation.
2. The developed models that describe components of space weather are still in their infancy. The basic modules can be coupled to each other, and to culminate in even more powerful tools.
3. The use of the CCMC is critical for running and maintaining models and thereby expanding accessibility of space weather tools. Efforts involving model validation (developing skill scores) and the coupling of models to describe interconnected phenomena should be developed in partnership with the CCMC. Ultimately, the CCMC benefits from and serves the space science community by developing greater accessibility and utility of the complex research tools it houses.

<sup>1</sup>Spence, H., Baker, D., Burns, A., Guild, T., Huang, C.-L., Siscoe, G., and Weigel, R., *Center for integrated space weather modeling metrics plan and initial model validation results*, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 1499, 2004

**APPENDIX E -- SUBGROUP 2: GLOBAL AND REGIONAL CLIMATE**

## Assessment of the Progress of the LWS Targeted Research and Technology (TR&T) Program on Achieving Strategic Goal 2:

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

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### 1. Introduction

The potential pathways by which solar magnetic activity can couple into the Earth’s climate system have been subjected to a diverse multitude of studies over the past decades. The Sun’s impacts range from the topmost layers of Earth’s atmosphere at the very interface of space down to the coupled systems of atmosphere, oceans, cryosphere, and landmasses that support human society. A recently released workshop report by the U.S. National Research Council (entitled “The effects of solar variability on Earth’s climate: a workshop report”, National Academies Press, catalog entry 13519) found that

“no satellite measurements have indicated that solar output and variability have contributed in a significant way to the increase in global mean temperature in the past 50 years.” On longer time scales, extending to well before the Industrial Revolution, such effects appear to exist, however. Moreover, the NRC report notes that “[I]ocally, however, correlations between solar activity and variations in average weather may stand out beyond the global trend; such has been argued to be the case for the El Niño-Southern Oscillation, even in the present day.”

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

solar irradiance. A number of presentations focused on the time scale of the solar cycle and of the satellite record and on the problem of extending this record back in time.”

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

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

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

The importance of Sun-climate coupling to society combined with the need to engage the climate-modeling community has caused the LWS program to sponsor proposals in that scientific area from 2004 onward, seeing a Focused Science Theme (FST) status in 2008. Since 2009, the Sun-climate science has been a standing theme within LWS TR&T. “The LWS Sun-Climate strategic objective is to *deliver the understanding of how and to what degree variations in the solar radiative and particulate output contribute to changes in global and regional climate over a wide range of time scales.*” [from [http://lwstrt.gsfc.nasa.gov/sunclimate\\_theme2012.htm](http://lwstrt.gsfc.nasa.gov/sunclimate_theme2012.htm)].

The theme’s description includes the following: “Two key issues must be addressed to make progress in quantifying the solar contribution to climate variability and change: (1) Observed decadal to centennial-scale climate signals throughout the atmosphere and at the surface must be categorized as either systematically related to solar activity changes or as spurious because of internal climate system variations on similar time scales. (2) The emphasis of solar impact studies in climate research must be broadened beyond mean radiative forcing to include both direct and indirect atmospheric impacts of spectral irradiance and particle precipitation variations over the full range of spatial and temporal scales. The intent of this Sun-Climate theme is to initiate cross-disciplinary research that will develop a

more solid mechanistic understanding of pathways by which solar variability affects the various levels of the atmosphere, and how these effects are communicated toward the troposphere and surface where they modulate global and regional climate. It also targets the pathways by which ongoing climate change influences the atmospheric response to solar forcing, both directly and via upward coupling.”

The metrics of success are formulated as follows (from the Sun-climate theme description):

- (1) Identifying and quantifying the relevant pathways by which solar forcing causes variability in climate parameters such as atmospheric temperature, circulation, and wave activity over a broad range of time scales;
- (2) Isolating the regional and global climate response to variations in these pathways with data that have enough sample (record length);
- (3) Assessing the sensitivity of these pathways to long-term change in the troposphere and atmospheric composition;
- (4) Incorporating solar forcing effects into coupled chemistry climate models (CCMs) to produce verifiable simulations of these effects on atmospheric processes;
- (5) Testing and improving the predictive capabilities of the CCMs and Earth System models with regard to solar-induced forcing.

The above ‘metrics of success’ apply to the Sun-climate activities of the LWS program; individual investigations should support progress towards a successful assessment of these metrics, which they may do by either directly affecting these metrics or by developing the quantitative knowledge and physical understanding needed to do so. Given the limited resources of the LWS program and the unique knowledge pool of heliophysics, the latter, indirect contribution of individual investigations or FSTs towards meeting the ultimate program goals appears to be a valuable and pragmatic pathway by which LWS can significantly contribute to climate science.

In our assessment of Sun-climate studies under the NASA/LWS program, we focus on the following general research areas (reflected in the sections below):

1. Understanding of solar spectral irradiance on daily to millennial time scales;
2. Impacts of solar spectral irradiance on the high terrestrial atmosphere;
3. Understanding of SEP/GCR variability;
4. Impacts of energetic particles on the terrestrial atmosphere;
5. Information flow from climate-related and geomagnetic research into heliophysics;
6. Information flow from astrophysics into heliophysics.

## 2. Decadal Progress toward quantifying Sun-climate couplings

### 2.1 LWS sponsored research in Sun-climate couplings

Among selections made in proposal rounds from 2004 through 2010 the following investigations and FSTs focus specifically on the Sun-climate coupling through support by the LWS program (information on selected investigations since 2010 is not yet available):

- 2004: "Response of the thermospheric density and composition to solar and high-latitude forcing", PI/lead Art Richmond;
- 2004: "Sensitivity of regional and global climate to solar forcing", PI/lead Terrence Nathan;
- 2004: "Creation of a Composite Solar Ultraviolet Irradiance Data Set", PI/lead Matthew DeLand;
- 2004: "The Sun's Role in Decadal Climate Change since 1980, and in the last Century", PI/lead David Rind;
- 2004: "Solar Forcing of Climate through Stratospheric Ozone Changes", PI/lead Yuk Yung;
- 2004: "Solar Proton Events and their Atmospheric Dynamical Influence", PI/lead Charles Jackman;
- 2006: "Solar Induced Variations of Stratospheric Ozone: Improved Observational and Diagnostic Analysis", PI/lead Lon Hood;
- 2006: "Implications of Energetic Particle Precipitation for the Stratosphere", PI/lead Cora Randall;
- 2006: "Solar Origins of Irradiance Variations", PI/lead James Klimchuk;
- 2007: "Long-term Atmospheric Effects of Solar Proton Events and their Contribution to the Polar Solar Cycle Variations", PI/lead Charles Jackman;
- 2008: "Sun-climate" FST, PI/lead Petrus Martens
- 2009: "Solar UV-Induced Responses of Stratospheric Ozone, Temperature, and Circulation on Decadal Time Scales", PI/lead Lon Hood;
- 2009: "Atmospheric Coupling via Energetic Particle Precipitations", PI/lead Cora Randall;
- 2009: "Global and Regional Climate Sensitivity to Solar Forcing in an Integrated Chemistry-Climate Atmosphere-Ocean Model Driven by SORCE Observations", PI/lead Drew Shindell;
- 2009: "Climate Response to Solar Forcing, Observational Analysis, Theory and Modeling", PI/lead Ka-Kit Tung;
- 2010: "Impact of the 11 Year Solar Cycle on the Gravity Wave Driven Circulation", PI/lead Scott England;
- 2010: "Atmospheric Effects of Solar Proton Events and Galactic Cosmic Rays", PI/lead Charles Jackman;
- 2010: "Impacts of Stratospheric Dynamics on Atmospheric Behavior from the Ground to Space under Solar Minimum and Solar Maximum Conditions", PI/lead Fabrizio Sassi;
- 2010: "The Impact of Spectral Solar Irradiance Variations on the Atmosphere and Climate: Model Simulations and Observations", PI/lead William Swartz;

- 2010: "Investigation of Climate Response to Solar Spectral Variability on Decadal, Centennial, and Millennium Time Scales", PI/lead Guoyong Wen;
- 2010: "Observational Study of Solar Variability Impacts on the Troposphere, Stratosphere and Mesosphere", PI/lead Dong Wu;
- 2010: "Climate Impacts of Solar Variation-Induced Changes in Tropospheric Particle Formation, CCN, and Cloud Properties", PI/lead Fangqun Yu.

A request for information was sent to all of these team leads and/or PIs. Their comments in general support LWS/TR&T as very important, and often crucial to, the stimulus of interdisciplinary research in the Sun-climate area. This is particularly evident for the influence of solar variability on the topmost layers of the Earth's atmosphere and into the overall climate system from there. Specific comments on the LWS program from the Sun-climate perspective included the following:

- “Current trends in solar observations and models seem to emphasize higher spatial and temporal resolution. However, the solar interaction with terrestrial climate frequently involves "Sun as a star" types of input. Scaling these high-resolution products to a more useful format, e.g. inputs for a GCM, is not always easy or obvious.”
- “In general, there is no question that the LWS program has greatly stimulated work on the Sun-stratosphere and Sun-climate problems. [...] The LWS grant has enabled me to attend important international meetings (AMS, SPARC, WCRP, etc.) and to present evidence of the importance of the Sun-climate and Sun-stratosphere problems to leading atmospheric scientists. This alone has been a major contribution since many of these scientists have tended to be very skeptical of solar effects in the lower stratosphere and troposphere.”
- “We certainly think that the LWS TR&T program has been extremely important for work on the influence of charged particles (protons and electrons) on the Earth's middle atmosphere and below. This work would most likely NOT have been done without the LWS TR&T program. The Earth and Heliophysics Science areas usually have a boundary at the stratopause (~50 km). Above the stratopause is generally Heliophysics Science and below the stratopause is Earth Science. Fortunately, the LWS TR&T program has no such boundaries and funds research which bridges the upper and lower atmosphere. After all, it is really a wholly connected Earth atmosphere.”
- Based on my current and past experience with this NASA program, I find the LWS program highly valuable to and appreciated by the community at large to the point that several outstanding successes (e.g., the vertical extension of WACCM to the exobase [...]) would have not been possible without LWS support. This is even more important if one considers that LWS is addressing a broad community, from solar physics to Sun-climate interactions, from geo-effective solar impacts to dynamical coupling between the lower and the upper atmosphere. From my specific view in the Sun-climate interactions, LWS has supported innovative ideas that are truly interdisciplinary.”
- FST teams are “a great way to get to know people in other disciplines and almost without fail educational.”
- Comments on the implementation and management of the LWS focused science topics

and the Sun-climate theme:

- “Perhaps it would be good to go into less detail regarding the LWS focus subjects, and maintain those foci for a longer time, to have some more permanency in the program.”
- “Consider explicitly mixing observational and modeling/theoretical expertise.”
- Sometimes “the FST focus is shaped by the team to be detrimental to the original proposal goals.” “Even if it does work to further understanding beyond the original plans, there is no easy path to implement that.”
- “Suggestions: solicit interdisciplinary teaming in FST, but carefully as that would be an unproven pathway. Perhaps only for a fraction as the cross-educational aspects of the current style are highly appreciated. On the other hand, why not compete FST team proposals” or “jointly redraw the goals after assembling the FST team,” or “define the FST narrowly so that teams are better coordinated.”
- “Intents to coordinate proposals do not necessarily lead to two or more being selected into an FST team”
- “Management of the team suffers from the absence of internal accountability.”

### 3. Status and Progress in advancing Sun-climate understanding

#### 3.1 Progress on understanding solar spectral irradiance

##### 3.1.1. Background on solar spectral irradiance

Solar radiation is the Earth's primary source of energy, exceeding by four orders of magnitude the next largest source, radioactive decay in the Earth's interior [Sellers, 1965]. Energy from the Sun drives the complex and tightly coupled atmospheric circulation and chemistry, and the interactions among the atmosphere, oceans, cryosphere, and land that maintain the terrestrial environment. A reliable, continuous record of total and spectral solar irradiance is essential for understanding the Earth's climate and how it changes and for attribution to the underlying physical processes.

NASA has identified solar irradiance as one of 23 crucial measurements for the NASA Earth Observing System (EOS) program [*EOS Science Plan*, 1999]. More recently, the Global Climate Observing System (GCOS, a joint undertaking of the World Meteorological Organization, the Intergovernmental Oceanographic Commission of the United Nations Educational Scientific and Cultural Organization, the United Nations Environment Programme, and the International Council for Science) has designated solar irradiance (total and spectral) as one of 27 Global Essential Climate Variables and recommends its continuity in the *Implementation Plan for the Global Observing System for Climate* [2010].

A continuous 34-year record of total solar irradiance (TSI) exists from space-based observations. Evident in this combined record is an 11-year cycle with peak-to-peak amplitude of approximately 0.1% and larger variations that are associated with the short-term transits of sunspots over the disk of the Sun. Variability in TSI occurs over a broad range of time scales, from day-to-day variations, to the 11-year solar cycle and longer. Because the Sun's energy input into the Earth's atmosphere and surface layers is so large, even the small relative fluctuations that occur during the 11-year solar activity cycle can cause detectable climate responses. In contrast to the direct measurements over more than three decades, the amplitude of longer-term changes must be deduced indirectly from proxy records tied to the existing TSI data record. The direct TSI records is, however, too short to fully identify the physical mechanisms of long-term solar variability. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change [*IPCC AR4*, 2007] estimates the direct radiative forcing due to changes in the solar output since 1750 to be  $0.12 \text{ W/m}^2$  (from its baseline value of  $1361 \text{ W/m}^2$ ) with an estimated uncertainty of a factor of two and with a low level of scientific understanding. Prior to 1750, the Maunder Minimum, which corresponded with the Little Ice Age in Europe, may have caused even greater changes in solar forcing.

The measurements made by individual radiometers providing the 34-year observational data record exhibit a spread of nearly 1% that is of instrumental rather than solar origin, far exceeding the 11-year or rotational solar variability. The individual TSI datasets from 1978 to the present time include observations made by ERB on Nimbus-7; ACRIM-I on SMM, ACRIM-II in UARS, and ACRIM III on ACRIMSAT; ERBS on the ERBE satellite; SOVA on EURICA; VIRGO on SOHO; and TIM on SORCE [Kyle et al., 1993, Willson, 1994, Froelich, 1994, Lee et al., 1995, Froelich, 1996, Willson, 2001, and Kopp et al., 2005]. While

instrument offsets are large, each instrument has high precision and is able to detect small changes in the TSI caused by variability in solar activity. Increases of 0.1% in TSI during times of high solar activity over the 11-year solar cycle are unambiguous. These data were all recorded with ambient temperature sensors, each of which has its own stated instrumental uncertainty, typically on the order of 0.1% (1000 ppm), with the exception of the Total Irradiance Monitor on SORCE, which has a 350 ppm uncertainty [Kopp et al., 2005]. Most of these instruments have internal degradation tracking methods, giving them the best stability of any on-orbit solar sensor so that long-term (secular) changes in solar variability can be monitored given measurement continuity.

In addition to total solar irradiance, reliable knowledge of solar spectral changes is required for understanding Sun-Climate connections. Because of selective absorption and scattering processes in the Earth's atmosphere, different spectral regions contribute to the vertical distribution of deposited radiative energy in distinct ways. The various potential mechanisms of climate response to solar variability that have been identified are dependent on wavelength. The solar radiation in the ultraviolet, at wavelengths shorter than 300 nm, plays a major role in the photochemistry, dynamics, temperature, composition, and structure of the middle atmosphere. The direct heating of the Earth's surface is a consequence of absorption of solar irradiance in the near ultraviolet, visible, and near infrared spectral regions. When averaged over the globe, roughly half of the incoming solar radiation is either absorbed in the atmosphere or scattered back into space, leaving the remaining half to be absorbed at the surface.

Continuous measurements of solar ultraviolet radiation began in 1978 with the Nimbus-7 Solar Backscatter Ultraviolet (SBUV) [Schlesinger and Cebula, 1992]. These measurements were followed by those from the Solar Mesosphere Explorer (SME) [Rottman, 1988], NOAA-9 SBUV/2, NOAA-11 SBUV/2, the Upper Atmosphere Research Satellite (UARS) Solar Stellar Intercomparison Experiment (SOLSTICE) [Rottman et al., 2001], the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) [Floyd et al., 2002], and the present-day SORCE SOLSTICE and SORCE Spectral Irradiance Monitor (SIM), providing a continuous record of the solar ultraviolet and its variability, albeit with different spectral coverage, resolution, and instrumental accuracies and stabilities. Although the ultraviolet region of the spectrum provides only a small fraction of the TSI, ultraviolet irradiance changes over the solar cycle can be several percent, and thus represent an important source of modulation of the energy deposition and composition in the middle and upper atmosphere. The measurement of the full solar irradiance spectrum from space is a much shorter record than TSI, commencing with the SIM on SORCE in 2003 [Harder et al., 2005].

Solar spectral irradiance inputs are essential for the next generation of Global Climate Models (GCMs), which include parameterizations of atmospheric processes from the surface to the mesosphere on increasingly finer altitude resolution grids and with interactive ozone photochemistry. In particular, while the GCMs in IPCC AR4 primarily used the total solar irradiance to specify solar forcing of climate change, updated state-of-the-art models planned for use in IPCC AR5 will require solar spectral irradiance binned onto their respective wavelength grids. The requirements for functional solar irradiance climate data records therefore include accurate time series of total and spectral irradiance in the ultraviolet, visible and infrared spectrum on time scales of days to centuries.

TSI and SSI are, obviously, not available by direct measurement prior to 1978, but climate models require information on these quantities for at least multiple decades if not for multiple millennia for paleoclimatological studies. The establishment of reliable TSI and SSI time series before that time is therefore necessarily based on observed solar activity or of its proxies available in terrestrial records. We return to this high priority in section 3.6.

### 3.1.2. LWS TR&T Progress in Solar Spectral Irradiance

One major project funded in this area under LWS TR&T was M. Deland and R. Cebula's *Creation of a Composite Solar Ultraviolet Irradiance Data Set*. Each of the ultraviolet measurements listed in the section above have a unique native calibration scale, sampling cadence, spectral resolution and sampling, which pose difficulties in deriving a composite spectral time series spanning the space-based UV irradiance measure era from 1978 to the present. Degrading spectral resolution onto a common slit function, sampling onto a common wavelength and time scale, filling observational gaps over part of the spectrum, reconciling calibration scales and drift in the instrument response functions, and comparing to proxy and model records are some of the primary tasks executed during this project which ended in 2007.

The Deland-Cebula UV irradiance composites are daily-averaged spectra over the wavelength range 120-400 nm, 1 nm sampling, covering the time period 8 Nov. 1978 to 1 Aug. 2005. This data set was created from SME, Nimbus-7 SBUV, NOAA-9 SBUV/2, NOAA-11 SBUV/2, UARS SUSIM, and UARS SOLSTICE measurements. Full details are provided in Deland and Cebula [2008].

Three LWS TR&T Focus Teams studied the solar causes of irradiance variations. The ***Solar Origins of Irradiance Variations Focus Team*** (lead: James Klimchuk) was formulated in 2006 “to understand how spectral irradiance variations from the Sun are produced and, in particular, to understand the physical processes causing variations in the solar spectral emissions. The prime measure of success for this work would be a substantial improvement in our ability to reproduce multi-spectral observations of active regions using physics-based models.” Goals were to understand the physical processes underlying the solar spectral irradiance, to determine how spectral irradiance depends on physical parameters such as magnetic field strength and flux, and to construct physics-based models of active regions.

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

The FST ***Measure the Properties of the Solar Dynamo That Affect Solar Irradiance and Active Region Generation*** (Chair, Peter Foukal) began in 2008 “to characterize the properties of the solar dynamo that determine the strength of the solar activity cycle and its terrestrial

consequences (e.g., through irradiance changes and geomagnetic effects).” **Goals were to** discriminate between and improve dynamo models, improve measurements of critical subsurface flows, clarify the connections between dynamo operation and the properties of the active regions that give rise to terrestrial effects, and improve understanding of what aspect of dynamo action gives rise to eruptive regions.

The primary focus of *Evolving Solar Magnetic Activity on Time Scales Relevant for Space Climate* (Petrus Martens) was “to explore the origins of, and decipher the evolution of solar magnetic activity over multiple time scales ranging from centuries to stellar and planetary evolutionary time scales” and “to produce accurate predictions for the Sun’s surface magnetic fields” that regulate the variations in the total solar irradiance.

These LWS-supported projects along with other national and international projects have significantly advanced our understanding of the multitude of processes involved in the establishment of long-term TSI and SSI records. But uncertainties and unknowns remain. We return to these in section 3.6.

In the area of understanding atmospheric impacts of solar spectral irradiance variations on the upper and middle atmosphere, more work is clearly needed on the time scale of the 11-yr solar cycle. Atmospheric observational records derived from satellite remote sensing measurements (available continuously since late 1978) are becoming long enough now to provide stronger constraints on model simulations on this time scale. However, the different satellite measurements are sometimes difficult to reconcile with one another due to inter-calibration issues; consequently, considerable effort is needed to analyze all of them and produce a combined record that can act as a strong constraint on GCMs. Although several studies have shown that the magnitude and spectral composition of solar variability have important consequences for the atmospheric and climate response to solar forcing, quantifiable uncertainty analysis in the observed trends in the observational record is required for climate modelers to test the sensitivity of model response over a plausible range of spectral variability. The relatively weak amplitude of the current cycle 24 maximum (possibly only half as large as the cycle 23 maximum) should result in correspondingly weaker responses in both the upper and middle atmosphere, which can afford a valuable test of our understanding of those responses. A better understanding of the whole atmosphere response to 11-yr solar forcing will result in better GCM simulations of the sun-climate signal on longer (centennial to Maunder Minimum) time scales.

Recognition of the importance of solar irradiance measurements and their interdisciplinary connectivity, particularly in those disciplines associated with the solar-terrestrial environment, is improving. The continuous measurement of solar irradiance, historically within NASA the domain of Earth science, has important ties to solar physics and space weather. Likewise, terrestrial climate change is now a component of the NASA Heliophysics division within LWS TR&T.

One important cross-disciplinary activity funded by the LWS Program is in improving solar models and our understanding of spectral solar variability. For example, the Solar Radiation Physical Model (SRPM) has been developed over several years [Fontenla et al., 2009] and provides the necessary physical basis for calculating high resolution spectra and their variations directly from solar theory and analysis of solar images. Using ground-based images of the solar disk and a set of models of active- and quiet-Sun features such as those of

Fontenla and Harder [2005], the sources of the UV, visible, and IR spectral irradiance variation observed by SIM are being explored. Further studies are underway to investigate visible and infrared variations in the SSI, and to improve modeling of the MUV and FUV spectral regions, where large non-LTE effects play an important role in solar emissions. The extension and improvement of these studies over the full rise and decay of a solar is needed for understanding the physics of the solar atmosphere in originating the observed SSI variations. This physical insight can guide much more reliable analyses of historical records and future expectations.

Finally, it should be noted that while there is broad international support for the continuity of solar irradiance measurements from space, and while NASA Earth Science has supported and managed most of the missions, it appears that Research and Analysis (R&A) support for solar irradiance studies occasionally “falls through the cracks,” with no proper place to call home. NASA Earth and Heliophysics divisions both provide some opportunities for solar irradiance-based studies, but generally within broader programs and at a relatively low level of emphasis. We recommend that cross-division collaborative support within NASA is needed to better address the many aspects of the solar-terrestrial environment and to provide the necessary resources to answer some of the outstanding questions in Sun/Earth/global change climate studies.

The three and a half decade solar irradiance climate data record has established the solar cycle variability, the relationship between solar irradiance and magnetic features (sunspots and faculae), and the level of irradiance of the quiescent Sun. And while substantial progress has been made in extracting the surface temperature response over the solar cycle, the patterns of regional climate variability associated with solar forcing, and new insights into top-down, bottom-up mechanisms and their coupling, much progress awaits through extension of the irradiance record backward via the proxy record, over multi-decadal to centennial and millennial time scales. Even within the observational record the change in irradiance from cycle to cycle is not known within climate quality accuracies. Progress on longer (than decadal) term variability, over which the Sun exerts its greatest influence on climate, requires a deeper understanding of the mechanistic processes of how irradiance varies.

It is within this venue where LWS TR&T can make a significant contribution. There is an extensive record in the published literature on correlations between Earth’s climate and solar variability, as represented by proxies to irradiance. The most notable study, by Eddy [1976], linked the climate of 17th Century Europe to the occurrence of few or no sunspots, a period called the *Maunder Minimum* (1645–1715). Many other studies, however, have come under question on statistical grounds [Gray, 2009]. New investigations are required into the physical linkages between solar magnetic activity, for which a number of proxies have been established, and solar irradiance, to enable higher-fidelity reconstructions of the historical variations of the solar irradiance. For example, current estimates of the reduction of the solar irradiance during the Maunder Minimum vary from a few tenths to as many as  $6 \text{ W m}^{-2}$ . An even greater challenge lies in resolving the spectral composition of solar variability because the mechanisms of climate response depend on variation with altitude within Earth’s atmosphere of solar radiative energy deposition, which itself is largely determined by wavelength.

Going forward, a better understanding of the relationship between solar magnetic behavior and irradiance may lead to improved predictions of solar irradiance and its subsequent impact on Earth's climate. Even while the foundation in establishing mechanisms connecting small changes in solar irradiance with climate response is still being built, improvements in constraining the range over which the Sun's irradiance has varied in the past is required for studies of Sun-Climate connections to evolve from the purely correlative studies to ones based on physical attribution. These are the challenges for which TR&T is ideally suited to attack and where future emphasis in Sun-Climate research should be directed.

Long term irradiance changes may be derived from proxies that are indicators of solar magnetic activity. Examples of proxies include cosmogenic isotopes, such as  $^{10}\text{Be}$ , which are produced by galactic cosmic ray (GCR) interactions with oxygen, nitrogen, and argon. GCRs (and  $^{10}\text{Be}$ ) are inversely correlated with solar activity/magnetic field strength. Reconstructions of solar activity can be derived from  $^{10}\text{Be}$  stored in ice sheets and ocean sediments or  $^{14}\text{C}$  in tree rings. Other proxies include indices of geomagnetic disturbance, solar radio flux (F10.7), and Mg II indices (core-to-wing ratio). Nearly all of these proxies exhibit variations that are not evident in sunspot numbers, because the minimum of the latter is zero. Therefore, long-term variability is not properly reflected in minimum-state sunspot numbers.

New LWS TR&T focused science area should be directed toward mapping the current measurements to century-to-millennial estimates: from proxies, to the heliospheric field, to the solar dynamo, to sunspot number, completing the circuit.

### **3.2 Progress on impacts of solar spectral irradiance variations**

Impacts of solar spectral irradiance variations range from effects of solar extreme ultraviolet (EUV) radiation on composition, ionization, and density in the thermosphere and ionosphere to effects of mid-UV radiation in the lower mesosphere and stratosphere. Solar UV radiation at wavelengths less than 242 nm is mainly responsible for the production of ozone in the upper and middle stratosphere. Ozone, in turn, is a key trace gas that absorbs biologically harmful near-UV radiation and is responsible for radiative heating of the stratosphere. It also plays a key role in the "top-down" mechanism for communicating direct solar UV-induced perturbations in the upper stratosphere to the lower stratosphere and troposphere.

The LWS program supported a number of investigations of upper atmospheric responses to magnetospheric and solar variability, including EUV variability. This work led to improved first-principles thermosphere-ionosphere models that accurately calculate the response to solar EUV flux variations, magnetic activity level, and orientation of the interplanetary magnetic field. In addition, variations of thermospheric density and composition in response to changing concentrations of greenhouse gases were investigated. Specific accomplishments included the development of more accurate and efficient methods for using solar spectral irradiance measurements or models to calculate dissociation rates and ionization throughout the upper atmosphere. These are necessary inputs for global time-dependent general circulation models (GCMs) of the thermosphere and ionosphere that are computationally economical. One modeling effort described the dynamical behavior of the upper mesosphere and lower thermosphere at the time of the major sudden stratospheric warming (SSW) of 2009. It found that the lunar and solar migrating semidiurnal tides, which modulate the

ionospheric plasma, were significantly enhanced following the peak of the 2009 SSW. Inclusion of the lunar tide, in particular, was therefore found to dramatically improve the ability of GCMs to reproduce the observed ionospheric response to a SSW. Finally, long-term changes of thermospheric neutral density estimated using a combination of satellite drag measurements and upper atmospheric GCMs have been shown to be a consequence of secular changes in the concentration of greenhouse gases, thereby allowing better predictions of long-term density changes under solar maximum and minimum conditions.

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

Recent SORCE SIM measurements suggesting a much larger solar cycle variation in the ultraviolet than expected from proxy-based reconstructions have stimulated a number of model studies intended to explore their possible implications for the solar cycle variation of ozone and OH. These studies generally find that the model-simulated ozone variation is negative above about 45 km altitude in the upper stratosphere if the SIM UV measurements are used but is positive at all altitudes in the upper stratosphere if the proxy-based reconstructions are used. Thus, the ozone variation expected according to the SIM measurements does not agree well in the upper stratosphere with observational results based on long-term satellite data records. On the other hand, the calculated solar cycle variation of the OH column amount is larger when the SIM measurements are used and agrees better with available observations during the most recent solar cycle. However, the shortness of the available OH record and the possibility that middle atmospheric chemistry models may not be complete suggest caution in interpreting the latter result.

A number of LWS-supported investigations have also addressed the extent to which direct solar UV forcing of the upper stratosphere can impact circulation in the lower stratosphere and troposphere. The importance of this "top-down" forcing is dependent on solar-induced changes in the propagation and absorption of planetary-scale Rossby waves that propagate from the troposphere into the stratosphere during winter-spring. Westward momentum deposited by these waves when they are absorbed slows the prevailing westerly zonal wind and induces a poleward meridional circulation (the Brewer-Dobson circulation; BDC).

Reductions in the strength of the BDC near solar maxima result in less tropical upwelling that may be responsible for observed ozone and temperature increases in the tropical lower stratosphere from solar minimum to maximum. Interactions between these waves and the mean zonal flow can also potentially amplify an initial weak zonal wind perturbation in the subtropical upper stratosphere as it propagates poleward and downward.

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

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

### **3.3 Progress on understanding energetic-particle variability**

#### **3.3.1. Background**

One could argue on the one hand that the LWS TR&T program has not funded any projects primarily focused on galactic cosmic ray (GCR) and solar energetic particle (SEP) variability and also specifically tied to the singular goal of understanding their impact on

climate variability. Typically, awards have instead focused on the motivating role that these populations of energetic particles have on the radiation environment throughout the heliosphere, most notably in the space environment near Earth, the Moon, Mars, and other human exploration targets. Because of their high energy (>10 MeV), such energetic particle populations penetrate significant amounts of spacecraft shielding and thus pose risks and hazards associated with ionizing radiation, whether it comes weakly yet incessantly (GCR) or impulsively but powerfully (SEP).

Of course, these same particles also penetrate the comparable shielding mass of Earth's upper atmosphere (and more so at Mars) in the same ways, and thus possess also the potential to influence climate variability. These pathways can be subtle, but yet still important. Despite the LWS program not focusing deliberately on SEP and GCR variability specifically through the lens of climate variability, it has nevertheless supported a great number of studies of energetic particle variability. The progress made in these studies underpins the many other related studies that consider their variability to Earth's climate (see section 3.4). This section of the report summarizes progress made on energetic particle variability since the inception of the LWS program over a decade ago.

### **3.3.2. Progress on understanding solar energetic particle variability**

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

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

Because of the large number of awards made over this time toward progress in SEP understanding, it is beyond the scope of this report to provide a full accounting, particularly because the preponderance of the projects did not have strong motivational links to climate variability. Other recent LWS TR&T and NRC reports document such progress over the past decade and so are summarized next in only a high-level form. Section 3.4 demonstrates that

the atmospheric community is already making the connection with climate using the basic research ongoing in SEP physics; a more deliberate focus by LWS on SEP variability aimed at climate variability would make those informal connections stronger.

Over the past decade, a consensus emerged that the energy tapped to create the most powerful space weather events, including SEPs, ultimately comes from the strongly sheared magnetic fields associated with active regions at the Sun. While we know where such events may occur in the corona, we still have only a rudimentary ability to predict when they will occur and what their magnitude will be. Work in the past decade on SEPs has been aimed at developing the basic physical understanding to improve that lack of predictability.

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

Knowledge of these acceleration mechanisms though are not enough to develop a predictive understanding. Through the past decade, there was also a growing understanding of the importance of the seed population of particles that eventually are accelerated to become the most energetic SEP population. Significant attention thus has gone to understanding the origins and variability of the suprathermal electrons, protons, and heavy ions that participate in the acceleration. We now know that without such seed populations, even favorable magnetic energy releases may not produce significant SEP populations. We recognize the importance of understanding how these seed populations vary on times scales of minutes to hours and how those variations feed into the overall accelerations mechanisms and considerable attention is now being placed on connecting the origins of those populations with SEPs.

### **3.3.2. Progress on understanding galactic cosmic ray variability**

Whereas the LWS program has supported several dozen studies on the basic physics of SEPs over the past decade, support for studies aimed at understanding GCR variability has been comparatively rare. This is probably the result of at least two factors. First, the LWS program has tended to emphasize space weather time scales rather than space climate time scales. From the point of view of space weather effects, solar explosive phenomena such as SEPs are compelling examples of prompt dramatic changes in the space environment, in this case those posing acute radiation risks to astronaut and robotic operations. From this perspective, it is natural to focus on phenomena (i.e., SEPs) with short time scales and which exhibit several orders of magnitude variability rather than those with long time scales (i.e.

GCR) and which exhibit only weak amplitude variation, at least as we have witnessed so far during the Space Age.

The second factor likely influencing the relatively fewer number of GCR-related awards to SEP-related awards is the relative degree of understanding and predictability in variability of the two sources. The basic theory on the solar modulation of cosmic rays is relatively well understood and models exist which describe and predict the slow, solar cycle evolution of GCR intensity and spectral shape in the inner heliosphere with fairly high fidelity. The same cannot be said yet with SEP modeling. SEPs can have multiple source locations and the energetics of those source regions depend on boundary conditions that we cannot typically determine easily. Furthermore, the subsequent transport of the SEPs can be significantly influenced by interplanetary conditions and configuration, again in ways that are not necessarily well known. Determining the details of their impulsive properties (onset time, rise time, maximum intensity, decay time) is usually the key motivation from a practical, predictive point of view. Even if the physics is completely understood, models are limited in use until they become sufficiently predictive. In that regard, SEP modeling is more of a challenge for space weather applications. As a result, it is likely that SEP understanding has warranted a higher program priority in terms of needed progress.

The same prioritization is not necessarily clear when climatological time scales become the primary consideration. At these time scales, we know that the Sun exhibits dramatic changes in terms of its magnetic structure which in turn determines the interplanetary conditions that ultimately modulate the onslaught of the inner solar system by GCR. During the space age, we have witnessed only comparatively minor variability in solar magnetism. However, through historic proxies, we know that the Sun's magnetism had periods of grand quiescence. During these periods, GCR intensities at Earth increase. On even longer time scales, as the solar system moves through its orbit through the Milky Way galaxy, we anticipate that it will move through regions of higher or lower density pockets within the interstellar medium. During these times, the heliosphere may contract or expand dramatically, an external factor that could significantly control the intensity of GCR at Earth's orbit. We also know that the Sun has evolved as a star; changes in a star's magnetism and rotation rate as it evolves could also dramatically affect GCR modulation on hence its impact on an atmosphere's longest term evolution.

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

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

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

### **3.4 Progress on understanding impacts of energetic particles on climate**

The Living With a Star Targeted Research and Technology (LWS TR&T) program has sponsored several investigations on the impact of energetic precipitating particles (EPPs) on climate. Here climate impacts are defined as: a) any impact on stratospheric ozone, which may affect the ultraviolet flux at the Earth's surface as well as modify atmospheric dynamics; and b) any impact on the tropospheric chemical composition, cloud cover, and/or dynamics.

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

- 1) Lower energy EPPs, such as auroral electrons, produce nitrogen oxides ( $\text{NO}_x$ ) in the polar thermosphere. This  $\text{NO}_x$  can be transported (predominantly in winter-time) through the mesosphere and into the stratosphere, leading to the destruction of high-latitude stratospheric ozone on time scales of weeks to months. The magnitude of this lower-energy EPP-caused change on stratospheric ozone varies dramatically from one year to another and is currently being studied.
  - Members of the LWS Focused Science Topic Team on Thermospheric Density and Composition have addressed auroral particle precipitation issues including the seasonal dependence of the energy input, the lower latitude variation of the input, and the Joule heating of the input. Some work by other LWS investigators has led to a better computation of the electron impact ionization for auroral electrons. This work on the thermosphere and the ionization by auroral electrons will likely lead to a better understanding of  $\text{NO}_x$  formation from these lower energy particles in the future.
  - LWS investigators have included auroral electrons in a global general circulation

model (GCM), which had a domain from the Earth's surface to the thermosphere. Also, there has been a good effort in analysis of measurements from at least five satellites (UARS, SCISAT-1, Envisat, POAM II and III) regarding this issue. Certain years (e.g., 2004, 2006, and 2009) have shown some descent of  $\text{NO}_x$  from the lower thermosphere to the upper stratosphere. Only 2004, however, showed significant ozone depletion from this  $\text{NO}_x$  source.

- 2) Medium-energy and higher-energy EPPs, such as solar protons, medium-energy and high-energy electrons, and galactic cosmic rays (GCRs), produce hydrogen oxides ( $\text{HO}_x$ ) and nitrogen oxides ( $\text{NO}_x$ ) at polar latitude. This can lead to a change in atmospheric ozone. The polar mesospheric and stratospheric  $\text{HO}_x$ -caused ozone loss is rather short-lived (days) due to the relatively short lifetime (hours) of the  $\text{HO}_x$  constituents, whereas the  $\text{NO}_x$ -caused ozone loss is on a longer time scale of weeks to months. Ozone increases in the lower stratosphere may result from the interference of  $\text{NO}_x$  constituents with chlorine- and bromine-containing gases. Ozone increases in the troposphere may result from the reaction of enhanced levels of  $\text{NO}_x$  constituents with volatile organic compounds (VOCs), i.e. smog-type reactions. The impact of solar protons on the middle atmosphere (stratosphere and mesosphere) is relatively well understood and quantified. In contrast, the effect of medium-energy and high-energy electrons and GCRs on the atmosphere still need to be reliably computed and validated.

→ The impact of solar proton events (SPEs) on the middle atmosphere was quantified by LWS investigators over short (days) to long (years) time scales with a GCM. These GCM results were compared with satellite measurements, whenever possible. Significant polar mesospheric ozone depletion >30% over a few days resulted from large SPEs (~15-20 in the past fifty years), which occurred sporadically near solar maximum. Although polar stratospheric ozone depletions >10% were computed to last for up to 5 months past the few largest SPEs in the past fifty years, the calculated annually averaged temperature and total ozone change were not found to be statistically significant.

→ Using a NASA satellite (EOS Aura), a group of European scientists found that precipitating medium energy electrons enhanced the polar mesospheric hydroxyl radical, OH, in the sub-auroral region (55° -65° geomagnetic latitude). There did not appear to be a measurable ozone response over the same geographic region. Some work by LWS investigators has led to a better computation of the electron impact ionization for medium and high-energy electrons.

→ Research efforts at NASA and in Europe have led to a much better quantification of the atmospheric ionization by GCRs. The European work has further led to computations of the influence of GCRs on atmospheric composition and dynamics. They found ozone increases of up to 3% in the troposphere (especially at southern latitudes) and ozone decreases up to 3% in the lower stratosphere (especially at northern polar latitudes). Work on the Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) project, funded by the NASA Applied Sciences Program, is now helping LWS investigators to quantify the impact of GCRs on the atmosphere.

- 3) The highest-energy EPPs, primarily galactic cosmic rays (GCRs), produce ionization

in the atmosphere that may impact cloud cover. These cloud-cover changes may result either from modified aerosol nucleation rates or an impact on precipitation through changes in the near-cloud electrification. The magnitude of this highest-energy EPP-caused change on clouds is controversial and needs further investigation.

→ LWS investigators in an ongoing study have found a relatively large sensitivity of cloud forcing to nucleation processes. This research suggests that a GCR-caused variation in ionization and, therefore, nucleation rate, may have significant consequences for the cloud cover over solar cycle time-scales. Future work is needed to quantify the GCR/cloud cover link.

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

**The National Science Foundation (NSF) also funds research related to the EPP influence on climate. It is anticipated that such NSF support will continue in the future. Although there have been initiatives, such as the 2005 NASA/NSF Partnership for Collaborative Space Weather Modeling, to coordinate and sponsor larger scale research activities related to some of the NASA LWS TR&T goals, so far, none of these activities has included the sun-climate field.**

**The European research community has a large number of scientists investigating the impact of EPPs on the terrestrial atmosphere. Some of these European researchers collaborated with LWS investigators to start the series of International High Energy Particle Precipitation in the Atmosphere (HEPPA) workshops, which are held approximately every 18 months and are partially sponsored by the LWS program. So far, four of these International HEPPA workshops have taken place (May 2008 in Helsinki, Finland; October 2009 in Boulder, CO; May 2011 in Granada, Spain; and October 2012 in Boulder, CO). The interaction among European and American scientists (including several LWS investigators), as well as those from other countries, at these HEPPA workshops has been extremely productive.**

**A subgroup of modelers and Envisat Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) instrument measurement investigators was formed at the very first HEPPA workshop to investigate in great detail the compositional changes after the October-November 2003 solar proton events. The MIPAS instrument measured changes in 11 constituents (NO, NO<sub>2</sub>, H<sub>2</sub>O<sub>2</sub>, O<sub>3</sub>, N<sub>2</sub>O, HNO<sub>3</sub>, N<sub>2</sub>O<sub>5</sub>, HNO<sub>4</sub>, ClO, HOCl, and ClONO<sub>2</sub>), which could be compared with model predictions. One paper has already been published summarizing this model/measurement intercomparison (MMI) work and another MMI collaboration is underway. This second MMI collaboration is focused on the possible influence of lower energy particles (primarily, auroral electrons) over the period 1 October, 2008 through 31 May, 2009, on the middle**

**atmosphere. This second MMI is still ongoing. Several LWS investigators have been involved with these intercomparisons, which include another meeting scheduled in May 2013.**

In summary, much progress has resulted from LWS TR&T support of several investigations on the impact of EPPs on climate. Most of this work would *not* have been completed without the LWS TR&T program. The NASA Earth and Heliophysics Science Divisions usually have a boundary at the stratopause (~50 km). Above the stratopause is generally Heliophysics Science and below the stratopause is Earth Science. The LWS TR&T program has no such artificial boundaries and funds research which bridges the upper, middle, and lower parts of the atmosphere. The support of whole atmosphere models, such as those that extend from the Earth's surface to the thermosphere, has helped facilitate better and more capable models.

Different populations of EPPs are now included in whole atmosphere models as a result of the LWS TR&T program. Although some impacts are relatively short-lived with the largest impacts in the thermosphere and mesosphere, such effects may have an ultimate influence on the Earth's climate. LWS investigators are working to include other populations of EPPs in their global models. The solar cycle (SC) drives many variations in EPPs, some in phase with the SC (e.g., SPEs) and some out of phase with the SC (e.g., GCRs). Thus, inclusion of the various EPP populations in global models is very important in computing climate impacts. Future research will no doubt reveal more about the influence of EPPs on climate.

### **3.5 Knowledge flow from geo-sciences to heliophysics**

The progress on understanding atmospheric impacts of solar spectral irradiance (SSI) variations reviewed in section 3.2 above has led to a number of positive feedbacks from the atmospheric sciences community to the solar and heliospheric physics communities. Most importantly, improvements in GCMs designed for use in both the upper atmosphere (thermosphere and ionosphere) and middle atmosphere (mesosphere and stratosphere) have continued to demonstrate the necessity of establishing the actual SSI variation over a solar cycle with high spectral resolution and accuracy. This is especially true at mid-UV wavelengths where observational uncertainties are currently large.

Radionuclide concentrations in the biosphere and cryosphere, most prominently  $^{14}\text{C}$  and  $^{10}\text{Be}$ , are influenced by climatic variability, geomagnetic changes, solar activity and – on very long time scales – variability in the GCR populations that envelop the solar system. The correct attribution of these distinct effects is clearly important to quantify the drivers of the terrestrial climate. But this process also enables the determination of the variability of the Sun's dynamo over time scales from years to millennia. This provides important constraints on dynamo theories that cannot be achieved by looking at an ensemble of Sun-like stars (see section 3.6): where the ensemble study of Sun-like stars can provide information that is important in understanding how TSI and SSI can vary depending on the surface patterns of the stellar magnetic field and can set constraints on the distribution and extremes of dynamo activity, only long-term data on solar activity can reveal the variability and fundamental patterns (if any) in the variability of the star that we live with.

### 3.6 Knowledge flow from astrophysics to heliophysics

Sun-climate couplings involve time scales that are longer, by definition, than a researcher's career and longer than the database of accurate space-based measurements of the solar irradiance. The modulation of the strength of the solar cycle and of the associated heliospheric field that affects the cosmic ray populations vary on time scales of decades and above, thus readily going beyond the records of temperature, precipitation, and other climate metrics in historical archives. Sun-climate research therefore necessarily relies on proxies of both the driving system – the Sun's magnetic dynamo - and of the responding climate system.

The proxies of solar activity that are most frequently used for Sun-climate studies are the sunspot number and cosmogenic radionuclides. The number of sunspots has been continually recorded since the discovery of that phenomenon in 1611 by several independent researchers utilizing the then newly invented telescope. Behind the overall continuity of the sunspot records over more than four centuries lies the problem that counting of sunspots depends on the telescope used and the seeing at the site (which determine the resolution and image contrast), and the psychology of the observer (which determines how small the smallest features are that are included and how sunspots are grouped into clusters). The common practice of counting sunspot groups exacerbates the problem of creating a uniform data set because it introduces a subjective bias that makes group sunspot records differ from observer to observer. The creation of an accurate, reliable, uniform sunspot (group) number over the past centuries continues to be an area of active research.

The solar spectral irradiance is determined by at least all of the magnetic elements on the solar surface, if not also by the coupling of field and convection below the surface. Thus knowledge of the patterns in the field associated with sunspot numbers as well as the influence of the distribution mechanisms of the solar field (i.e., convective random walk, differential rotation, meridional large-scale flows, and some yet-to-be quantified consequences of radial flux transport from emergence to submergence or expulsion) needs to be established in order to translate sunspot numbers into solar total and spectral irradiance.

Concentrations of cosmogenic radionuclides (primarily  $^{14}\text{C}$  and  $^{10}\text{Be}$ ) measured in ice cores from, e.g., Greenland and Antarctica form a second proxy for solar activity that extends in principle over many thousands of years. The concentrations of the radionuclides are determined by the modulation of the galactic cosmic rays (GCR) penetrating the heliosphere to Earth against the scattering and overall outward advection by the magnetized solar wind. The cosmic-ray density thus depends on the strength of the wind, and on the mean strength, pattern, and intrinsic variability of the Sun's open magnetic field carried by that wind. The translation from these solar wind properties of the primarily open magnetic field to the solar spectral irradiance that is primarily determined by the closed magnetic field is subject to substantial uncertainty. Correlations have been established, but these are based on the patterns in the solar surface and heliospheric fields observed during the past half century, although some extensions beyond that period have been enabled by the use of yet another variable parameter that is at play: the Earth's magnetic field and its variability on time scales from hours to centuries.

Much work has been done to transform the radionuclide and sunspot records into estimates of total solar irradiance. Nevertheless, the uncertainties in the variety of processes mentioned above has resulted in a range of estimates for the contrast in total solar irradiance (TSI) from Maunder Minimum to present-day cycle minima from decreases of  $0.7 \text{ W/m}^2$  up to  $6 \text{ W/m}^2$  [see the review by Solanki, 2013, *Astronomical Notes* 334, 145]. In order to establish, test, and validate the models of the solar spectral irradiance (SSI) estimated from sunspot numbers and radionuclide concentrations, we have, of course, the option of waiting for the Sun to go through all of its possible states so that we can empirically prove that any given SSI model accurately describes the observed SSI, and that a given GCR or solar wind model faithfully mimics the observed GCR population and solar wind variability. As we can readily infer from the radionuclide concentrations and the few centuries of sunspot observations, the Sun's magnetic dynamo is modulated on time scales from that of the sunspot cycle up to the longest records available without only a weak tendency for dominant periodicities in these records. Consequently, we need to rely on models for the Sun's dynamo, for the effects of the magnetic field on SSI, and for the open-field component on the solar wind and the GCR population (assuming that knowledge of the Earth's magnetic field is obtained from geological, paleontological, and historical studies). The large uncertainty in the TSI values derived to date, and the difficulties in establishing reliable SSI records from proxies demonstrates that validation of these models must rest on ongoing observations of the Sun and heliosphere as well as on observations of the ensemble of Sun-like stars. Observations of Sun-like stars can provide information in a multitude of different ways. For example, dynamo patterns have been observed in dozens of Sun-like stars for several decades, and now for tens of thousands of stars with NASA's Kepler satellite, and correlations between surface magnetism, starspot coverage, and (spectral) irradiance variability are within our empirical grasp. The spectral irradiance of Sun-like stars that appear to be in a Maunder-minimum state can be observed from X-rays to radio waves with the observational tools at our disposal. Models of the solar dynamo can be guided by observations of stars with fundamental properties both similar to and distinct from those of the Sun, thus enabling dynamo theorists to probe which parameters are most important as well as to test their models with. Properties of evolving stellar filaments or of large flares as proxies for coronal mass ejections can be established. Even the loss of angular momentum over millions to billions of years enables us to better understand the solar wind and its effects on GCR populations. All of these empirical stellar data allow the development and validation of the models that we need to connect the proxies of solar activity available to us for long-term studies to reliable, accurate determinations of SSI over time scales up to multiple millennia, critically important for the development of the solar input into the Earth's climate system on multi-century time scales that enables key long-term runs to validate global climate models subject to external driving.

#### **4. Research needs and opportunities for the near future**

The preceding sections describing the recent work on the Sun-climate connection lead us to formulate the following as the most important areas in which the LWS TR&T program can effectively contribute given the expertise of the researcher pool that fall within its domain and the available research budget:

Establishment of a reliable SSI record that combines all available measurements collected during the space age, and that is associated with quantified uncertainties. This project should be executed by two or more independent groups in order to ensure that independent validation of the results is performed.

More work is needed in the area of understanding atmospheric impacts of solar spectral irradiance variations on the upper and middle atmosphere on the time scale of the 11-yr solar cycle. Such understanding will contribute to improved GCM simulations of the Sun-climate coupling on centennial time scales.

Development of the understanding and tools needed to transform radionuclide and sunspot records over past centuries to millennia into estimated SSI values, with an assessment of the associated uncertainties. This effort includes:

The study of recent minimum-activity states of the Sun in comparison with the state during the Maunder Minimum to provide a baseline reference level for TSI and SSI variability over multiple centuries.

The utilization of observations of Sun-like stars from X-ray to infrared to guide and test the SSI model(s) developed for the Sun.

Study of the chemistry and dynamics of the middle and upper terrestrial atmosphere subject to X-ray, (E)UV, and energetic-particle exposure, in order to effectively couple such SSI models to global circulation models. Such studies are needed to deepen our understanding of couplings with the terrestrial climate system from oceans and landmasses up to the top of the thermosphere (including the different roles and efficiencies of top-down and bottom-up mechanisms).

The separation of responsibilities for the NASA Heliophysics and Earth Science divisions now lies at the stratopause. Research shows that the climate system couples across this rather arbitrary administrative divide. Hence, we recommend that the impact of the division of responsibilities within NASA's SMD on Sun-climate science be assessed and ways be identified to minimize its negative effects while optimizing utility of available resources: collaborative efforts between NASA's Earth Sciences and Heliophysics divisions should be strategically developed to effectively meet the needs of Sun-climate science and should be designed to provide the necessary resources to address the outstanding questions.

In partnership with NOAA and NSF establish the variability in regional climates and correlate these with SSI records over the time interval over which reliable SSI information is available. On the short term, this means focusing on the most recent three decades. Once the proxy-based SSI data are demonstrated to be accurate and reliable, the period can be extended to the beginning of the 20<sup>th</sup> Century for which many solar observations are available. Eventually, this work can be extended to multiple centuries once it has been demonstrated that SSI records can be reliably based on sunspot numbers or even radionuclide data.

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In partnership with NSF and SMD's Astrophysics Division, support the development of a predictive dynamo model of the Sun that incorporates both the small-scale near-surface dynamo and the deeper-seated global dynamo, guided by both solar and stellar observations.

## 5. Recommendations for the Future of the TR&T program Implementation

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

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

Among the specific suggestions for inter-agency efforts are improvement of standardization and sharing of data products;

a broad assessment of available proxy data for both climate and solar and heliospheric activity;

intercalibration of satellite-based atmospheric remote sensing measurements for missions supported by NASA Earth Science and Heliophysics to provide a combined assessment of solar cycle signals in key parameters such as ozone,

a coordinated effort to combine solar and stellar information on dynamo processes and on spectral irradiance variability, and

laboratory experiments on cloud nucleation.

The resources of the NASA/LWS program preclude, by itself, the formation and funding of research projects that range from the solar drivers to long-term global circulation models.

Unless partnerships can be developed that enable such comprehensive research efforts, the LWS TR&T program should stimulate key independent projects that are well defined by the proposing team and judged to be feasible by the review team. We recommend against the formation of teams after the proposal selection as is done in the FSTs: the range of expertise needed for Sun-climate studies is so wide that the likelihood of successful formation of a team based on post-selection grouping appears dangerously small and detrimental to the project

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success. On the other hand, we recommend the development of a process by which PIs feel stimulated to assemble larger teams to address promising and important projects that require a more substantial investment than the commonly requested magnitude of about M\$0.5/yr. The selection process should fairly judge scientific importance and likelihood of success in the ranking of larger and smaller proposals.

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

**APPENDIX F -- SUBGROUP 3: MAGNETOSPHERIC**

## **Assessment of the Progress of the LWS Targeted Research and Technology (TR&T) Program on Achieving Strategic Goal 3**

*Deliver the understanding and modeling required for effective forecasting/specification of magnetospheric radiation and plasma environment*

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### **1. Introduction**

During the last 10 years, the LWS TR&T Program on Strategic Goal 3 has been guided by the following rationale, articulated by the Science Definition Team:

“National infrastructures are increasingly dependent on satellites orbiting Earth. With advances in miniaturization, these systems are becoming more sensitive to variations in their space environment. This goal aims to develop the space technology developers and to protect these assets through improved characterization of magnetospheric particle populations and electric and magnetic fields through their full range of variations. A part of this endeavor is an understanding of the physical processes responsible for these variations and especially for their extremes.”

The LWS TR&T Program has contributed very substantially to various facets of Strategic Goal 3. These contributions should be viewed in the context of progress in this area over the last decade, summarized in the Decadal Strategy study, component “Solar and Space Physics: A Science for a Technological Society”, released recently (August 2012) by the National Research Council. Among the highlights from the last decade are:

“Significantly deeper knowledge of the numerous processes involved in the acceleration and loss of particles in Earth’s radiation belts;”

“New understanding of how oxygen from Earth’s own atmosphere contributes to space storms;”

“Major advances in understanding the structure, dynamics, and linkages in other planetary magnetospheres, especially those of Mercury, Jupiter, and Saturn;”

“New understanding of the temporal and spatial scales involved in magnetospheric-atmospheric coupling in Earth’s aurora.”

As also discussed in the Decadal Strategy Study (see, in particular, Chapter 2, sub-section on “Solar Wind-Magnetosphere Interactions”), there have been several notable developments

over the last ten years. In what follows, we discuss these developments briefly, mapping them on to the efforts supported by the LWS TR&T program.

## **2. Progress Toward Strategic Goal 3**

In this section, we report briefly on the Focus Science Topics (FSTs) and Strategic Capabilities (SCs) that the program has invested in over the last ten years. We present a list and brief summary of these topics chronologically, followed by a commentary on how such investments have contributed to the furthering of Goal 3.

### *2.1 Focus Science Topics and Strategic Capabilities*

The following is a chronological list of FSTs invested in Goal 3 in the last 10 years:

2004: Formation and loss of new radiation belts in the slot region;

2005: Solar wind plasma entry and transport in the magnetosphere;

2006: Effects of ionospheric-magnetospheric plasma redistribution on storms;

2007: Toward combined models of acceleration, loss, and transport of energetic electrons and protons in the magnetosphere;

2008: Integrate non-MHD/kinetic effects on magnetic reconnection, particle energization, and plasma heating into global models;

2009: (i) Determine the behavior of the plasmasphere and its influence on the ionosphere and magnetosphere;

(ii) Plasma-neutral gas coupling;

2010: Incorporating plasma waves in models of the radiation belts and ring current;

2012: Interaction between the magnetotail and the inner magnetosphere and the impact of that interaction on the radiation belt environment.

The Strategic Capability (SC) that is primarily relevant to Goal 3 occurred under the auspices of the NSF-NASA-AFOSR Partnership for Collaborative Space Weather Modeling is:

2005: A comprehensive magnetosphere-ionosphere model.

### *2.2 Accomplishments*

We now discuss below how research carried out under the auspices of the FSTs and the SC (listed above) have produced results towards furthering Strategic Goal 3. Several of these accomplishments have been articulated in the Decadal Strategic Study.

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

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

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

global simulations confirmed the major role ionospheric outflow plays in the creation of sawtooth intervals.

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

### **3. Future Directions for Strategic Goal 3**

Carry out integrated studies of the coupling and feedback between the magnetosphere-thermosphere-ionosphere system under variable solar wind conditions

Advance physical understanding of the magnetosphere and its coupling to the ionosphere and thermosphere by comparing models against observations from different planetary magnetospheres

Synthesis of global and particle models in predicting the production, energization and loss of energetic particles in the magnetosphere

Establish how fast reconnection and secondary instabilities are triggered in the plasma environment of the magnetosphere and how they drive mass, momentum, and energy transport

**APPENDIX G -- SUBGROUP 4: UPPER ATMOSPHERE AND  
IONOSPHERE**

## Assessment of the Progress of the LWS Targeted Research and Technology (TR&T) Program on Achieving Strategic Goal 4:

*“Deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation and the solar wind, and to coupling above and below.”*

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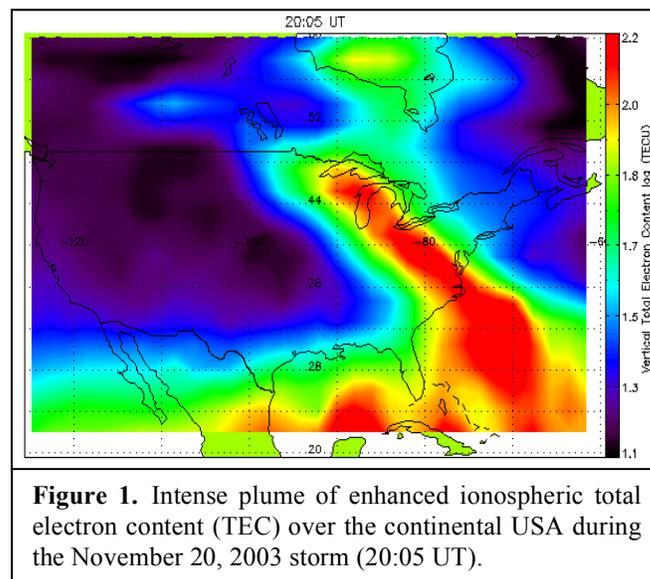
### 1.1 Introduction

The thermosphere and ionosphere occupy the altitude region of the Earth’s atmosphere between about 100 – 1000 km and they represent the transition region between the lower atmosphere and space plasmas as represented by the magnetosphere and solar wind. As such, the thermosphere and ionosphere are subject to a large number of processes involved in coupling to the regions above and below. Thus, their variability depends to a large extent on drivers above and below, and as a result the characteristics of the thermosphere and ionosphere are strongly dependent on local time and geographic latitude. Key properties of the neutral gas in the thermosphere include the neutral density and composition, temperature, and the neutral wind velocity (horizontal and vertical). Key properties of the ionosphere include the global 3-D electron density distribution, and the motion of the plasma under the influence of electric and magnetic fields. The most important drivers of the I-T system are solar EUV and UV radiation, magnetospheric forcing at high latitudes, and planetary-scale upward propagating waves and tides from the lower atmosphere. Each of these forcing terms can vary on timescales ranging from seconds to years. Less important forms of external forcing include direct solar wind particle precipitation at high latitudes, and coupling between the ionosphere and inner magnetosphere (plasmasphere and radiation belts) at lower latitudes. The ionosphere and thermosphere are also strongly coupled to each other, and so changes in one produce changes in the other. For example, neutral wind speeds are partially determined by the ion drag force, which depends on the ionospheric electron density. Gravity waves propagating through the neutral gas drive corresponding motions in the ionospheric plasma, which manifest as traveling ionospheric disturbances. On longer timescales, non-migrating tides generated in the middle and lower atmosphere propagate into the thermosphere and produce signatures in ionospheric parameters including total electron content (TEC), and the diurnal tide is an important factor in ionospheric behavior at low latitudes.

### 1.2 Societal Relevance:

Because many of our modern technologies utilize or depend upon the thermosphere and ionosphere for their reliable operation, thermosphere-ionosphere science has more direct applications than other branches of space physics. As society becomes increasingly dependent on technology, we become more susceptible to variations in the ionosphere and thermosphere because of their effects on these technological systems, ranging from position, navigation, timing, communications, and surveillance systems, the power grid, oil pipelines, banking systems, and satellites. The risk to some of these critical infrastructures from geomagnetic storms is so large that special workshops have recently been convened to study them. Some of these effects are described below:

**1.2.1 Ionosphere:** Because of its plasma properties, the ionosphere interacts with a broad range of electro-magnetic waves at frequencies that are important to civilian and military activities. It therefore plays a major role in communications, navigation, and surveillance operations. The ionosphere can affect radio systems at all frequencies, either through large-scale variation of the electron density (e.g. the ionosphere may not support High Frequency radio communications at certain frequencies at certain times of day), or through small-scale irregularities (e.g. GPS navigation capability is disrupted by scintillation of GPS signals due to the presence of ionospheric irregularities).



An example of an ionospheric phenomenon that has numerous operational consequences is illustrated in Figure 1. It shows an intense plume of enhanced ionospheric total electron content (TEC) measured over the continental USA at the time of the maximum phase of the November 20, 2003 magnetic storm (20:05 UT). The plume feature is called “Storm Enhanced Density” (SED). When it occurs, it can have significant impacts on navigation, communication and surveillance systems. For example, SEDs have caused complete outage of the FAA’s Wide Area Augmentation System (WAAS) [Diehl, 2004] that is based on GPS

signals and is designed to facilitate higher cadence aircraft landings by providing improved positioning and navigation capabilities. The WAAS, and other GPS-based systems, are susceptible to further outages from SEDs in the future. We do not understand exactly what causes SEDs, and we can only predict their occurrence and location on a statistical basis, therefore features like the SED and their effects on radio systems speak to the need for a better understanding of the ionospheric variability.

There is a need to specify current ionospheric conditions and also to forecast ionospheric behavior more accurately. It continues to be a challenge to adequately predict many aspects of ionospheric behavior in many important circumstances. While climatological models can be useful in certain circumstances, the ionosphere is extremely variable. The ultimate goal of ionospheric research is to develop first principles models that have the external drivers, the coupling to other regions, and the internal processes sufficiently well described so that the ionospheric behavior can be accurately simulated from the largest scales (100 km), which affect thermospheric behavior, to the small scale (1m) irregularities that cause scintillation of GPS signals. While assimilative models can contribute to improved specification of the current state of the ionosphere, there is generally too little data for ingestion, leaving large uncertainties in the global electron density distribution.

**1.2.2 Thermosphere:** The thermospheric neutral density exerts drag on Low-Earth Orbiting (LEO) satellites. Changes in the density, temperature, winds, and composition of the neutral atmosphere create variable satellite drag, adversely affecting missions like maneuver planning, re-entry prediction, collision avoidance, risk analysis, and identification and tracking of objects in space using narrow field-of-view sensors. This is a priority Space Hazard identified in the LWS Science Architecture Team Report to SECAS ([http://lws.gsfc.nasa.gov/docs/LWSSAT\\_SECASreport\\_30Aug01.pdf](http://lws.gsfc.nasa.gov/docs/LWSSAT_SECASreport_30Aug01.pdf)), and this high priority was maintained in the LWS TR&T report published in 2003. A major reason for tracking orbiting objects is for manned space flight safety and the protection of space assets. For example, the International Space Station is frequently reoriented or boosted to a higher orbit to avoid collisions with orbiting debris. During shuttle missions, USSTRATCOM computed possible close approaches of other orbiting objects with the shuttle's flight path. The US Strategic Command (USSTRATCOM) tracks about 8,500 man-made space objects orbiting Earth that are 10 centimeters or larger. About 7 percent are operational satellites, 15 percent are rocket bodies, and about 78 percent are fragmentation and inactive satellites. For the next few years, worldwide, about 120 new satellites per year are conservatively expected to be launched, and this number will multiply if the dream of nano-satellite fleets ever becomes reality.

There is a need to specify current thermospheric conditions and also to forecast its behavior more accurately up to several days in advance. Climatological models of the thermosphere are heavily used, and can be useful in certain circumstances, but the thermosphere is extremely variable. The ultimate goal would be to develop first principles models that have the external drivers, the coupling to other regions, and the internal processes sufficiently well described that the thermospheric behavior can be accurately simulated from the largest scales (1000 km) to the scale of auroral arcs (1 km). There are currently far too few measurements available to specify thermospheric properties, including density, composition, temperatures and winds.

While 3-D global models of the thermosphere exist, there is inadequate data to verify their behavior. What are needed are collocated simultaneous measurements of all the relevant parameters needed to understand both the thermospheric and ionospheric behaviors and their coupling on different spatial and temporal scales.

Finally, the thermosphere is subject to the effects of greenhouse gases, and appears to be undergoing climate change. The cause of these changes is not fully understood, but there seems to be a consistent cooling of the thermosphere and consequent reduction of thermospheric density. In turn, this means that LEO satellites can remain in orbit for longer than might previously have been possible.

This section focuses specifically on the Strategic Goal related to the upper atmosphere and ionosphere:

***Strategic Goal #4: deliver understanding and predictive models of upper atmospheric and ionospheric responses to changes in solar electromagnetic radiation and solar wind, and to coupling to adjacent regions above and below.***

and its associated Objectives and Priorities:

***Objective 1: Predict the effects of space weather on the global behavior of ionospheric density in the altitude range from 100 to 1000 km.***

*Priorities:*

- *Develop a dynamic thermosphere-ionosphere model.*
- *Develop the capability to specify low and mid-latitude electric fields.*

***Objective 2: Determine the effects of long and short-term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe these effects with accuracy better than 5%.***

***Objective 3: Understand and predict satellite drag variations during geomagnetic storms and during the solar activity cycle.***

*Priorities:*

- *Develop accurate empirical neutral wind models.*
- *Develop more advanced thermosphere density and composition models*

***Objective 4: Quantify the influence of space weather on the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.***

*Priorities:*

- *Develop accurate onset and evolution models of plasma instabilities in the ionosphere.*
- *Develop and test models of electrodynamics at low and mid latitudes.*

## **2. Decadal Progress toward Goal 4**

### **2.1 Focused Science Topic (FST) and Strategic Capability investments in Goal 1**

A list of the nine (9) FST groups and two (2) Strategic Capabilities that incorporate the upper atmosphere and ionosphere category is provided below.

#### Focused Science Teams

- 2010: “Low-To Mid-Latitude Ionospheric Irregularities and Turbulence”, PI/lead J. Huba  
2009: “Determine the Behavior of the Plasmasphere and its Influence on the Ionosphere and Magnetosphere”, PI/lead P. Brandt  
2009: “Neutral-Plasma Coupling”, PI/lead G. Crowley  
2008: “Determine and Quantify the Responses of Atmospheric/Ionospheric Composition and Temperature to Solar XUV Spectral Variability and Energetic Particles”, PI/lead E. Talaat  
2007: “Determine the sources of daily variability in the thermosphere and ionosphere”, PI/lead S. Solomon  
2006: “Effects of Ionospheric-Magnetospheric Plasma Redistribution on Storms”, PI/lead W. Lotko  
2006: “Global Distribution, Sources and Effects of Large Density Gradients”, PI/lead R. A. Heelis  
2005: “Storm effects on global electrodynamics and middle and low latitude ionosphere”, PI/lead T. Fuller-Rowell  
2004: “Response of thermospheric density and composition to solar and high latitude forcing”, PI/lead A.D. Richmond

#### Strategic Capabilities

- 2005: “A Comprehensive Magnetosphere-Ionosphere Model”, PI/lead Aaron Ridley  
2008: “Integrated Model of the Atmosphere-Ionosphere System”, PI/lead Rolando Garcia

The FST groups included specifically focused ionospheric and thermospheric research, but also included one team with coupling to the plasmasphere, and another with coupling to the magnetosphere. There is no FST group involving in coupling to the lower atmosphere, however, the Strategic Capabilities included one group modeling the explicit coupling to the lower atmosphere, and the other modeling the explicit coupling to the magnetosphere.

It is the nature of research that scientists make incremental steps before making discoveries and developing publishable results. It should be noted that many of the scientists funded by the LWS TR&T program are also funded by other agencies, including NSF, and various branches of the DoD. Therefore, it is difficult to isolate results of LWS TR&T research from other programs. The LWS TR&T Program has contributed very substantially to various facets of Strategic Goal 4. These contributions should be viewed in the context of progress in this area over the last decade, as summarized for example in the Decadal Strategy study, component “Solar and Space Physics: A Science for a Technological Society”, released in

August 2012 by the National Research Council. In that report, some of the advances in ionospheric and thermospheric science were categorized as follows:

Active Ionosphere During Solar Minimum  
Global Density Structure and Reactive Feedback  
Storm Dynamics  
Tropospheric Driving  
Thermospheric Climate Change

This LWS TR&T program decadal report reaches similar conclusions. Progress has been made during the past 10 years in each of the four (4) Objectives listed above for Strategic Goal 4, and their corresponding Priority areas. In this report, we first identify results and discoveries according to one of these four Objectives, and then we also identify scientific results related to coupling between regions. All of the results listed here were provided to NASA as part of annual or final reports to the LWS program. It should also be noted that the LWS TR&T program has from time to time included other elements in addition to FST and Strategic Capability grants, namely Tools and Methods, which have provided opportunities to develop new infrastructure for research including new or validated datasets, new analysis methods or measurement techniques, and new software modules or model capabilities. It is the opinion of the Ionosphere-thermosphere community that these infrastructure-building grants are a valuable adjunct to the FST and SC grants.

## **2.2 Objective 1: Predict the effects of space weather on the global behavior of ionospheric density in the altitude range from 100 to 1000 km.**

The generation and re-distribution of plasma in the ionosphere during major storms are dramatic phenomena with significant deleterious impacts on critical communication and navigation systems. Many of the changes in the ionosphere are induced by the imposition of electric fields from the magnetosphere, modified by the changed ionospheric conductivity. Ionospheric plasma can be transported across many degrees of latitude at sub-auroral latitudes, sometimes resulting in the well-known polar cap patches that have been studied for over twenty years.

One of the most surprising discoveries of the past decade is the enhancement of the TEC in the middle-latitude dayside ionosphere that is observed during geomagnetic storms. This large scale structuring of the ionosphere is called the Storm Enhanced Density (SED) feature, and it is particularly important because of the strong gradients associated with the SEDs. Sightings of such structures seem to have a preference for US longitudes for reasons that are not entirely understood. Discovery of these features has been made possible by the availability of ubiquitous low-cost measurements of GPS-TEC (total electron content) across the US and other countries during the past decade,

Understanding of penetration electric fields has moved to the fore, and there has been some success including those effects in global models and understanding their effects on the middle-to-low latitude ionosphere. Empirical models of low latitude E-fields have also been developed. Storm time signatures of the ionospheric zonal ion drifts at middle latitudes and their relationship with particle precipitation have been studied. During the main phase of

superstorms, ion drifts driven by the magnetosphere penetrate to latitudes as low as the dip equator on the dusk side but extend only a few degrees equatorward of the auroral zone on the dawn side. Evidence for ion drifts driven by disturbance dynamo from middle and low latitude wind systems may be found during the storm recovery phase when the interplanetary magnetic field is less strongly southward or turns northward. Electric fields also play a role in changing locally the net production of ionization as well as transporting it. For example, after uplift of the low latitude ionospheric F-layer by a strong stormtime penetration electric field, the enhanced plasma fountain can interact with stormtime neutral wind surges that travel from high to low latitudes, resulting in plasma convergence in altitude and the formation of additional ionization layers underneath the EIA crests.

Coupling of the ionosphere to the thermosphere has also been studied. The ionosphere and thermosphere occupy the same volume, and are generally strongly coupled with important feedbacks on each one that are still being explored and are not fully understood. In fact, the Decadal Survey called out Plasma-Neutral Coupling as a key area for continued study. While there are well-developed first-principles models, there are still many processes and mechanisms that need to be elucidated, and the models often use various parameterizations of important physical processes that only approximate reality and need further study. Most first-principles models of the ionosphere do not extend to 1000 km, and therefore exclude the topside ionosphere and plasmasphere, although this is being remedied by the coupling of plasmaspheric models with I-T models, as discussed below in Section 2.6.1.

### **2.3 Objective 2: Determine the effects of long and short-term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe these effects with accuracy better than 5%.**

Our understanding of the global response of the thermosphere to external stimuli has improved during this decade, mainly via modeling and from the analysis of data from the CHAMP and GRACE missions. In particular, the effects of solar radiative variability and high latitude forcing, including energetic particles are much better understood. The propagation of tides and planetary scale waves from the lower atmosphere, and their effects on both the thermosphere and ionosphere have been noted above. There has also been a growing level of awareness of the importance and complexity of wave-wave coupling. At smaller scales, the ubiquitous presence of gravity waves in the thermosphere has been recognized, including their possible contributions to the global atmospheric structure via energy and momentum fluxes. However, in spite of their importance, there is no global climatological model of gravity waves in the thermosphere/ionosphere.

Given the CHAMP, GRACE and other datasets, along with solar UV data and improved numerical models, there has been a significant advance in our understanding of thermospheric behavior on both long and short scales. Thermospheric total mass density was earlier predicted to decrease with time due to increasing CO<sub>2</sub> concentrations. This has been confirmed by studies of long-term variations in satellite orbits, with an overall trend of  $-2.68 \pm 0.49\%$  per decade and trends of  $\sim -5\%$  and  $-2\%$  per decade at solar minimum and maximum, respectively, in quantitative agreement with theoretical predictions. The global

average density trends also depend on the phase of the year, with the strongest trends around October and weak trends in January.

The thermospheric semiannual/seasonal density variation has been known to exist for many years. Evaluation of historical radar observational data processed with special orbit perturbations for over twenty satellites has revealed that the semiannual variation is extremely variable from year to year. The magnitude of the maximum yearly difference, from the July minimum to the October maximum, can vary by as much as 100% from one year to the next, and the timing of the maxima and minima can also shift significantly. A high correlation exists between this maximum difference and the phase of the solar cycle as indicated by solar EUV data. New solar indices for the EUV and FUV wavelengths have been developed that can accurately describe the variations in the observed yearly semiannual amplitude in semi-empirical models.

The thermospheric semiannual/seasonal density and composition variation had previously been explained in terms of seasonal thermospheric winds. However, closer evaluation revealed that the thermospheric wind effect is too small. The annual insolation variation due to the Sun-Earth distance can cause an annual variation; large-scale inter-hemispheric circulation can cause a global semiannual variation; and geomagnetic activity can also have a small contribution to the semiannual amplitude. Simulations, using first principles models indicate that a candidate for the semiannual density variation is change in composition, driven by eddy mixing in the mesopause region, which has a strong seasonal variation. Model-data comparisons have shown that transmission of turbulent mixing from the lower atmosphere may contribute to seasonal variation in the thermosphere, particularly the asymmetry between solstices that cannot be explained by other mechanisms.

With the inclusion of reasonable high latitude and solar forcing, the goal of 5% accuracy using first principles models of the thermosphere is now within reach for lower altitudes, on a daily basis for geomagnetic quiet times. However, our ability to model regional features of the thermospheric density are still lacking, and our understanding and ability to model the exosphere are rudimentary due to the presence of lighter species such as H and He, and their non-fluid behavior at altitudes above about 500 km (the exobase). Geomagnetic forcing is difficult to specify in the models, and is a limiting factor in our ability to model the observed thermospheric density variations.

#### **2.4 Objective 3: Understand and predict satellite drag variations during geomagnetic storms and during the solar activity cycle.**

Satellite drag depends on the ballistic coefficient, thermospheric density, temperature, and neutral winds. The effects of in-track winds have been shown to be generally on the order of <5%, although in the polar regions during times of geomagnetic activity, when winds can approach 1000 m/s, the in-track wind effect may not be negligible. The neutral wind is also important because it drives ionospheric plasma directly via ion-neutral collisions, and indirectly via dynamo processes, making it important for understanding ionospheric behavior. The neutral wind is also a sensitive parameter by which first-principles models can be validated and calibrated, making it a valuable measurement to help with model improvement.

Unfortunately, our understanding of the thermospheric neutral wind and its variability is lacking, due to the sparseness of measurements. During the last decade, a new empirical model of the neutral wind has been developed, which provides a statistical representation of the horizontal wind fields of the Earth's atmosphere from the ground to the exobase (0 to 500 km). It includes representations of the zonal mean circulation, stationary planetary waves, migrating tides, and the seasonal modulation thereof. It is comprised of two components, a quiet-time component for the background state and a geomagnetic-storm-time component. The lack of neutral wind measurements to specify the climatology represents a challenge, and points to the need for more neutral wind measurements in the thermosphere.

The study of thermospheric density and satellite drag has been enabled by the availability of accelerometer data from the CHAMP and GRACE satellites. A great deal of effort has been expended to calibrate and validate the neutral densities derived from these data.

At high latitudes, the electric field and its variability drive corresponding variability and structuring in the high latitude thermospheric density and composition, however they are also a major driver of global thermospheric variability. These density perturbations affect satellite drag, and therefore satellite orbits.

The effects of high-latitude ionospheric electric field variability on Joule heating and the mechanical energy transfer rate have received a great deal of attention during this decade, and are much better understood. Part of our new understanding stems from the term analysis of forces in model simulations, which has given us insight into the physical mechanisms causing various phenomena. The balance of forces and the corresponding response to magnetospheric inputs varies as a function of altitude. The amount of Joule heating and mechanical energy transfer rate in the thermosphere is significantly altered by taking into account the electric field variability and its space-time structure. The altitude distribution of the energy deposition also strongly affects the thermospheric response.

A quasi-nine day thermospheric density variation has been discovered during this decade. The quasi-nine day variation is caused by corresponding variations in the solar wind speed, known as High Speed Streams, which are caused by rotating solar coronal holes. In turn, the solar wind variation drives corresponding variations in geomagnetic forcing, and a strong global I-T response. The thermospheric density response is reflected in thermospheric composition, and in the peak value and the peak height of the F-region electron density at all latitudes. The quasi-nine day cycle repeated many times during the solar minimum interval from about 2005-2010, and was easier to observe due to the lack of random geomagnetic activity from coronal mass ejections during that time period.

The high latitude inputs to GCMs have been represented by climatological and assimilative models of the electric fields and particle precipitation. Recently, the Poynting Flux has also been studied as a model driver, and the discovery was made that the cusp region can experience unexpectedly strong downward Poynting Flux. This local deposition of significant energy can produce large thermospheric neutral density maxima. These large Poynting Flux events tend to occur during conditions with a strong IMF By component. Cusp density enhancements were discovered by the CHAMP satellite mission, although their cause remained a mystery until recently. They can only be reproduced by first principles models that utilize high fidelity high latitude drivers, rather than climatological drivers, which are too smooth. These cusp region density enhancements are completely separate phenomena than

the density cell structures that are driven by momentum forcing, and have completely different characteristics and morphology. Both types of structure have corresponding neutral composition variations that contribute to the observed neutral density structure.

**2.5 Objective 4: Quantify the influence of space weather on the intensity and location of plasma irregularities in the 100 km to 1000 km altitude region.**

On smaller scales, the growth of ionospheric irregularities is of great interest, due to their effects on operational radio frequency (RF) technological systems, as noted above. Yet this topic presents many challenges. Satellite observations have revealed that these irregularities can extend for hundreds of kilometers in the north-south direction. New ground-based technologies have become available to measure and monitor ionospheric irregularities. These new technologies include both measurements of perturbations on GPS/GNSS signals and variations in 6300 airglow radiances to detect ionospheric irregularities. While these measurements have shed new light on the morphology and distribution of ionospheric irregularities at both high and low latitudes, there are insufficient observations to reliably map the irregularities either from the ground or from space. The lack of data adds to the difficulty of developing models to predict the onset and evolution of ionospheric irregularities. Since we know generally what are the instability criteria, and that the height of the ionospheric F-region is an important component in determining instability, it is sometimes possible to use mechanistic models driven by available measurements to predict the likelihood of instability and the formation of irregularities. There have also been first-principles approaches to simulate generic ionospheric irregularities. These simulations have shown that the formation of the plasma depletion shell of low latitude ionospheric bubbles is consistent with the latitudinal/altitudinal shear in the zonal plasma flow. Other key findings include the following: a ‘super fountain’ effect can occur in the initial stage of irregularity formation with upward ion velocities  $\sim 1$  km/s; plasma depletions can be enhanced by the ‘drainage’ of  $H^+$  ions along the geomagnetic field; molecular ions (e.g.,  $NO^+$ ) can be ‘lifted’ to high altitudes ( $\sim 400$  km); ions and electrons undergo both cooling and heating during bubble evolution (the main cause of cooling is adiabatic, associated with the increase of the flux tube volume as the plasma bubble rises. Ion heating is primarily caused by the compression of ions as they stream down the converging magnetic field. The electrons are heated by collisional coupling with the ions. Additionally, it is found that the electrons are heated at altitudes  $>1200$  km because of thermal conduction, and that hydrogen ions can be heated at relatively altitudes near  $\sim 300$  km because of ion-neutral frictional heating). The spatial variation in the upward ExB drift velocity is caused primarily by the altitude dependent field-line integrated conductivities. This is also a factor in the maximum bubble altitude. However, no systematic study has been performed to explicitly identify what stops bubbles from rising. This is an important issue that must be addressed in the future. In addition, there are competing theories about what could trigger the growth of plasma bubbles: gravity waves or shears in the bottomside ionosphere. Although there have been several modeling approaches, it is still not possible to accurately predict the occurrence of the irregularities that cause ionospheric scintillation. The C/NOFS satellite is making comprehensive measurements of the equatorial ionosphere, and these data should be further analyzed together with ground-based data and modeling studies to better

understand equatorial plasma bubbles and irregularities, and their effects on radio signals such as ESF on HF systems, and scintillation on L-band and UHF signals.

## **2.6 Coupling to Regions Above and Below**

In the past, the various atmospheric layers were studied in isolation from each other. However, in the last 10 years, a much more system-wide view has been taken, with the recognition that each layer affects neighboring layers. In this vein, the coupling of the ionosphere-thermosphere region with the lower atmosphere below, and the magnetosphere above has received significant attention, with advances described below. Models of the thermosphere and ionosphere are being coupled with models of the plasmasphere, ring current, and MHD models of the outer magnetosphere. They are also being extended to the ground by coupling to lower atmosphere models, several of which are assimilative so that the lower atmosphere drivers are expected to be very realistic, producing realistic space weather effects in the upper atmosphere.

### ***2.6.1 Coupling with the Magnetosphere (and Plasmasphere)***

The ionosphere has important impacts on both the inner magnetosphere (plasmasphere) and outer magnetosphere, mainly by providing ionized plasma that affects the characteristics and behavior of these regions. During this decade, the role of different types of ionospheric outflows in global magnetospheric dynamics, and of the feedback of magnetospheric changes on the dynamic state of the ionosphere has been explored for various solar wind drivers and magnetospheric conditions.

Work has been performed to determine the physical processes that regulate auroral and cusp-region outflows from the ionospheric F-region up to the low-altitude boundary of global magnetosphere models. Correlation studies based on FAST satellite data have provided new knowledge of the role of Alfvén waves, dc Poynting flux, electron precipitation and low-frequency turbulence in driving ionospheric outflows. This research has also seen the development of “scaling law” representations of ionospheric outflows in terms of causal drivers, including electromagnetic power and electron precipitation characteristics. Accomplishments also include: upward ion flux in response to auroral precipitation; clarification of the relationship of the occurrence of lobe ion beams to the occurrence of ionospheric redistribution events and their effects on ionospheric outflow and transport; incorporation of lumped transport models of causally driven ionospheric outflows into global ionospheric-magnetospheric models; evaluation of the role of different types of ionospheric outflows in global magnetospheric dynamics; and the feedback of magnetospheric changes on the dynamic state of the ionosphere for various solar-wind drivers and magnetospheric conditions; determined how the plasma sheet distribution and composition change during a storm and for different solar wind drivers; determined changes in the state of the plasmasheet including ion composition over the course of a storm and how these changes influence the ring current and the boundary conditions used to drive ring current models.

The presence of ionospheric  $O^+$  in the magnetosphere-ionosphere convection cycle has the capacity to regulate solar wind-magnetosphere coupling by undermining the dayside-nightside balance of reconnection. Specifically, the inertia of  $O^+$  ions flowing into the nightside merging region from the lobes diminishes reconnection there, without simultaneously moderating the

dayside rate. This imbalance cannot persist, and either the nightside merging line must migrate earthward to enable a higher inflow of magnetic flux, or dayside merging must decrease on average. Which state ensues depends on the flux, velocity and location of the ionospheric outflow. Electromagnetic power flowing from the solar wind dynamo into geospace is reduced as dayside and nightside reconnection synchronize at a lower average rate. Convection and, thus, the cross-polar cap potential are also reduced, as is the flux of outflowing ionospheric ions, access of solar wind plasma to the inner magnetosphere, and the amplitude of magnetopause surface waves.

The 2-5 hour planetary-scale oscillation of the geospace system known as the sawtooth mode was discovered in geostationary satellite data 20 years ago, yet its origins remain unknown. A breakthrough in understanding the phenomenon is emerging from multifluid simulations of the solar wind-magnetosphere-ionosphere (SW-M-I) interaction, which show that ionospheric  $O^+$  outflows can induce sawtooth oscillations for steady SW driving. The threshold for oscillation depends on the bulk properties and spatial distribution of the outflow.

### ***2.6.2 Coupling with Lower Atmosphere***

There has been a realization that tides and waves propagating from the lower atmosphere produce signatures in the thermosphere neutral density, composition, temperatures, winds, and electric fields, with corresponding effects on the ionosphere. As mentioned above, this has led to the development of Whole Atmosphere models extending from the troposphere to the thermosphere, including the funding of a Strategic Capability by the LWS TR&T program. Numerical experiments indicate the amplitudes of the main tidal modes can be forecast several days ahead indicating a possibility for prediction of the electrodynamic and ionospheric response.

While tidal effects are always present, there are shorter-lived effects such as Stratospheric Sudden Warmings (SSWs) that are caused by wave-wave Interactions and that have large effects on the global ionosphere. Observations have shown that lunar tides could be important for ionosphere variability (and possibly for satellite drag), and can display large short-term variability during SSWs.

Studies of the whole atmosphere have also revealed how changes in one region of the atmosphere can have global repercussions. These phenomena are known as whole atmosphere teleconnections. Observed temperature anomalies from the stratosphere to the lower thermosphere (15-110km) reveal a clear correlation pattern over the whole atmosphere during Northern Hemisphere winter, independent from SSWs. These patterns are closely tied to anomalies in the circulation driven by planetary waves and gravity waves.

### 3. Assessment of importance of the special structure of the TR&T program to achieving progress.

Much has been written in previous sections about the unique structure of the LWS TR&T program, and how that has led to its success. Most people believe that the team structure of the FSTs has helped retain focus and accountability, and the interactions have sparked new collaborations and interactions that are beneficial to the advancement of science. These interactions are often interdisciplinary in nature. The I-T community has also benefitted from the Tools and Methods infrastructure grants, which have led to many new analysis techniques, new datasets and/or new software modules to perform specific tasks within numerical models. Some of these products are briefly listed here:

the CHAMP and GRACE density estimates are now understood to have suffered from biases of up to 30% in the past, but they have now been refined to provide a better resource for thermospheric research;

the unique data set represented by topside ionograms from the Alouette 2, ISIS 1, and ISIS 2 topside sounders between 1962-1990 were rescued from the original analog telemetry tapes and digitized;

a new technique was developed for determining midlatitude O<sup>+</sup>/H<sup>+</sup> transition heights from topside ionograms;

development of a time-dependent solver for electron and ion energy equations, as a part of an ionospheric model (the new implementation also enables the model to better resolve the thermosphere/ionosphere energetics, since the ion-neutral collision is one of the dominant thermospheric heating sources);

extended a gravity wave parameterization scheme based upon Lindzen's linear saturation theory, by including the Coriolis effect to better describe inertia-gravity waves (IGW). (The new parameterization affects the wave breaking level and acceleration rates mainly through changing the critical level. Quasi-biennial oscillations (QBO) can be internally generated with the proper selection of the parameters of the scheme. The characteristics of the wind oscillations thus generated compare well with the observed QBO. These experiments demonstrate the need to parameterize IGWs for generating the QBO in General Circulation Models);

addition of two new sources of CO to model chemistry: reaction of CO<sub>2</sub> with ionized oxygen, O<sup>+</sup>, and extreme ultraviolet photodissociation (EUV) of CO<sub>2</sub>. (Both these sources are found to be important in the lower thermosphere, and bring model predictions closer to observations);

forward model for simulating IMAGE/EUV images of the plasmasphere

a new empirical model of the neutral wind provides a statistical representation of the horizontal wind fields from the ground to the exobase (0 to 500 km). It includes representations of the zonal mean circulation, stationary planetary waves, migrating tides, and the seasonal modulation thereof. It is comprised of two components, a quiet-time component for the background state and a geomagnetic-storm-time component;

an improved Solar Spectrum Representation has been developed. It uses a four-temperature model code to obtain a spectrum for which the temperatures are a combination of quiet Sun,

active network, active region/plage, and coronal loop temperatures. The four temperature divisions are coincident with four spatial features that are identified and implemented in separate code for automated image feature extraction. These improved solar spectral representations are expected to improve thermospheric modeling;

a solar EUV parameterization scheme has been developed that extends through the Schumann-Runge continuum of the FUV spectral range, and is required for thermospheric modeling;

simplified empirical models have been developed of the electron and ion auroral energy inputs, Poynting flux and of the electric and perturbation magnetic fields that depend on the magnitude and orientation of the IMF, as well as on season, latitude, and magnetic local time. These simplified models of the high-latitude auroral precipitation and electrodynamics are being implemented to specify energy inputs to a thermosphere-ionosphere GCM.

#### 4. Research needs and opportunities for the next 10 years

In addressing the LWS TR&T focus for the next 10 years, one should ask whether the original goals have been met, and where work needs to continue, and what are the new topics that were not addressed by the previous Objectives and Priorities. In reviewing the Objectives and Priorities of Strategic Goal #4, one is forced to conclude that although tremendous progress has been achieved in the past 10 years, a great deal of work remains to be done to accomplish the original objectives.

##### *Thermosphere:*

The study of thermospheric neutral density was aided by the availability of accelerometer data from the CHAMP and GRACE satellite missions. These missions have now ended, but data from two new ongoing missions, GOCE and Swarm, are available and should be used for continuing studies of thermospheric density and satellite drag. This is especially relevant because of the advances in first principles thermospheric modeling that is entering a new phase of development with high fidelity drivers of the high latitudes and lower boundaries, together with assimilative capabilities.

Except for the development of a new empirical global wind model, global neutral dynamics (thermospheric winds) have generally been ignored, yet they are an important driver of the ionosphere, driver of dynamo E-fields, driver of composition, and they are extremely variable due to external drivers and coupling from above and below. Empirical wind models suffer from a lack of thermospheric wind data, and there is a lack of wind measurements for validating models or diagnosing thermospheric dynamics and wind-dynamo effects. It is time to deploy a large number of inexpensive ground-based instruments to measure the thermospheric neutral wind on a global basis, and to deploy a new satellite instrument. The development of new capabilities for measuring global thermospheric winds under all solar and geomagnetic conditions should be pursued. Analysis of existing winds data should be made a priority.

The ubiquitous presence of gravity waves in the thermosphere has been recognized, including their possible contributions to the global atmospheric structure via energy and momentum fluxes. However there is no global climatology of gravity waves in the thermosphere/ionosphere. During the next decade, we should discover what are their global characteristics, and sources, and we should learn more about how they propagate and dissipate. Their dissipation in particular is thought to drive effects on the global atmospheric structure, including the thermospheric energy and momentum balance. Similarly, these waves have large effects on the ionosphere, leading to the phenomenon of Traveling Ionospheric Disturbances (TIDs). TIDs are an important aspect of Space Weather that affect many operational systems, and therefore have societal relevance.

The semi-annual or seasonal variation of thermospheric density and composition drive corresponding changes in the ionosphere. To improve first principles models and their ability predict densities for satellite drag, they must be enhanced to simulate these large amplitude perturbations using appropriate parameterizations of eddy mixing or other mechanisms. We are just beginning to understand the role of energetic particle precipitation on the lower thermosphere, and the subsequent downward transport of reactive species to the stratosphere.

This work has implications for global change, and should be pursued. The fluxes of precipitating low, medium, and high-energy particles should be included in whole atmosphere models.

The impacts of solar spectral irradiance variations range from the effects of solar extreme ultraviolet (EUV) radiation on composition, ionization, and density in the thermosphere and ionosphere, to effects of mid-UV radiation in the lower mesosphere and stratosphere. Improved physics-based thermosphere-ionosphere models need to be developed that accurately calculate the response to solar EUV variations, including effects of magnetic activity and IMF orientation.

### ***Ionospheric Response to Storms:***

The ionosphere has probably the highest societal impact for space weather as noted above. There has been a great advance in our ability to model the ionosphere over the past 10 years, although these studies have mainly focused on understanding the global distribution of electron density, which is relatively easy to measure. As noted above there are still many unsolved problems. The capability to routinely specify low and mid-latitude electric fields is still a top priority for many aspects of ionospheric physics.

An area that has started to receive attention, and yet remains poorly understood is Geomagnetically Induced Currents (GICs). The generation, morphology and technological impacts of GICs are important because of the threat they pose to the US power grid (which can be destabilized, and components can be damaged) and oil pipelines (which can experience enhanced corrosion). The largest recorded magnetic storm occurred between August 27 and September 7, 1859 and is known as the 'Carrington Event'. The primary issue is not whether these storms will occur again, but the possibility of catastrophic damage to the U.S. electric grid, leaving millions without power for months to years. This possibility led to a 2011 JASON Summer Study funded by the DHS. During geomagnetic storms significant GIC can persist for hours, punctuated by short bursts of intense flow. Because high-voltage transformers are built to be very efficient, even relatively small GIC can saturate their cores during one half of the power cycle, causing heating and failure. False tripping of relays when GIC harmonics are present also poses a problem for the grid. A model needs to be developed to provide interconnect-scale simulation of the North American power grid for applications ranging from planning, operational support and optimization, market analysis as well as vulnerability and resiliency. Simulations are needed to understand past disruptions and prevent future ones. These simulations will require knowledge of the ground conductivity among other parameters.

The ionospheric conductivity is a key parameter that affects both high latitude coupling between the ionosphere and magnetosphere, and at low latitudes it helps to determine the distribution of electric fields in the E- and F-regions. The conductivity plays a controlling role in electrodynamics, and therefore knowledge of the conductivity (and sometimes its integrated value, conductance) is important. The ability to measure and model across many length and time scales the ionospheric conductivity, especially its gradients, is required. Recent simulation results indicate the conductivity is critically important in determining observed distributions of convection in both the ionosphere and magnetosphere and in the distribution and rate of magnetic reconnection at the magnetopause. These effects are practically

impossible to tease out with observations alone, so synergy between data and model approaches is essential.

### ***Ionospheric Irregularities:***

Although there have been several modeling approaches, it is still not possible to accurately predict the occurrence of the irregularities that cause ionospheric scintillation. Therefore it remains a priority to develop accurate onset and evolution models of plasma instabilities in the ionosphere.

The spatial variation in the upward ExB drift velocity is caused primarily by the altitude dependent field-line integrated conductivities. This is also a factor in the maximum bubble altitude. However, no systematic study has been performed to explicitly identify what stops bubbles from rising. This is an important issue that must be addressed in the future. In addition, there are competing theories about what could trigger the growth of plasma bubbles: gravity waves or shears in the bottomside ionosphere

The C/NOFS satellite is making comprehensive measurements of the equatorial ionosphere, and these data should be further analyzed together with ground-based data and modeling studies to better understand equatorial plasma bubbles and irregularities, and their effects on radio signals such as ESF on HF systems, and scintillation on L-band and UHF signals.

### ***Coupling with magnetosphere***

What are the relationships between large scale convection and precipitation patterns for adequate modeling capabilities? How should temporal variations in the convection and precipitation be included in global models of the ionosphere and thermosphere?

Develop a better understanding of collisionless transport in low-altitude (~ 1 RE) auroral and cusp acceleration regions. Much is known about basic physical mechanisms for accelerating ions and electrons in various types of waves and turbulence but this understanding is not very useful in a global simulation environment because the wave fields cannot be causally determined from global simulation variables. What are needed are transport laws like: Alfvénic power in (or electron precipitating flux in) – ion flux out, gated by physical variables such as the energy and number flux of the precipitation, the spectrum of the incident Alfvénic power, etc.

### ***Coupling with troposphere***

While the importance of lower atmosphere tides and waves as drivers of the I-T system is no longer in question, LWS should continue to emphasize studies that deconvolve the influence of upward coupling (planetary waves, gravity waves, tides) vs. in situ forcing by solar and particle inputs. Understanding of "space weather" depends on the ability to model both the upward coupling and the in-situ effects properly. We are finally are on the verge of having the modeling capability to do this, although complete coupling of dynamics/chemistry model components with full electrodynamics modules is still a work in progress.

### ***Modeling and Prediction***

A great deal of progress has been made in modeling and simulation during the past 10 years. The new model capabilities include coupling between atmospheric regions, and have largely been used for post-event analysis and to provide insight into the mechanisms that cause variability. The true test of models is their ability to make predictions, and many of the models are ready for transition from research tools to an operational basis, where they can be run in near-real time in a space-weather forecasting mode.

Assimilative models have also started to be developed, in which data can be used to improve the specification of an atmospheric region. Assimilative models have been used for decades by the meteorological community, but they are still relatively new in the thermosphere-ionosphere. Several assimilative models are either being developed or already in use for ionospheric and thermospheric specification, and this should be encouraged.

Integration of ionosphere-thermosphere models with magnetosphere models driven by the solar wind and IMF has progressed in the last decade. A particular weakness is evident in treating mass fluxes between the IT and M models. Fidelity of global simulation results depends critically on this ability.

The nonlinear equations describing the atmosphere are known to be a deterministic chaotic system, which has been extensively studied since Lorenz (1963). A characteristic feature of such systems is that small errors introduced in the initial conditions grow exponentially with time until they “saturate.” This exponential error growth fundamentally limits the predictability of numerical models. This error growth has been thoroughly studied in the context of tropospheric model predictability, but not in upper atmosphere models. As a result, the error growth in these models is still not well understood. It is thus desirable to further study the error growth in the extended models and the middle/upper atmosphere models and how the error growth rates in different atmospheric regions may affect each other. The data assimilation of the middle and upper atmosphere, which is becoming increasingly important with the growing amount of ground-based and satellite observations of the middle/upper atmosphere, also requires better understanding of the error growth in the extended models. A related but different need is to investigate the effects of a spatially and temporally adaptive covariance model on data assimilation.

One of the modeling challenges is concerned with the ambiguity of the height within hydrostatic models that use atmospheric pressure as vertical coordinates. Because the height is also a derived quantity from temperature, composition, and pressure in the model, it makes it difficult to map observations sampled at given heights to model pressure coordinates. It is important to use the height information that is consistent with the analysis of temperature and composition. In the future the uncertainty of the height associated with the inference of the temperature and composition needs to be incorporated as part of the representation errors.

### ***New tools and Datasets***

Many of the principles of I-T science have been established, and the need now is to compare models with comprehensive datasets so that hypotheses about mechanisms can be tested, and the predictive abilities of the models can be validated. Unfortunately, serendipity rarely provides the comprehensive datasets that are needed with different parameters being measured simultaneously and at the same location. The collection of such datasets has to be planned in

advance, and may include well-instrumented satellites, or multiple satellites in conjunction with ground-based measurements.

The selection of the ICON and GOLD missions by NASA will provide a much-needed boost to the I-T research community, and will provide the kind of simultaneous, collocated comprehensive datasets needed by that community. At the same time, these satellites also have limitations in coverage, and they must be complemented by ground-based measurements. Still missing will be comprehensive neutral wind measurements, and this could be remedied by more ground-based wind instruments.

The ability to model and predict ionospheric irregularities that cause scintillation of RF signals will require new data sets. Unlike TEC measurements, there are currently insufficient scintillation monitors to map the irregularities, and to track their growth and their motion. Suitable ground-based and ocean-based scintillation monitors have already been developed and could contribute to such studies. Ultraviolet remote sensing can also be used to map the irregularities on the nightside, and this could be achieved using Cubesats with existing UV instruments.

Cubesats offer an inexpensive alternative to large missions. While large missions may provide very precise measurements close to the satellite track, they are limited in their instantaneous spatial coverage. There is an argument to be made for launching constellations of Cubesats with inexpensive instruments. Although these measurements are likely to have larger error bars, the sheer quantity of data from a constellation would enable new approaches to scientific questions.

## **5. Recommendations for the Future of the TR&T Program Implementation**

One of the advantages that has been exploited by the LWS TR&T program is the diversity of different funding arrangements, ranging from focused science topics, strategic capabilities, tools and independent science, LWS postdocs, cross disciplinary infrastructure, and community workshops. This approach recognizes that no single approach can solve all problems. The I-T community therefore recommends that all of these approaches should be retained in the next decade, even though emphases may vary over time. There is a gap in funding for technology development, and this might also be included under the LWS TR&T umbrella.

The I-T community has benefitted from the Tools and Methods grants, which have led to many new analysis techniques, new datasets and/or new software modules to perform specific tasks within numerical models. These tools do not naturally emerge from purely research-focused grants. Therefore infrastructure grants should be a continuing component of the LWS TR&T program, since they enable infrastructure that in turn facilitates scientific investigation and discovery.