Chapter 4

LWS Program Elements

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

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

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

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

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

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

Basic Science Components

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

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

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

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

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

Models

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

Observations

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

Products

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

Potential User Base

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

Metrics and Assessment

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

Types of Investigation

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

Implementation Specifics

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

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

Basic Science Components

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

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

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

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

Predictive Goal

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

Models

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

Observations

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

Products

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

Potential Users of Products

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

Metrics and Assessment

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

Types of Investigations

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

Implementation Specifics

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

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

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

Basic Science Components

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

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

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

Predictive Goal

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

Models

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

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

Observations

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

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

Products

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

Potential Users of Products

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

Metrics and Assessment

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

Types of Investigations

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

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

Team Makeup and Responsibilities

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

Implementation Specifics

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

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

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

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

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

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

Target Description

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

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

Basic Science Components

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

Predictive Goal

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

Models

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

Observations

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

Products

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

Potential Users of Products

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

Metrics and Assignments

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

Types of Investigations

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

Implementation Plan

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

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

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

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

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

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

Basic Science Components

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

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

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

Predictive Goal

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

Models

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

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

Observations

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

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

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

Products

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

Potential Users of Products

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

Metrics and Assignments

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

Two types of metrics are encouraged:

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

Types of Investigations

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

Research Teams and Responsibilities

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

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

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

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

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

Implementation Plan

Several existing Focused Science Topics (FST) with the Living With a Star program, which are relevant to TEC prediction, have been solicited by the program or are currently in progress. These include:
- Thermospheric wind dynamics during geomagnetic storms and their influence on the coupled magnetosphere-ionosphere-thermosphere system
- Determine the Behavior of the Plasmasphere and its Influence on the Ionosphere and Magnetosphere
- Plasma-Neutral Gas Coupling
- Global Distribution, Sources and Effects of Large Density Gradients
- Storm effects on global electrodynamics and middle and low latitude ionosphere
- Response of thermospheric density and composition to solar and high latitude forcing
- Lower-upper atmosphere coupling for determining pre-conditioning and background conditions
- Sources and effects of large electron density gradients

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

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

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

SSA-5: Ionospheric Irregularities and Scintillation

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

Basic Science Components

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

Predictive Goals

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

Models

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

Observations

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

Products

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

Potential Users of Products

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

Metrics and Assessment

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

Types of Investigations

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

Implementation Specifics

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

SSA-6, Physics-based Radiation Environment Forecasting Capability

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

Target Description

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

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

Basic Science Components

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

Predictive Goals

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

Models

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

Observations

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

Products

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

Potential Users of Products

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

Metrics and Assignments

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

Types of Investigations

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

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

Implementation Plan

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

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

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