CHAPTER 2

CAPABILITIES, GOALS, AND STRATEGY

2.1 Background

Space weather services are currently provided by the National Oceanic and Atmospheric Administration (NOAA) Space Environment Center (SEC) and the United States Air Force (USAF) 55th Space Weather Squadron (55 SWXS), both in Colorado. The former serves civilian customers, while the latter serves the needs of the Department of Defense (DOD). At these centers, forecasting space weather is approached in much the same way as forecasting tropospheric weather. Data are collected, checked for quality, analyzed, fed into models, and displayed graphically. Forecasters mentally integrate numerical products, images, and other analyses, using experience, physical understanding, and empirical tools. A "most likely" scenario emerges of what the forecaster believes the state of the environment will evolve to from its present state. If a significant event (severe weather) is forecast, it must be assigned onset time, intensity, duration, and, if possible, how it will affect specific regions of the environment.

In assessing present capabilities we distinguish between four different types of space weather products--warnings, nowcasts, forecasts, and post-analysis--as follows:

A *warning* is given for an event that has the potential to harm satellites, equipment, and humans in the near-Earth space environment or on the ground. Warnings apply to phenomena that require a customer to take action in order to protect assets. The Earth-bound analogy is a warning issued for thunderstorms, tornadoes, etc. The key to a warning is the ability to specify when an event will occur, how intense it will be, and how long it will last. Warnings cover the 0- to 24-hour period and are based on observations of causal events (like solar flares), observations of actual events (such as a geomagnetic storm onset), or extrapolations of trends (such as increasing proton fluxes). Most warnings are issued immediately (within minutes) upon observation of a certain event or condition.

A *nowcast* begins with a specification of current conditions, typically based on observations and models that assimilate data and fill the gaps, then projects those conditions into the near future. The time range for this projection is usually slightly shorter than the time required to update the observations. Nowcasts are issued on a regular basis and may include a warning if an event is in progress.

The *forecast* differs from the nowcast in the timeframe it covers and the techniques involved in producing it. Short-term forecasts cover the period from 6 hours to several days. Mid-term forecasts extend these forecasts out to several months. Long-range forecasts can cover some parameters of the solar cycle out through 10 years. Short-term and mid-term forecasts provide general conditions and may also include warning-type events, but they are not intended to provide the timing accuracy necessary to give the fidelity that a customer may want for taking protective action. They are issued on a daily schedule that allows time for the full use of all computing tools, albeit within a rigid timeline. Longer-range solar cycle forecasts are issued monthly and computed automatically.

Post-analysis is used to identify the space weather factors that may have contributed to operational anomalies of systems affected by space weather. Observations are critical for analyzing the state of the environment when the anomaly occurred. Immediate post-analysis is required to identify whether observed anomalous behavior of a system was caused by space weather or by other factors such as mechanical failure, engineering design problems, or software errors. Post-analysis is a valuable tool in providing input into improvements in engineering designs of systems.

Although specification is not a product, it is the starting point for the products described above. Specification refers to the fusion of all available observations into a coherent and realistic representation of the state of the environment at the time of the observations. This step is critical in order to accurately initialize predictive models, perform after-the-fact analyses, and provide the forecaster with a reliable picture of present conditions. The ability to nowcast is only as good as the quality and timeliness of the observational data received and the effectiveness of models in fusing the data into coherent representations of the environment.

2.2 Current Capabilities

This section provides general information on the current operational observing systems and the models supporting forecasting operations at the NOAA Space Environment Center and the Air Force's 55th Space Weather Squadron. Figure 2-1 graphically depicts the current space weather support structure showing both ground and space-based systems and delineating civil, military, and international systems.

The section concludes with an assessment of the overall capabilities of these operational systems. Information on future operational observing systems is contained in Chapter 5 on technology transition. Descriptions of research observing systems and models are in Chapter 3.

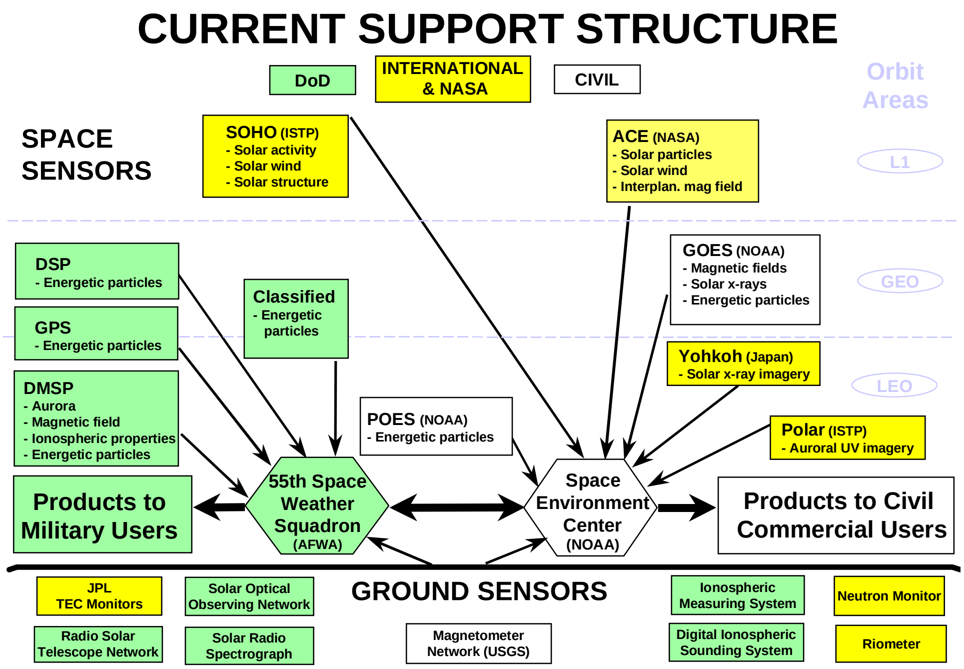

Figure 2-1. Current Space Weather Support Structure

2.2.1 Operational Observations

GOES Space Environment Monitor. The Space Environment Monitor (SEM) aboard the Geostationary Operational Environmental Satellite (GOES) measures in situ the effect of the Sun on the near-Earth solar-terrestrial electromagnetic environment, providing real-time data to the Space Environment Center (SEC). The SEM subsystem consists of four instruments used for measurements and monitoring of the near-Earth (geostationary altitude) space environment and for observing the solar x-ray output. An energetic particles sensor (EPS) and high-energy proton and alpha detector (HEPAD) monitor the incident flux density of protons, alpha particles, and electrons over an extensive range of energy levels. Solar output is monitored by an x-ray sensor (XRS) mounted on an x-ray positioning platform, fixed on the solar array yoke. Two redundant three-axis magnetometers, mounted on a deployed 3-meter boom, operate one at a time to monitor Earth's geomagnetic field strength in the vicinity of the spacecraft. The SEM instruments are capable of ground command-selectable, in-flight calibration for monitoring on-orbit performance and ensuring proper operation.

POES Space Environment Monitor. The SEM-2 Space Environment Monitor aboard the NOAA Polar-orbiting Operational Environmental Satellites is a multi-channel charged-particle spectrometer which senses the flux of charged particles at the satellite altitude, and thus contributes to knowledge of the solar-terrestrial environment. SEM-1 units have been in orbit on the TIROS-N series since 1978. SEM-2 consists of two detectors: the total energy detector (TED) and the medium energy proton and electron detector (MEPED) along with a data processing unit (DPU).

DMSP. The Defense Meteorological Satellite Program (DMSP) is now operated by the Department of Commerce as part of the convergence of polar orbiting environmental satellite programs. POES and DMSP will be replaced by the National Polar-orbiting Operational Environmental Satellite System (NPOESS) beginning in about 2008. The DMSP program designs, builds, launches, and maintains several near polar orbiting, Sun synchronous satellites monitoring the meteorological, oceanographic, and solar-terrestrial physics environments. The satellites are Sun synchronous at an altitude of approximately 830 km above the Earth. The orbit period is approximately 101 minutes. Since there are usually two satellites, separated in longitude by approximately six hours of local time, global coverage is provided every six hours.

Each DMSP satellite monitors the atmospheric, oceanographic and solar-geophysical environment of the Earth. The visible and infrared sensors collect images of global cloud distribution across a 3,000 km swath during both daytime and nighttime conditions. The coverage of the microwave imager and sounders is one-half the visible and infrared sensors' coverage, thus they cover the polar regions above 60° latitude on a twice daily basis but the equatorial region on a daily basis. The space environmental sensors record along-track plasma densities, velocities, composition and drifts. The space environment instruments on DMSP are the SSJ/4 (Precipitating Electron and Ion Spectrometer), the SSIES (Ion Scintillation Monitor), and the SSM (Magnetometer).

The data from the DMSP satellites are received and used at operational centers on a continual basis. The data are sent daily to the National Geophysical Data Center (NGDC), Solar Terrestrial Physics Division (STPD) for creation of an archive.

Advanced Composition Explorer (ACE). The Advanced Composition Explorer (ACE) flies at the L1 libration point approximately 1.5 million kilometers sunward from Earth. The ACE RTSW (Real-Time Solar Wind) system provides data to continuously monitor the solar wind and to allow SEC to produce warnings of impending major geomagnetic activity, up to one hour in advance. The RTSW system gathers data at high time resolution from four ACE instruments (MAG - magnetic field vectors, SWEPAM - solar wind ions, EPAM - energetic ions and electrons, and SIS - high-energy particle fluxes), packs the data into a low-rate bit stream, and broadcasts the data continuously. With a combination of dedicated ground stations (Communications Research Laboratory [CRL] in Japan and Rutherford Appleton Laboratory [RAL] in the United Kingdom), and time on existing ground tracking networks (NASA's DSN and the USAF's AFSCN), the RTSW system can receive data 24 hours per day throughout the year. The data are downloaded, processed, and dispersed within five minutes from the time they leave ACE. The raw data are immediately sent from the ground station to the Space Environment Center, processed, and then delivered to the CRL Regional Warning Center at Hiraiso, Japan, to the USAF 55th Space Weather Squadron, and placed on the World Wide Web. The low-energy energetic particles information from ACE RTSW are used to warn of approaching interplanetary shocks and to help monitor the flux of high-energy particles that can produce radiation damage in satellite systems. The ACE data became operational on January 21, 1998, and drive a model developed to predict geomagnetic K-indices up to two hours in advance of their observation at Earth. Alerts and warnings of geomagnetic storms based on ACE data have been implemented in SEC.

Ionosonde Network. The Air Force's 55th Space Weather Squadron operates the USAF Digital Ionospheric Sounding System (DISS) network in order to observe and specify the global ionosphere in real time. There are over a dozen fully automated digital ionosondes deployed worldwide to perform this function. These fully automated ionosondes are derived from the well known Digisondes developed at the University of Massachusetts at Lowell (UML). They are nearly identical to UML's Digisonde 256 (D256), which has been available since the mid-1980s. Additional ionosondes exist to supplement the DISS network, but they do not report observations in real time. Their data satisfy Air Force needs for 6- to 24-hour delayed summaries. The DISS network ionosondes are found primarily in the mid-latitude Northern Hemisphere, particularly in the continental United States.

The DISS network provides data for many USAF products, including specification and forecasts of primary and secondary HF radio propagation characteristics, ionospheric electron density and total electron content, ionospheric scintillation, environmental conditions for spacecraft anomalies, and sunspot number. DISS products are used by the Air Force, Army, Navy, Coast Guard, and the DOD's Unified Commands. NASA Wallops Island and the Arecibo Observatory are also customers for DISS products.

Scintillation Network Decision Aid (SCINDA). SCINDA is a regional nowcasting and short-term forecasting system for UHF and L-band scintillation at equatorial latitudes. It accepts data from ground-based instruments measuring amplitude fluctuations from UHF and L-band receivers and uses these data to generate tailored nowcast and forecast products for tactical users in a graphical depiction. Furthermore, it can accept measurements from DMSP satellites that show areas where scintillation is likely to form in a given night. Basic proof-of-principle validation is currently underway.

Magnetometers. Magnetometers measure variations in the Earth's magnetic field. The United States Geological Survey (USGS) operates one of several networks of ground-based magnetometers. Several of these magnetometers provide the data used at the Air Force's 55th Space Weather Squadron to compute the level of geomagnetic activity in real time. These indices are used to analyze for satellite drag and ionospheric propagation conditions, as well as providing an indication of the strength of currents flowing in the upper atmosphere and the near-Earth space environment.

GPS Receivers. The worldwide network of 170 GPS receivers managed by NASA's Jet Propulsion Laboratory continuously monitors the dual frequency L-band signals from GPS satellites. Each receiver is capable of receiving signals from more than eight satellites simultaneously. The data collected from this network include carrier phase and group delay to derive the total electron content (TEC) of the ionosphere along these different ray paths to the satellites. The TEC data are interpolated to obtain Global

Ionospheric Maps (GIM) of TEC every 15 minutes. Differential maps indicating the percentage change of TEC between magnetically quiet and disturbed periods have also been generated to monitor storm-induced TEC perturbations every 15 minutes.

Ground-based Coronagraphs. Coronagraphs provide images of the Sun's corona, the outermost layer of the solar atmosphere. Ground-based coronagraphs complement space-based instruments. A white light coronometer is located at the Mauna Loa Solar Observatory in Hawaii, operated by the High Altitude Observatory, National Center for Atmospheric Research. A hydrogen-alpha coronograph is located at the Pic du Midi Observatory in France. Coronagraphs provide observations of coronal mass ejections.

Ground-based solar optical and radio observatories. The Air Force's Solar Electro-Optical Network (SEON) consists of both solar radio and optical telescopes. The radio telescopes provide information on the level of solar activity by monitoring radio noise. Intensities of solar radio emission during quiet and flare times are measured over the frequency range of 30 kHz to 100 GHz. Interpretation of the data is done on-site and forwarded to the forecast center in terms of Type I to Type V radio flare emission and in terms of impulsive (seconds to 10 min) or gradual (10 mins to days) events. The optical telescopes are used to make images in H-alpha and white light, as well as line-of-sight magnetograms of the surface magnetic field. These data are analyzed on-site and messages are forwarded to the forecast center, giving the current level of flare activity and filament disappearances that can lead to coronal mass ejections. Depending on the complexity of phenomena observed for the active regions, a 24-hour flare warning is issued.

2.2.2 Operational Models at the Space Environment Center

Magnetospheric Specification Model. The magnetospheric specification model developed for operational use by Rice University, with funding from the USAF and start-up funding from NOAA, is run on a regular production basis using geomagnetic indices as driver data. The model currently runs every three hours as an operational tool to provide retrospective and real-time maps of charged particle fluxes throughout the inner and middle magnetosphere. Input data from satellite and ground stations drive the model, whose primary input parameters may include Kp, magnetopause standoff distance, polar-cap potential drop, auroral boundary index, and Dst. In addition, the model can operate with reduced suites of input data and will run, if necessary, from Kp alone. The model follows particle drifts through the magnetosphere using time-dependent electric and magnetic field models while keeping track of loss by charge exchange and electron precipitation into the ionosphere. It assumes particle transport by $\mathbf{E}\times\mathbf{B}$, gradient, and curvature drift. An isotropic particle distribution is assumed to be maintained by pitch-angle scattering mechanisms that do not change particle energy. Data-based algorithms are used to specify initial condition and boundary condition particle fluxes. The model is designed to specify fluxes of electrons in the energy range responsible for spacecraft charging, ~100 eV to ~100 keV.

PROTONS. PROTONS is used to predict the temporal parameters and intensity of solar proton events once activity is observed on the Sun. The model is driven by soft-ray observations from the GOES 1-8 nanometer Space Environment Monitor and by observations from the ground-based Solar Electro-Optical Network including radio burst type (Type II and Type IV) and solar flare position. It produces a prediction of the delay and rise time to maximum and the maximum intensity of the flux of protons with energy greater than 10 MeV. The model is based on the use of parametric solutions to particle propagation equations, which are fit to actual observations of solar and energetic particle observations.

Wang and Sheeley Model. The Wang/Sheeley model is used in the SEC to predict the background solar wind speed and IMF polarity at Earth 3 to 4 days in advance. This forecasting tool is a modified version of the original Wang/Sheeley model. Using a traditional approach, the Wang/Sheeley model makes daily predictions at 1 AU for the next solar rotation based upon synoptic maps of the photospheric field from the previous rotation. Arge/Pizzo have modified the Wang/Sheeley model used in the SEC so as to take full advantage of the most recent photospheric magnetic data available; their implementation updates the synoptic charts with new magnetograms as frequently as possible and makes new predictions after each update. This modified model uses an empirically deduced function to relate the solar wind speed at the source surface with the coronal field expansion factor derived from a source surface model. The coronal divergence factors are determined by tracing the magnetic field lines down to the photosphere and calculating the ratio of the magnetic field strengths at the endpoints of each magnetic field line, relative to what is expected for purely radial expansion. The solar wind is then propagated from the source surface out to Earth using a simple mass-flux conservative algorithm to account for stream interactions along the way.

Costello Model For Predicting Kp. As implemented in SEC, the model uses ACE real time solar wind data to predict Kp. The current prediction algorithm is the Costello Neural Network (CNN) [Kirt Costello, PhD Thesis, Rice University, 1997]. Input to the CNN for each Kp output consists of two consecutive 1-hour averages of three solar wind parameters, Velocity (V), IMF magnitude (B-total), and IMF Bz component (Bz, in GSM coordinates). Effectively, pKp is computed at the location of ACE and the prediction is propagated to Earth by adding a computed lead-time to the current time. The lead-time is computed by dividing ACE's upstream distance (X-coordinate) by the measured plasma velocity, V. Lead-times are usually in the range of 30 to 60 minutes.

2.2.3 Operational Models at the 55th Space Weather Squadron

Ionospheric Activity Index (IACTIN). Provides ionospheric corrections for regional areas.

Real-Time Ionospheric Correction Maps from a CTIM. A coupled thermosphere ionosphere model (CTIM) is being used to produce an ionospheric correction map for the peak F-region electron density (NmF2) and total electron content (TEC), at middle to high latitudes. The correction map is designed to scale climatological values of NmF2 and TEC, for a given solar flux and season, in order to correct for the effects of geomagnetic disturbances including severe storms. Geomagnetic activity can cause large regional depletions (negative phase) or increases (positive phase) of electron concentration, with a distribution that depends on season and local time. The model is driven by the real-time auroral power index (PI) derived from measurement by the TIROS/NOAA polar orbiting satellite. The PI is an estimate of the auroral power input to one hemisphere of the Earth and is updated about every orbit (1.5 hours). PI values are calculated from the satellite data with a time resolution of about 45 minutes and are then used to drive the physical model to update the ionospheric correction maps.

Bent Model. This ionospheric model performs ray traces through detailed electron density profiles and is used to calculate TEC for radar signal ionospheric corrections at 55th SWXS. This analysis allows space operators to accurately locate satellite objects and to conduct threat detection propagation. The Bent Model accurately describes the ionosphere to obtain high precision radar signal delay and directional change due to refraction. Tile data upon which the Bent Model is based was collected from 1962 to 1969 and includes the solar cycle maximum and minimum. Bent Model inputs include the date, Universal Time, transmitter/receiver locations, operating frequency, space vehicle elevation and altitude rate of change, solar flux, and sunspot number. Model outputs include vertical and total electron content above the transmitter, a vertical electron density profile, and the total electron content along the path between the satellite and the tracking site.

Improved Auroral Prediction Model (IAPM). This model provides the capability to continually monitor the global position of the auroral precipitation boundary and the position of the boundary relative to Air Force installations or systems of interest. The program is a command driven system which builds and plots the auroral climatology relative to the surface of the Earth. It provides the capability to continually monitor the global position of an auroral precipitation boundary and the position of the boundary relative to Air Force installations or systems of interest. Plots of the aurora and its boundaries are based on Defense Meteorological Satellite Program (DMSP) electrostatic sensor SSJ/4 data or geomagnetic index Kp input to an electron precipitation model. The program is interactive, started manually by the user and controlled by commands or series of commands stored as macros. Options provide the capability for the user to define grid points, triangles, plotting grids, and various parameters such as date and time.

Ionospheric Communications Enhanced Profile Analysis and Circuit (ICEPAC). ICEPAC predicts the expected performance of high frequency (HF) broadcast systems, and in doing so is useful in the planning and operation of HF transmissions for the four seasons, different sunspot activities, hours of the day, and geographic location. The ICEPAC computer program is an integrated system of subroutines designed to predict high-frequency (HF) sky-wave system performance and analyze ionospheric parameters.

Ionospheric Communication Analysis and Prediction Program (IONCAP). This program predicts the maximum useable communication frequency (MUF), the frequency of optimum transmission (FOT), and the lowest useable frequency (LUF) between two transmit and receive points. It is one of several climatological ionospheric models used for applications to generate tailored warfighter products. In the IONCAP model, the numerical coefficients are functions of geographic latitude for both solar maximum and minimum. It also takes into account the retardation below the F2 layer. For the MUF computations the model uses the corrected form of Martyn's theorem. As the absorption equations using the secant law do not work for lower frequencies at altitudes below 90 km, these equations have been modified in the IONCAP program. The IONCAP provides two programs: 1) the ITS-78 (see more information below in the ITS-78 section) on short path geometry, and 2) the path >10,000 km geometry. In addition to the ITS-78 model, the path computations now include the F1 mode, the over-the-MUF mode, D and E region absorption losses, and sporadic E losses. A correction to frequency dependence is added for low frequencies reflected from altitudes below 90km.

Magnetospheric Specification Model (MSM). See description in Section 2.2.2.

Magnetospheric Specification and Forecasting Model (MSFM). The MSFM provides a nowcast of magnetospheric conditions based on first principles of physics. It is intended to provide accurate information to help prevent and diagnose spacecraft malfunctions due to charging and other environmental causes in real time. It is also capable of forecasting low-energy electron fluxes at geosynchronous altitudes for space weather forecasting.

The MSFM forecasts the near-Earth magnetospheric conditions. Information provided focuses on the fluxes of inner magnetospheric electrons, protons, and O+ ions in the energy range of up to 100KeV. This information is of value to organizations having satellites in orbit about the Earth. The AFRL space weather forecasting codes tell the operators when a satellite might encounter problems, such as disruption to electronic and communication components, due to surface charges caused by the space environment. The value of the model is that it can "read the environment" to determine if the space environmental conditions may be conducive to temporary disruption or malfunction of satellites. Once the source of the problem has been identified, operators can then circumvent the problem by finding an alternate means of collecting data from the satellite.

Parameterized Real-Time Ionospheric Specification Model (PRISM). The ultimate goal of PRISM is to provide increased accuracy for current electron density profiles, atmospheric densities, and auroral disturbances. Operators of HF and satellite communications, radar navigation systems, and operators concerned with predicting satellite orbits already use current and predicted space weather information to more efficiently operate their assets. Daily, worldwide mapping of large volumes of refreshed ionospheric data can reduce modeling errors significantly. Inputs of real-time ionospheric data can potentially improve PRISM output data. The Parameterized Real-Time Ionospheric Specification Model (PRISM) was developed by Computational Physics Incorporated (CPI) for use by the Air Force 55th Space Weather Squadron. PRISM's purpose is to provide an accurate real-time ionospheric specification for DOD use. "Ionospheric specification" specifies the state of the ionosphere globally or regionally at a given time in terms of electron density profile parameters, actual electron density profiles, or both. The most common application of PRISM is through the use of real-time measurements of certain ionospheric parameters to update a database of electron density profiles. The database is generated using specialized software that models various regions of the ionosphere based on physical principles. This database can be updated with data received from a number of different sensors at any time and the effects of the ionosphere on tracking measurements are computed by integrating the total electron current (TEC) along the appropriate line-of-sight.

WideBand Model (WBMOD). WBMOD is a radio frequency ionospheric scintillation code which specifies scintillation parameters, as a function of a variety of geophysical parameters, between any location on the globe and a satellite above 100 km altitude for any frequency above 100 MHz. This information is used to support military systems for communications, command and control, navigation, and surveillance that depend on reliable and relatively noise-free transmission of radio wave signals through Earth's ionosphere. Small-scale irregularities in the ionosphere's density can cause severe distortion of both the amplitude and phase of these signals. WBMOD is used to assess and forecast the radio wave scintillation resulting from these irregularities. The model was developed based on analysis of data from the Defense Nuclear Agency (DNA) Wideband satellite experiment. Due to the limited coverage of the data used in developing the model (a single station at high latitudes and two stations at equatorial latitudes), a recent validation of the WBMOD model showed that it was deficient in a number of areas.

Proton Prediction System (PPS). PPS has been constructed to model protons that are accelerated during energetic solar events (i.e., those associated with flares) near the solar surface. It does not model proton acceleration that might occur in an interplanetary shock propagating towards Earth. The model generates a computerized time-intensity profile of the solar proton intensity expected at the Earth after the occurrence of a significant solar flare on the Sun. Predictions of solar protons, alpha particles, and iron nuclei are available. This forecast is based on location of the solar flare in the heliocentric coordinates and the magnitude of the Sun's output in x-ray or radio wavelengths. Data collected from numerous spacecraft formulate the basis for the mathematical expression relating the Sun's output to the flux of energetic solar particles during the course of an event. Inputs to the model are solar flare time, location, and intensity. The flare intensity may be input using x-ray or radio data. The outputs of PPS include the polar cap riometer absorption maximum and time, high altitude radiation dose level and time, Extra-Vehicular Activity (EVA) radiation dose level and time, protons (greater than 10 p/cc greater than 5,10, and 50 MeV) maximum flux and time, and total fluence.

Ramsey-Bussey Total Electron Content (RBTEC). The Ramsey-Bussey Total Electron Content [RBTEC (APBA)] program was developed as an effort to produce a realistic electron density profile (EDP) based on parameters which can be forecast reasonably accurately. The output produced by the APBA program is used to aid in predicting errors occurring in range and azimuth of satellite tracking radar due to the effects of ionospheric retardation and refraction. The model was developed to predict electron densities from 0 to 1000 km altitude.

Shock Time of Arrival (STOA). This model forecasts the time of arrival of a solar wind shock at the Earth based on solar x-ray and radio data. The STOA model is a physically-based model derived from three-dimensional magnetohydrodynamic simulations. The model inputs are flare time, location, type II radio burst speed, solar wind background velocity, and flare intensity in x-rays and decay times. Model outputs include the time of arrival at the observer (default is Earth - 1 AU), the speed of the shock (Mach number), the total propagation time, and a two-dimensional shock front map at 3-hour intervals.

Global Ionospheric Forecast Model (IFM). The Air Force's three-dimensional, time-dependent model of the global ionosphere was streamlined in an effort to develop a computationally fast, user friendly, reliable, Ionospheric Forecast Model (IFM). The model yields predictions for the molecular and oxygen ion densities and the ion and electron temperatures over the globe at E and F region altitudes. The model also contains a simple algorithm for predicting H+ densities in the F region. The inputs needed by the IFM are global distributions of the neutral densities, temperatures, and winds, the auroral oval precipitation, the magnetospheric and dynamo electric fields, and the topside electron heat flux. Because of the model's modular construction, the IFM can readily accept different global input patterns and, hence, has the capability of being driven by real-time inputs from Air Force satellites or ground-based sites. In the current version of the model, the input patterns have been selected and the IFM is therefore self-contained and can be driven by simple geophysical indices.

Combined Release and Radiation Effects Satellite Electron Model (CRRESELE). CRRESELE is used to map the electron flux models into a three-dimensional grid specified by the user. CRRESELE predicts the omni-directional electron fluences for 10 energy intervals (0.5-6.6 MeV). The CRRESELE software uses flux models created from data collected by the high-energy electron fluxmeter on board the CRRES system. CRRESELE is actually eight different electron fluence models. Six of the eight are parameterized by geomagnetic data. The other two models are for average conditions and a model for the maximum flux values. CRRESELE inputs include magnetic field model choice, energy channel (10 levels with central energies between 0.65 - 5.75 MeV electrons), and geomagnetic activity level (Ap, AVE, or MAX). The CRRESELE output is a 3-D gridded data set of proton flux for the selected energy channel and activity level (including AVE and MAX) in units of #/cm2/sec/KeV. The CRRESELE model is accessible as a science model in GEOSpace, a workstation software suite developed by the Air Force's Phillips Laboratory.

Combined Release and Radiation Effect Satellite Proton Flux Model (CRRESPRO). CRRESPRO is used to map the proton flux data sets used to create a three-dimensional grid specified by the users. CRRESPRO science and application modules are a UNIX port of the PC program developed and released by the Air Force Research Laboratory. CRRESPRO predicts the proton omni-directional fluence per year and integral omni-directional fluence per year at selected energies in the range 1-100 MeV for an orbit that the user specifies. The CRRESPRO software uses flux models created from data collected by the proton telescope on board the CRRES system. CRRESPRO inputs include magnetic field model choice, energy channel (22 levels between 1-100 MeV protons), and active or quiet conditions. Active conditions use data after the March 1991 storm that produced a significant third radiation belt. Quiet conditions use the data before the storm. The CRRESPRO output is a 3-D gridded data set of proton flux for the selected energy channel and activity level in units of #/cm2/sec/MeV. The CRRESPRO model is also accessible as a science model in the GEOSpace suite.

Combined Release and Radiation Effects Satellite Radiation Dose Model (CRRESRAD). CRRESRAD measures the energy deposited by radiation in a material per unit mass of the material. CRRESRAD predicts the amount of radiation received in a specific orbit by various levels of aluminum shielding during a user-specified time period. The prediction is based on empirical models of accumulated radiation measured by the Space Radiation Dosimeter on board the CRRES. The minimum energies required for particles to penetrate the domes of various thicknesses and accumulate doses in the silicon detectors underneath were 20, 35, 50 and 75 MeV for protons and 1, 2.5, 5 and 10 MeV for electrons. Geomagnetic activity is classified as quiet (before the March 1991 storm), active (after the March 1991 storm), or average (average of quiet and active data). CRRESRAD inputs include magnetic field model choice, hemisphere, channel (LOLET or HILET), and geomagnetic activity (QUIET, ACTIVE, or AVERAGE). The CRRESRAD output is a 3-D gridded data set of the dose rate in units of Rads/Si/sec for the selected shielding level and channel. The CRRESRAD model is also accessible as a science model in the GEOSpace suite.

International Union of Radio Science Coefficients for CY88 (URSI-88). The establishment of a new set of coefficients to numerically map the global variation of foF2 has been developed by a working group under the auspices of the International Union of Radio Science. Global maps that represent the monthly median behavior of ionospheric parameters have been an integral part of ionospheric modeling efforts and propagation prediction methods for over 25 years. Following the 1966 work of Jones and Gallet to adopt a set of CCIR numerical coefficients that could be used to represent the monthly median critical frequency of the F2 region, foF2 can be calculated at any point on the globe at a given universal time. These coefficients were determined from a spherical harmonic analysis of data observed between 1954 and 1958 at over 150 ionosonde locations around the world. In 1970, the CCIR adopted yet another set of coefficients derived from a similar data set but containing a better representation of the solar cycle variation of foF2.

ITS-78 Ionospheric Model. This is the most widely used numerical model for ionospheric predictions. ITS-78 is a major climatological ionospheric model used to generate circuit operational parameters such as the maximum usable frequency (MUF), optimum traffic frequency (FOT), and the lowest usable frequency (LUF). The ITS-78 model and its computer programs were developed by the Institute of Telecommunication Sciences, Earth Sciences Services Administration, Boulder, Colorado. The model is based on the presentation of the ionospheric characteristics in a form of synoptic numerical coefficients developed by Jones and Gallet (1960) and improved by Jones. The important features of the ITS-78 model are the parameters for the D, E, sporadic E and F2 layers of the ionosphere.

Orbit-Application Module (ORBIT-APP). The Orbit application module in GEOSpace provides an interface to the orbit generation and prediction codes. The interface and code generation are shared among several modules requiring code generation. The ORBIT application module provides an interface to the LOKANGL and SGP4 or bit generation and prediction codes. Other modules using the orbit generation modules are the CRRESRAD, CRRESPRO, and CRRESELE applications. Input to the ORBIT application comprises orbital elements and start and stop times of the orbit interval to be predicted. Several methods for inputting the orbital elements are available. The input window is logically divided into three areas: a propagator/element type section, an orbital element input section, and an auxiliary input area. The ORBIT application allows the orbit to be generated by using either the LOKANGLE or SGP4 orbit propagator codes. In addition, the orbital elements to be used by the propagator may be specified in a variety of ways.

Magnetic Field Models (MFM). The Earth's magnetic field is usually modeled as the sum of the "main" internal magnetic field, which is, for the most part, attributed to currents within Earth's core, and an "external" field, attributed to ionospheric and magnetospheric currents. The magnetic field of the Earth dominates over the Interplanetary Magnetic Field (IMF) in the near-Earth environment area called the magnetosphere. Several magnetic field models have been developed to specify the field in the magnetosphere. The code calculates corrected geomagnetic (CGM) coordinates and several other geomagnetic field parameters for geographically specified points on Earth's surface or in near-Earth space. The underlying geomagnetic field is the Definite/International Geomagnetic Reference Field (DRG/IGRF).

Parameterized Ionospheric Specification Model (PIM). PIM is the base ionospheric model on which the Parameterized Real-time Specification Model (PRISM) operates. PRISM uses data from ground-based and satellite-based sources to adjust the parameterized model, giving a near real-time specification of the ionosphere. The PIM science module is a relatively fast global ionospheric model based on the combined output of several physical ionospheric models.

2.3 Assessment of Current Capabilities

Table 2-1 illustrates current capabilities in each space weather region to warn, nowcast, forecast, and provide post-analysis products for space weather events. Red means there is no capability to meet the requirements for the events in the given region, yellow/red indicates very limited capability, and yellow indicates some capability short of meeting operational requirements. No areas are coded green because user-specified needs cannot be met in any area at the present time.

Table 2-1. Current Capabilities Based on Requirements

	Warning	Nowcast	Forecast	Post-Analysis
Solar/Interplanetary	Yellow/Red	Yellow/Red	Yellow/Red	Yellow
Magnetosphere	Red	Yellow/Red	Red	Yellow/Red
Ionosphere	Red	Yellow/Red	Red	Yellow
Neutral Atmosphere	Red	Yellow/Red	Red	Yellow/Red

The following paragraphs summarize the current capabilities in each of the four product areas.

Warnings. Very little capability exists to warn for space weather events. Causal solar events can be detected in real time, but warnings based on these events lack sufficient reliability for immediate mitigation actions and do not provide useful lead time or information on magnitude and duration of the event. Capability is strongest (albeit very limited) in the solar/interplanetary region because of the 24-hour observing system of solar observatories.

Nowcasts. Limited nowcasting capability based on rudimentary models exists at operational centers. However, the models offer little capability beyond information available from empirical methods and climatology. Capability is best when data to initialize the models are received in a timely manner.

Forecasts. Forecasting capability suffers from the same weaknesses as warning capability, and in addition the challenge is greater because forecasting requires longer lead times. This in turn requires a more complete understanding of both the solar events that drive space weather and the way the space environment reacts to those events.

Post-Analyses. Current capabilities are the strongest in support of post-analysis requirements; however, significant deficiencies still exist. The relatively strong capability in this area derives from the fact that some post-analyses are not required in real time. This allows the analyst to gather data that may not have been immediately available to operators and to assimilate it at leisure.

In summary, these limited capabilities come from a basic understanding of space weather combined with a limited observation base and still rudimentary computer models. However, they lack the necessary accuracy and four-dimensional detail to meet operational requirements.

2.4 Assessing Capabilities with Metrics

A "space weather metric" is a quantitative measure of the ability of a scientific algorithm or model to predict or nowcast the value of a physical parameter involved in space weather. A specific metric has three elements:

- A parameter defined at some position and time (for example, the F-region peak electron density at mid-latitude every hour for the next day).
- An observable to which a prediction can be compared (e.g., density measurement by an incoherent-backscatter radar facility).
- A criterion by which the metric is quantified (e.g., RMS difference between prediction and observation).

The Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA) and the U. S. Air Force 55th Space Weather Squadron provide space forecasts and nowcasts for a wide variety of practical applications. Those agencies have developed "application metrics" for measuring the value and validity of the specific services they provide. However, for the purpose of measuring the overall progress of the NSWP, it is useful for the scientific community to define a separate and broader set of metrics, for the following reasons:

- Application metrics change as technologies change. Metrics for the NSWP must remain valid at least for the ten-year life span of the Program.
- Scientific metrics must be open to the scientific community. Although application metrics developed by the NOAA Space Environment Center are public and involve no proprietary information, some applications metrics often involve defense secrets (military) or trade secrets (commercial users).
- Although there is remarkable overlap between parameters that are important to the application community and scientifically important parameters, the overlap is not 100%. For example, ring-current ions are an important element of magnetospheric physics but have little direct effect on present technological systems.
- To measure progress, scientific metrics should have a scale that encompasses both presently available scientific algorithms and the best that we could hope for by the end of the NSWP. Present algorithms are not good enough to make useful predictions of all aspects of space weather and might thus score zero on some application metrics. There is also a chance that our ability to predict some parameters will, by the end of the NSWP, exceed what is needed for present technologies. A good scientific metric should encompass both extremes.

Although metrics play a major role in some fields of physical science (notably meteorology), their use is far from universal and most space scientists are unused to dealing with them. To study the use of metrics for assessing progress in the NSWP, the National Science Foundation convened three study panels. The metrics study panels were designed to include representatives from NOAA/SEC and the Air Force who are familiar with the needs of the users of space weather services, and to include some people with experience with metrics. A major goal of the study was to acquaint the space physics research community with the idea of metrics and to initiate scientific discussion of the subject. To this end, a special session was held at the Fall 1997 meeting of the American Geophysical Union, and metrics presentations have been given at three other large meetings.

The panels recommended that the following types of metric evaluations be undertaken as soon as possible to establish a regular program of scientific metrics for space weather capabilities:

Type 1. Measurements should be made at a regular cadence and compared systematically with algorithm or model predictions to establish statistically valid baseline metrics. In addition to the overall averages, average errors should be recorded for different conditions (e.g., *Kp* levels in the case of magnetosphere-ionosphere metrics).

Type 2. When groups of scientists carry out event studies, comparing various models and other algorithms to observations, they should evaluate their models and algorithms in terms of the same standard metrics used in the statistical analyses of Type 1. This would help to tie event studies and campaigns, which are a regular feature of cooperative research programs (e.g. CEDAR, GEM, SHINE) as well as some NASA spacecraft programs, to progress of the NSWP.

Care must be taken to withhold from the input suite any data that will be used to test the model. In some cases, withholding those data may artificially degrade model performance. This is an advantage of testing of Type 2 as part of scientific campaigns, which generally utilize more data than is routinely available at the forecast centers. Those additional data could be used for testing without degradation of the input stream.

This metrics study was divided into three disciplinary areas: Ionosphere-Thermosphere (I-T), Magnetosphere-Ionosphere (M-I), and Solar-Interplanetary (S-I). The following paragraphs list metrics appropriate for each area as well as concerns specific to each. The physical systems are, of course, closely coupled. A physical model of Earth's magnetosphere must be driven by information about the solar wind, and a physical model of the Earth's ionosphere and thermosphere must be driven by inputs from both the magnetosphere and the Sun. Therefore, some of the metrics listed in the M-I section were, in fact, forced by the needs of I-T models, and all of the metrics listed in the S-I section represent requirements of the M-I and I-T models.

2.4.1 Ionosphere-Thermosphere Metrics

The principal ionosphere-thermosphere parameters that need to be predicted are shown in Table 2-2, grouped according to priority. Ability to forecast or nowcast ionosphere-thermosphere weather should be judged according to ability to deal with the parameters listed.

For each physical parameter, metrics should be defined that measure ability to forecast and nowcast the climatological mean, the one-sigma limits in the daily values ("day to day variability"), a particular time interval (e.g., one-day forecast), and the departure from the climatological mean over a particular interval. An additional set of metrics is needed to specify and forecast macroscopic features that can dominate certain regions of the ionosphere-thermosphere domain, including the Appleton anomaly, high-latitude features (sub-auroral trough, tongues and holes in polar cap ionization, neutral density holes), equatorial pre-reversal enhancement in vertical ion drift, transient ionospheric disturbances (TIDs), and the ratio of atomic oxygen to molecular nitrogen column abundance.

Table 2-2. Priority List of Key Physical Parameters for the Ionosphere and Thermosphere

First Priority:
Electron density N_e, including intrinsic variability
Neutral mass density ρ, including intrinsic variability
$\delta N_e/N_e$, the amplitude of the electron density irregularities
Second Priority:
Neutral and ion composition
Thermospheric winds and temperatures
Low-latitude ion drifts
Third Priority:
Electron and ion temperature
Fourth Priority:
Minor species

No single metric adequately represents our overall ability to forecast and nowcast the state of the ionosphere and thermosphere. Table 2-3 presents a focused set of five. The best single metric is judged to be the first entry of Table 2-3: the RMS error in the electron density from 200 km to 600 km, for stations at low, middle, and high latitudes. The selection in Table 2-3 is based on two criteria – the importance of the parameter in describing the state and condition of the I-T system, and the availability of routine, accurate measurements for quantifying our forecast and nowcast capabilities. The details for the first high priority metric from the table above are described in Figure 2-2.

Table 2-3. Priority Ionosphere-Thermosphere Metrics

Category	Parameter	Place	Time	Cadence	Data	Criterion
F-region ionosphere	*Minimum:* NmF2, hmF2 *Desired:* N_e(200-600), Δh ~20 km	Low, mid, and high latitudes	03-09 LT 09-15 LT 15-21 LT 21-03 LT	Hourly	Ionosonde or incoherent scatter radar (Jicamarca, Arecibo, Millstone Hill, and Sondre Stromfjord)	RMSE
High-latitude structure	N_e (~800 km)	Orbit plane of polar satellite Poleward of 45 deg mag lat Δx ~100 km	Every orbit	Every orbit	DMSP - SSIES	RMSE
Pre-reversal enhancement	Peak magnitude of vertical ion drift V_i (400 km)	Magnetic equator	16-20 LT	Daily	Incoherent scatter radar (Jicamarca)	Obs-model or RMSE
Scintillation/ Ionospheric irregularities	σ_ϕ, S_4 at 250 MHz and 1 GHz	Between +20 and -20 deg dip latitude	18-04 LT Δt ~ 1 hr	Daily	Geostationary and GPS satellites	RMSE
Electron content	Peak TEC and N/S latitude location of Equatorial Ionization Anomaly	N/A	Every orbit of observation	Every orbit of observation	TOPEX	Obs-model/ obs or RMSE

The four incoherent scatter radars of the U. S. meridional chain represent a convenient means to routinely measure electron densities in the altitude range 200 km to 600 km with 20 km altitude resolution. Because the radars are operated for at least 24 hours continuously approximately each month in support of the World Day experiments, metrics can be determined on nearly a monthly basis. This ensures adequate sampling as a function of season. The numerous observation periods per year will also ensure good sampling during quiet, moderate, and disturbed geomagnetic periods.

The NSWP ionosphere-thermosphere metric to be determined for each of the four incoherent scatter radars is given by the following formula:

$$\Delta = \frac{1}{24 \times 21} \sum_{t=0}^{23} \left\{ \sum_{h=200,20}^{600} \left[n_{o;t}(h) - n_{m;t}(h) \right]^2 \right\}^{1/2}$$

Where $n_{o;t}(h)$ is the observed density at altitude h and time t and $n_{m;t}(h)$ is the corresponding model value. This gives the RMS error in the density measured/computed hourly at 21 altitudes, averaged over 24 hours.

Allowed inputs for the models include A_p, K_p, F10.7, and all normally available satellite data.

Figure 2-2. NSWP Ionosphere-Thermosphere Metric 1

2.4.2 Magnetosphere-Ionosphere Metrics

Table 2-4 lists major aspects of the Earth's magnetosphere and its coupling to the ionosphere. A central difficult issue for the Magnetosphere-Ionosphere Panel has been how to cover all of the important aspects of the many-faceted system with just a few metrics. The aspects listed are coupled to each other in various ways, but the ability to forecast one does not imply the ability to forecast others. The dynamical behavior of the radiation belts, for example, is quite different from the dynamical behavior of the aurora or the plasmasphere.

Table 2-5 lists top-priority magnetospheric metrics as well as details related to data collection methods. The ionospheric electric field and the precipitating electron fluxes were chosen partly because of their importance as inputs for ionosphere-thermosphere models. Several magnetic indices were included because of their wide use and because they are designed to indicate global conditions. Magnetospheric electron fluxes were

Table 2-4. Major Features of the Magnetosphere-Ionosphere Coupled System

Feature	Includes
Magnetic field configuration	Global magnetic structure, including dayside, tail; ground magnetic variations
Electric field configuration	Ionospheric and magnetospheric. Represents effects of solar-wind/magnetosphere coupling, magnetospheric convection
Auroral precipitation	Precipitation from polar cusp, polar cap, main auroral zones and plasma sheet
Trapped energetic particles	Includes ring current and inner and outer radiation belts, from ~ 1 keV to ~ 100 MeV
Cold particles	Plasmasphere, plasmapause, suprathermal ions
Plasma sheet, plasma-sheet boundary layer	Kilovolt electrons and ions that extend into the tail
Magnetopause	Shape and position, reconnection, transfer processes, boundary layers
Waves and small-scale effects	Cause particle loss by pitch-angle scattering, allow magnetic reconnection, accelerate auroral particles

included because of their importance as space weather parameters. The list is restricted to the top-priority parameters that are regularly measured by ground stations or full-time monitoring spacecraft. Since the relevant observing stations, whether space- or ground-based, operate continuously, the comparisons should be made continuously.

The best single metric for the magnetosphere-ionosphere system is the ionospheric electric field, as specified in the top line of Table 2-5, and described in Figure 2-3. This metric covers nearly all magnetospheric field lines and a wide range of physical processes. It combines magnetospheric convection, substorm effects, magnetic storms, polar cap phenomena, and, to a modest extent, low-latitude effects. Convection has a major effect on the cold plasma structure and dominates ring-current injection. However, the metric defined in the top row of Table 2-5 is certainly not comprehensive. For example, it is not an indicator of magnetopause position or of the state of the radiation belts. The ionospheric electric field is predicted by a range of empirical and first-principles models.

Table 2-5. Priority Magnetosphere-Ionosphere Metrics

Category	Parameter(s)	Place	Averaging interval	Data	Criterion*
High-latitude ionospheric electric field	Component of **E** along track of polar-orbiting spacecraft above 50 deg invariant latitude	~ 1000 km altitude, from dawn-dusk orbit	100 km along s/c track	Ion drift meter on DSMP spacecraft	Mean absolute error in component of **E** along satellite path
Auroral electron flux	Latitude-integrated energy flux, number flux. Latitudinal centroid of energy flux	~ 1000 km altitude, from nightside auroral zone crossings.	100 km along s/c track	Precipitating electron flux measured by DMSP or NOAA spacecraft	Mean absolute error
Magnetic indices	AE (electrojets) Dst (ring current) Kp (overall activity)	Ground stations	Time resolution of index	Ground magnetometers	Mean absolute error
Magnetospheric electron fluxes	Fluxes of > 10 keV and > 1 MeV electrons	Geosynchronous orbit	15 minutes	LANL and NOAA spacecraft	Mean absolute error in log(flux)

*Mean absolute error = $\langle |F_{predicted} - F_{observed}| \rangle$

Let $v_{\perp o}$ be the observed drift velocity perpendicular to both the satellite trajectory and the magnetic field. Divide the satellite track into 100 km segments. In each segment compute the average value of $v_{\perp o}$.

Let $\mathbf{E}_m$ be the electric field vector from a model. Then

$$v_{\perp m} = \frac{\mathbf{E}_m \cdot \hat{\mathbf{s}}}{|\mathbf{B}| \sin\psi}$$

where $\hat{\mathbf{s}}$ is the unit vector pointing along the satellite track and ψ is the angle between the magnetic field and the satellite trajectory.

Average the model velocity in the same segments as were used for the observed velocities. Calculate the value of the metric for each satellite pass by:

$$\Delta = \frac{1}{N} \sum_{i=1}^{N} \left| v_{\perp o;i} - v_{\perp m;i} \right|$$

If desired, the per pass metric can be averaged over multiple satellite passes to derive a single metric for an event.

The allowed inputs include the solar wind velocity, density, and IMF at the L1 libration point as well as Kp and Dst. These models may **not** use ground magnetometer measurements, electric field or plasma drift measurements.

If the model uses solar wind inputs, it must have a well-defined algorithm for determining the appropriate delay between the L1 measurement and the ionospheric response. In particular, the model may **not** determine the delay by finding the delay that gives the best comparison between model and observation.

Figure 2-3. NSWP Magnetospheric Metric 1

2.4.3 Solar-Interplanetary Metrics

Crucial solar and solar-wind parameters that are required by physical models of the thermosphere, ionosphere, magnetosphere are listed in Table 2-6, along with proposed metrics. The primary metric is described in Figure 2-4.

Table 2-6. Priority Solar and Interplanetary Metrics

Category	Parameters	Observing Location	Averaging Interval	Data Source	Criterion	Needed for
Solar EUV	Intensity of strong spectral lines (e.g., 30.4 nm) Integrated EUV flux	L1	1 day	SOHO	RMSE	Ionosphere and thermosphere models
Solar x-rays	Intensity of 0.1-0.8 nm flux	Earth orbit	1 hour	GOES	RMSE	Ionosphere models
Solar protons	Proton flux	Geosyn-chronous orbit or L1	1 hour	Proton detector on GOES spacecraft, ACE or other upstream monitor	Mean absolute error in log	Ionosphere and radiation belt models
Solar wind	n, P, v_x, B_x, B_y, B_z, ram pressure, E_y, E_z, Akasofu ε	L1 solar-wind monitor	5 minutes	ACE spacecraft	Mean absolute error	Magnetosphere model
Disturbance departure times from the Sun	Time when disturbance leaves Sun	Earth's surface	N/A	SOHO, Mauna Lea Solar Obs, and other ground locations	Mean absolute error	Thermosphere, ionosphere, and magnetosphere models
Solar wind transit times	Transit time from Sun to Earth	L1 solar-wind monitor	N/A	ACE spacecraft	Mean absolute error	Magnetosphere model

Define a sudden, major change in the solar wind speed to be 50 km/sec within three consecutive five-minute averages. Every five minutes constitutes a separate trial for an algorithm, which is required to predict (at its option) *either* the time (t′) of the next major change, *or* the end time of an interval during which there will be no such changes (t″). If the algorithm yields a t′, a t″ is also assigned, for the purposes of the metric, one half hour earlier than t′. By definition, a t″ is assigned for each trial, whereas a t′ is only assigned if the algorithm predicts an event.

With respect to t′, the algorithm succeeds if the next sudden, major change occurs within plus or minus one half hour of t′. With respect to t″, the algorithm succeeds if no sudden, major change occurs before t″.

The metric is a set of four histograms showing the predictions for t′ and t″ separately for successes and failures. The overall predictive power of the algorithm can be judged qualitatively by examining the ratio of successes to total trials as a function of advance prediction time. Specific quality factors t_{90} and t_{50} are defined as the longest advance prediction time within which the algorithm succeeds in 90% and 50% of the cases.

Figure 2-4. NSWP Solar and Interplanetary Space Weather Metric 1

The highest priority prediction in the Solar-Interplanetary regime is the timing of sudden, major changes in the basic properties of the solar wind, such as wind speed. The useful time-scale of advance prediction starts at about one hour, since a spacecraft at L1 can give one hour of warning to the Earth, and one wants to improve on this.

2.5 Marking Progress with Metrics

Setting up a system of scientific metrics and arranging for their routine evaluation for different algorithms will take both time and effort. However, the effort is clearly worthwhile and represents a necessary step toward establishing major practical benefits from space weather research and clearly marking the most expeditious pathways to operational capability. The metrics will provide an objective measure of progress within the NSWP as well as providing useful input for leadership and management action. The NSWP and its participating agencies should use the metrics to determine where additional funding or new research efforts are most needed to achieve the goals of the Program. A space weather metrics program will also promote scientific advance, by stimulating competition and encouraging algorithm developers to confront observational data in a new way that is both rigorous and objective.

Having reviewed current capabilities and after establishing the metrics framework for assessing progress, it is time to look forward by setting operational goals and determining what needs to be done to reach those goals.

2.6 Operational Goals

The goals of the National Space Weather Program (NSWP) are listed in Table 2-7, which shows the parameters that must be specified and forecast in 15 space weather domains. These were established by the civilian and DOD communities in response to customer operational support requirements. Some of these parameters, the neutral atmospheric temperature, for example, are used to drive forecast models. Others, such as the occurrence of coronal mass ejections, are needed to enhance warning capabilities. This list is subject to change as the NSWP proceeds. It will be reviewed and updated periodically as research improves the physical understanding of space weather and as customer needs change.

2.7 What Needs to be Done

Although considerable progress has been made in the last three years, additional advancements are needed so that forecasting abilities can achieve desired levels of accuracy, timeliness, and reliability. Some limited progress can still be made without improving our understanding of the physical mechanisms that generate space weather. This requires ongoing examination and application of data to develop or improve statistical or empirical models. However, in parallel, as our understanding of the space environment improves, physics-based research models must continue to be developed and modified. These models express what we have learned, serve as a test bed for new concepts, and tell us where we still need more work before our understanding is sufficient to meet operational goals. When our understanding of physical processes is satisfactory, we must place operational sensors in the field and transition our research models into operational models that can run on simple computer systems, assimilate operational data, and produce results within operational timelines.

This overall process is expressed in Figure 2-5 showing the NSWP Roadmap. Research must continue in the three areas of physical understanding, model development, and observations. Crosscutting these areas are the three regions of the space environment—solar/solar wind, magnetosphere, and ionosphere/thermosphere. Chapter 3 summarizes advances made in the last three years and additional research that needs to be accomplished to meet the NSWP goals. Appendix A provides a more detailed description of the research objectives and background information for each region of the space environment. Chapter 4 presents timelines for achieving these research goals.

As research provides sufficiently mature knowledge, the new information is adapted for operational use through a well-planned and well-executed technology transfer (T^2)

Table 2-7. Space Weather Domains and Goals

Space Weather Domain	Goal
Solar coronal mass ejections	Specify and forecast occurrence, magnitude, and duration
Solar activity/flares	Specify and forecast occurrence, magnitude, and duration
Solar and galactic energetic particles	Specify and forecast at satellite orbit
Solar UV/EUV/soft x-rays	Specify and forecast spectral intensity and temporal variations
Solar radio noise	Specify and forecast intensity and variations
Solar wind	Specify and forecast solar wind density, velocity, magnetic field strength, and direction
Magnetospheric particles and fields	Specify and forecast global magnetic field, magnetospheric electrons and ions, and strength and location of field-aligned current systems; specify and forecast high-latitude electric fields and electrojet current systems
Geomagnetic disturbances	Specify and forecast geomagnetic indices and storm onset, intensity, and duration
Radiation belts	Specify and forecast trapped ions and electrons from 1 to 12 R_E
Aurora	Specify and forecast auroral optical and UV background and disturbed emissions, the equatorward edge of the auroral oval, and total auroral energy deposition
Ionospheric properties	Specify and forecast electron density plasma temperature, composition, and drift velocity throughout the ionosphere
Ionospheric electric field	Specify and forecast global electric field and electrojet current systems
Ionospheric disturbances	Specify and forecast sudden and traveling ionospheric disturbances; specify and forecast critical propagation parameters
Ionospheric scintillations	Specify and forecast between 200 and 600 km
Neutral atmosphere (thermosphere and mesosphere)	Specify and forecast density, composition, temperature, and velocity from 80 to 1500 km

process, employing but not limited to the Community Coordinated Modeling Center and Rapid Prototyping Centers. This process is described in Chapter 5. The result will be a series of physics-based models that are coupled to account for the interactions between processes in the three regions of the environment. These operational models will be supported by observations from operational sensors, which again will come from the results of research on sensor requirements and technology, and a planned program of technology transfer.

The suite of new models, supported by deployed sensors, will provide a description of the environment sufficient to support production of appropriately accurate, timely, and tailored products. These products will be designed to address the specific needs of customers—commerce, defense, or society as a whole—at a given location and time. The Air Force will issue tailored products to support DOD. SEC will use the model output to provide warnings and alerts to civilian users and will otherwise provide model output to allow private-sector users to generate their own tailored products.

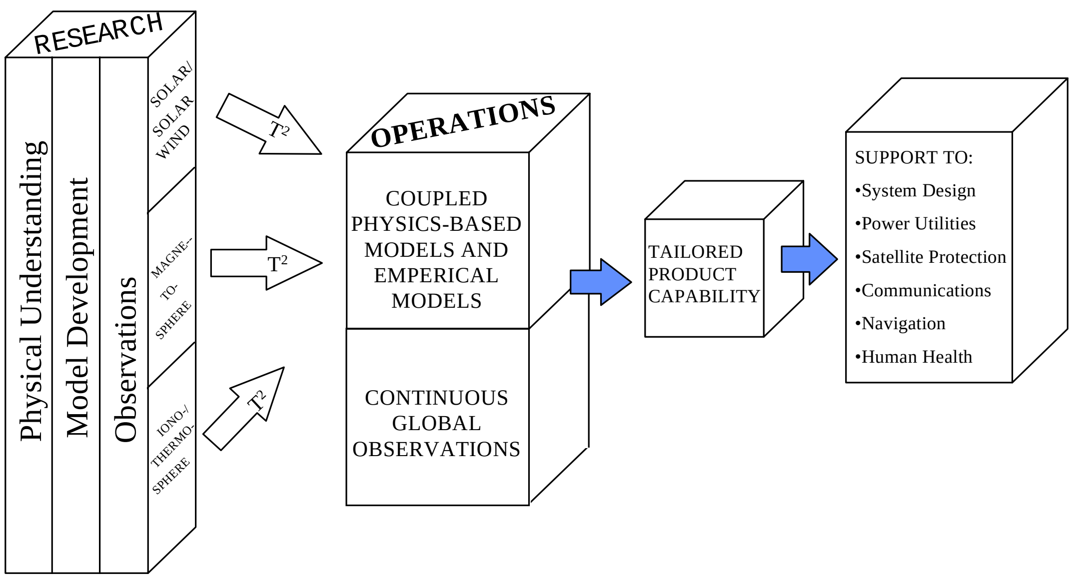

Figure 2-5. NSWP Roadmap