APPENDIX A

NATIONAL SPACE WEATHER PROGRAM RESEARCH

To achieve the goals of the National Space Weather Program (NSWP), we must improve our physical understanding of the space environment, improve empirical models, develop physics-based models that adequately specify and forecast that environment, and develop a suite of sensors to provide the observations necessary to drive those models. This appendix provides detailed information on how those objectives may be accomplished. For each of the three primary aspects of research--physical understanding, model development, and observations--the information is organized by space weather domain as presented in Table 2-2 or Figure 3-1. For reference, these domains are listed below.

- Coronal mass ejections
- Solar activity/flares
- Solar and galactic energetic particles
- Solar UV/EUV/soft x-rays
- Solar radio noise
- Solar wind
- Magnetospheric particles and fields
- Geomagnetic disturbances
- Radiation belts
- Aurora
- Ionospheric properties
- Ionospheric electric fields
- Ionospheric disturbances
- Ionospheric scintillations
- Neutral atmosphere (thermosphere and mesosphere)

Although it is convenient to deal with each of these domains separately, the coupling of the physical processes between the regions of the space environment represented in this list (solar/solar wind, magnetosphere, and ionosphere/thermosphere) must not be overlooked. *The goals of the National Space Weather Program can be achieved only when the representation of space weather is coupled into a seamless system, starting at the Sun and ending at the Earth*.

A.1 Physical Understanding

The greatest challenge in improving our ability to specify and forecast space weather is in understanding the physical processes that drive it. Until we improve this basic understanding, we cannot develop and deploy valid models. Nor can we adequately define our observational requirements. This section addresses the fundamental need for basic knowledge in the space weather domains listed above.

A.1.1 Coronal Mass Ejections (CMEs)

The research objective is to understand

- ***the physics of the CME initiation process and the factors that determine CME size, shape, mass, speed, and internal field strength and topology.***
- ***how to predict the above on the basis of planned observing systems.***
- ***how to predict CME-caused solar wind disturbances and solar energetic particle events near Earth.***

The major non-recurrent geomagnetic storms are generally associated with the solar wind disturbances created by fast CMEs. In addition, most major solar energetic proton events observed near Earth seem to result from acceleration of some solar wind particles by the CME-driven interplanetary shock wave. Substantial advances in space weather forecasting can be made by learning more about the solar processes that initiate CMEs, and by learning how to predict their interplanetary consequences from observable signatures at the Sun and from in situ solar wind plasma, magnetic field, and energetic particle observations.

The slower CMEs eventually (far from the Sun) attain speeds comparable with that of the normal, slow solar wind, but do not generate significant solar wind disturbances, energetic particle events, or geomagnetic disturbances. On the other hand, the faster CMEs produce major solar wind disturbances as they overtake, compress, and accelerate the slower ambient solar wind ahead. Large CME-driven interplanetary disturbances are usually preceded by strong shocks that are effective accelerators of particles and sources of radio emissions. Strong magnetic fields are also commonly found in these disturbances both behind the leading shocks and within the CMEs themselves. These strong fields are primarily a result of compression caused by the interaction between CMEs and the ambient wind. When the compressed fields in the ambient wind and/or within the CMEs have substantial southward components, major geomagnetic storms result as they interact with Earth's magnetosphere.

A.1.2 Solar Activity/Flares

The research objective is to understand

- ***the solar dynamo.***
- ***the precursors to solar activity--the short-term process of active region development and the long-term buildup of polar fields.***
- ***the dynamics of magnetic energy buildup in the solar corona and magnetic field topologies, and their role in occurrence of solar flares.***

Solar activity (sunspots, faculae, flares, etc.) arises from the eruption of fields formed within the solar interior as part of dynamo processes. To understand solar activity, it is essential to understand the solar dynamo—how magnetic fields are amplified within the solar interior. To predict future activity, it is essential to understand the precursors of solar activity—on long time scales, the buildup of polar fields, and on short time scales, the behavior of individual active-region development.

Electromagnetic radiation propagates from the Sun to Earth on time scales of minutes. Thus any warning capability for ultraviolet (UV), extreme ultraviolet (EUV), and x-ray or microwave bursts requires some method for flare forecasting. At this time, no completely reliable predictors of flare occurrence are known. Although, because flares are due to the release of magnetic energy, an obvious forecasting strategy is to search for signatures of magnetic energy buildup in the solar corona and specific magnetic field topologies that lead to the occurrence of flares. Recent research has linked sigmoidal signatures to subsequent flare events.

Solar activity can take many forms, ranging in size from tiny x-ray bright points to giant eruptive flares. All these forms of activity are believed to share a common underlying physical process, the conversion of magnetic energy in the solar chromosphere and corona to plasma energy. The best known and, perhaps, most important example of this process is solar flares. A large flare can release up to 10^{32} ergs of magnetic energy into the solar atmosphere on time scales as short as 100 seconds. There are several results of flare energy release that are significant for space weather. The main result is that large masses of coronal and chromospheric plasma heat to temperatures in excess of 10 million degrees Kelvin (K). Radiative and conductive cooling of this plasma produces UV, EUV, and x-ray bursts, from 0.1 to 100 nanometers (nm), which heat and ionize Earth's upper atmosphere and ionosphere.

Flares also produce enhancements of optical emission, especially in spectral lines formed in the chromosphere, but sometimes even in continuum white-light emission. The term flare has now become synonymous with a large soft x-ray burst, and the commonly used flare classification is now in terms of peak soft x-ray intensity. Flares are categorized as X, M, C, or B with the strongest flares being category X. In addition to UV, EUV, and x-ray bursts, flares can produce large numbers of energetic particles that escape to interplanetary space and result in major solar energetic particle (SEP) events. A third important space weather effect of flares is the production of strong radio bursts, although there is considerable ambiguity as to which of these are associated with CME initiation as opposed to the flares themselves.

A.1.3 Solar and Galactic Energetic Particles

The research objective is to understand

- ***the origins of high-energy (MeV and GeV) particles and how they propagate through the interplanetary medium.***
- ***the related physical processes that modulate the flux at 1 astronomical unit (AU) of cosmic rays originating in galactic space.***

Very energetic particles, whether of solar or galactic origin, can cause single event upsets or latchups in satellite electronic components, especially highly packed memory chips. Although the exact time of failure of individual components cannot be predicted, the overall rate of upsets is proportional to the flux of particles, which is controlled by solar activity and details of the ambient interplanetary medium.

Considering solar energetic particle events, two independent mechanisms for particle acceleration have been identified: processes associated with impulsive solar flares, and shock waves driven by a coronal mass ejection. Particles observed in major solar energetic particle events are accelerated over a period of days over an extended region of solar longitudes, and are associated with interplanetary shocks. The profiles of flux intensity versus time for both these types of events depend on the three-dimensional (3D) topology of the interplanetary magnetic field lines. Research into the particle acceleration mechanisms for both processes is ongoing.

Considering intergalactic cosmic rays, which are more energetic than solar particles, their influx is negatively correlated with the 11-year solar cycle. Apparently, the repeated episodes of solar mass ejections prevalent near sunspot cycle maximum create a complex pattern of interplanetary fields that tend to exclude (scatter) cosmic rays away from the inner solar system. This effect can be seen for individual events; there are obvious decreases in cosmic ray flux at Earth coincident with shock-associated coronal mass ejections.

A.1.4 Solar UV, EUV, and Soft X-Rays

The research objective is to understand the variabilities of the Sun in the short wavelengths and how these variabilities affect the ionosphere and thermosphere.

The upper atmosphere and ionosphere of Earth are subject to extreme spatial and temporal variability induced by solar short-wavelength radiation with wavelengths less than 180 nm, as well as by charged particles precipitating from the magnetosphere and the polar cap, which may be open to interplanetary space. The variability in the solar short-wavelength radiation occurs on time scales from minutes to that of a solar cycle. The ability to predict the often rapid changes in Earth's upper atmosphere and ionosphere rests on our knowledge of the sources of these variations. At present, most of our understanding of the variability of the solar short-wavelength radiative outputs comes primarily from measurements made by the Atmosphere Explorer satellite and several rockets flown in the last two decades.

Variations in solar short-wavelength radiation occur on three basic time scales related to flares, active-region evolution, and the solar cycle. The latter two are emphasized here because flare signature and predictability are essentially covered in section A.1.2. However, it should be repeated that the flare-related enhancements of the short-wavelength radiation can be quite large (over 1000 times background levels) and endure for minutes to hours. Over moderate time scales, say to several solar rotations, short-wavelength solar radiation can show enhancements of as much as 20-30% in response to the emergence, interaction, and evolution of active regions. These variations are further modulated by the passage of the active regions across the visible hemisphere. The variations occurring on these time scales are superimposed on a longer-term modulation of solar radiative output related to and occurring in phase with the solar cycle. During the 3 to 4 years in the rise of an activity cycle, the solar emission in the 10- to 100-nm spectral range can increase by a factor of 2, and for wavelengths less than 10 nm by a factor of 10.

A.1.5 Solar Radio Noise

The research objective is to understand solar radio noise emission processes in the upper corona.

The predominant processes responsible for solar radio noise are related to active regions and their formation and development. Solar radio emission is so closely tied to solar activity that the 10.7-centimeter (cm) flux of solar radio noise is often chosen as a better proxy than sunspot number for solar activity. Nevertheless, proxies are not equivalent to understanding or predicting.

As a factor in space weather, solar radio noise is an operational nuisance and hazard to radar and communication operations if the antenna pattern intercepts the Sun and solar noise swamps the desired signal. The solar radio signals of most interest include noise bursts at 245 megahertz (MHz) and 2.695 gigahertz (GHz) because they interfere with commonly used communication frequencies.

The occurrence rate of solar radio bursts is roughly correlated with the solar activity cycle. However, solar radio noise is also likely simply when there are complex sunspot activity regions in view. Whether this signifies the occurrence of minor flares or slower CMEs with no other identifiable signatures is unknown at this time.

A.1.6 Solar Wind

The research objective is to understand the means by which the solar wind is heated and accelerated, and the non-uniform characteristics of its flow.

Today, advances in understanding the solar wind are being made because of synergistic developments of theory, modeling, and observations. In particular, 3D models, ranging from source-surface treatments to 3D magnetohydrodynamics (MHD) coronal and solar wind models, have the potential to help us understand both how to interpret what we experience at Earth in terms of its coronal origins, and the role that the coronal magnetic field geometry plays in determining the solar wind characteristics. New observations that help to establish the boundary conditions at the Sun have the potential to merge with the models and allow definitive tests of their validity. However, most of these cross-comparisons have not been done. Moreover, the processes acting in the solar wind acceleration region are not completely defined in classical MHD models and are not readily observed by present-day remote sensing techniques.

The solar wind establishes the prevailing condition of the magnetosphere prior to transient (e.g., shock or CME) interaction, is the medium through which solar energetic particles travel (and in many cases are generated in), and is itself a source of moderate interplanetary plasma and field disturbances.

A.1.7 Magnetospheric Particles and Fields

The research objective is to understand

- ***the coupling of the solar wind with the magnetosphere.***
- ***the onset, expansion, and recovery of substorms.***
- ***the transport and energization of plasma throughout the magnetosphere.***

Specifying and forecasting the magnetospheric environment requires a detailed understanding of particles and fields throughout the magnetosphere. Because the magnetosphere is determined largely by properties of the solar wind, a complete understanding of the magnetosphere depends on our knowledge of the physical mechanism or mechanisms behind its coupling to the solar wind. The magnetosphere is a dynamic region that undergoes dramatic changes in response to substorms. Therefore, it is also important to understand the physical processes leading to the onset, expansion, and recovery phases of substorms. Much of the energetic plasma in the magnetosphere resides in the plasma sheet, but our understanding of the origin of the plasma sheet is still incomplete. A significant portion of the plasma sheet ions is provided by the ionosphere, but there is yet no agreement about the mechanisms that transport ions up field lines. These transport mechanisms depend on both storms and substorms in the magnetosphere.

The magnetic field configuration of the outer magnetosphere varies in complex and dramatic ways with changes in the solar wind. On the sunward side of the magnetosphere, Earth's dipole field is compressed by the ram pressure of the supersonically flowing solar wind, and the magnetosphere shrinks when the solar wind ram pressure increases. On the night side, interaction with the solar wind stretches geomagnetic field lines out into an enormous, long tail that extends for hundreds of Earth radii (R_E). A strong southward component of the interplanetary magnetic field (IMF) increases the degree of magnetic connection between the solar wind and magnetosphere, further stretching the magnetic field in the tail. In the expansion phase of a magnetospheric substorm, which typically follows a period of southward IMF, nightside field lines collapse to a less stretched shape, releasing energy. In a magnetic storm not only are there typically strong substorms, but the Earth-centered westward ring current also increases, inflating the magnetic field.

A.1.8 Geomagnetic Disturbances

The research objective is to understand

- ***magnetospheric disturbances and the modulating role of the magnetosphere, ionosphere, and neutral upper atmosphere.***
- ***the currents that magnetospheric disturbances induce in the ground.***

Magnetic activity at Earth's surface is modified by electric currents in the magnetosphere and ionosphere. Understanding of geomagnetic disturbances depends critically on our knowledge of those currents as well as induced currents in the ground. Areas where greater physical understanding is particularly needed include (1) magnetospheric processes that govern field-aligned currents and conductivity, and produce particle precipitation, especially during substorms and storms; (2) processes that determine rapid spatial and temporal variations of the auroral electrojets (it is the rapid temporal variations that are linked to the ground-induced current effects); and (3) the manner in which spatially and temporally varying ionospheric currents interact with nonuniform ground conductivity to induce large potential differences over long distances.

A.1.9 Magnetospheric Radiation Belts

The research objective is to understand the transport, production, and loss processes that determine the intensity of radiation belt particles in both quiet and storm times.

The radiation belts are the high-energy parts of the populations of electrons and ions that are trapped by Earth's magnetic field. They are distinguished by the energies of their particles, by their spatial properties, and by the variations in time of the fluxes of their particles. They are subdivided into inner and outer belts, separated by a region of minimum particle flux, the slot region, located at about 1.5 to 2 R_E above the equator. The South Atlantic Anomaly is the location where inner belt particles come closest to Earth, owing to the offset between the magnetic dipole axis and Earth's center. The outer belt extends beyond the altitude of geosynchronous satellites.

Although typically thought of as regions of trapped radiation, the radiation belts exhibit variations on nearly all time scales: secular, solar cycle, solar rotation, and storm time. The outer belts exhibit the greatest variability. The outer belt MeV electrons, often called “killer electrons” because of their effect on spacecraft, exhibit a persistent behavior during magnetic storms, yet their origin is still not understood. Even the inner belt particle populations, which are usually considered stable, can be modified during large magnetic storms. For example, in 1991 an interplanetary shock wave created a second inner proton belt, which, because of the long time scales associated with loss processes, persisted for many months.

The transport, production, and loss processes that determine the fluxes of energetic particles in the radiation belts have been studied for many years, but it is still not possible to account for all the observed variability. Transport, production and loss of radiation belt particles result from atmospheric processes such as charge exchange and Coulomb collisions, pitch angle diffusion produced by wave-particle interactions, and radial diffusion caused by large-scale magnetic and electrostatic impulses. The determination of numerical values for the various diffusion coefficients is a critical step for understanding and predicting the evolution of the radiation belts. This will require a detailed specification of the electromagnetic and electrostatic fields present in the radiation belts, as well as a suitably robust model of the large-scale magnetic field.

A.1.10 Aurora

The research objective is to understand the processes that guide, accelerate, and otherwise control particle precipitation and produce auroral substorms.

Much has been learned over the past two decades about the climatology of auroral particle precipitation. As we understand more about where magnetic fields map, we are better able to tie features in the precipitation patterns to source regions in the magnetosphere and magnetosheath and to processes that guide, accelerate, and otherwise control particle precipitation. Adding the dependence of the climatology on the IMF direction may help to define the physics of these processes. Critical questions still exist relative to the acceleration mechanisms for auroral particles and the causes of structure of arcs and other auroral forms. We must better understand magnetosphere-ionosphere coupling and feedback processes. The dynamics of the aurora reflect the extreme temporal variability of the magnetosphere and the coupling processes. Many of the research models are run under steady boundary conditions to produce diurnally reproducible results. Time-varying effects are often not well modeled. Yet the solar wind, the magnetosphere, and the ionosphere vary considerably on time scales of hours and even minutes. On the global scale we must evolve from static, statistically based pattern descriptions of electric fields, currents, and precipitating particles to dynamic time-varying real-time descriptions of the physical processes controlling these phenomena. Accurate simulation of time-varying phenomena at scales of a hundred kilometers to across the globe is an essential part of space weather prediction.

A related problem is the triggering mechanism of substorms and the modeling of the dynamics of the expansion phase, including the processes that lead to the “injection” of intense fluxes of energetic particles into the near-geosynchronous region. There is a lack of agreement in the community on the physical processes that cause substorm initiation, although focus has moved toward the inner magnetosphere in the last few years. It is ultimately important that the physics of substorm onset be identified and be the driver of onset in numerical models rather than any ad hoc mechanism or numerical diffusion within the model.

A.1.11 Ionospheric Properties

The research objective is to understand

- ***the formation mechanisms associated with large-scale and medium-scale electron density structures, and the basic response of the ionosphere to geomagnetic storms and substorms.***
- ***the production, transport, and loss mechanisms associated with electron density structures.***

Earth's ionosphere displays a marked variation with altitude, latitude, longitude, universal time, season, solar cycle, and magnetic activity. This variation is reflected in all ionospheric properties: electron density, ion and electron temperatures, and ionospheric composition and dynamics. This is primarily a result of the ionosphere's coupling to the other regions in the solar-terrestrial system, including the Sun, the interplanetary medium, the magnetosphere, the thermosphere, and the mesosphere. The main source of plasma and energy for the ionosphere is solar EUV and UV radiation, but magnetospheric electric fields and particle precipitation also have a significant effect. The magnetospheric effect is determined, in part, by the solar wind dynamic pressure and the orientation of the interplanetary magnetic field (IMF). Also, tides and gravity waves propagating up from the mesosphere influence the thermospheric neutral densities, which, in turn, affect electron and ion production and loss rates. The various driving mechanisms act in concert to determine the global electron density distribution, but important time delays and feedback mechanisms are also associated with the coupling processes. The external driving mechanisms can also be localized, spatially structured, and unsteady.

Of particular importance to space weather systems is the electron density distribution. Despite the complicated nature of the forcing processes, this distribution exhibits (generally) repeatable features at equatorial, middle, and high latitudes. At mid-latitudes, the average electron density distribution tends to be uniform, with a gradual transition from dayside high densities to nightside low densities across the terminator. At equatorial latitudes, a pronounced latitude variation of electron density in the F-region of the ionosphere, known as the Appleton anomaly, is encountered during the daytime. At high latitudes, additional large-scale density features are evident, including a tongue of ionization, a polar hole, a main trough, and an overall enhancement in the auroral oval. In addition to these quasi-steady-state features, the ionosphere also exhibits a considerable amount of structure. There are small-scale (~1 km), medium-scale (~10 km), and large-scale (100-1000 km) density structures, and they can appear at any location and time. The small-scale structures are usually produced within and on the edges of the larger structures through plasma instabilities and are typically referred to as density irregularities. The medium- and large-scale structures at high latitudes can appear in the form of propagating plasma patches, boundary blobs, auroral blobs, and localized depletions, and they can be created by a variety of mechanisms. At the magnetic equator, large-scale features known as equatorial bubbles or plasma depletions appear after sunset and are associated with large-amplitude density irregularities at a variety of scale sizes.

A.1.12 Ionospheric Electric Fields

The research objective is to understand

- ***the small-scale electric field (E-field) structures and the large-scale electrostatic fields within the ionosphere, how they couple with the magnetosphere, and how they respond to changes in the interplanetary magnetic field.***
- ***the penetration of E-fields from high latitudes to low latitudes.***
- ***the E-field variability generated by thermosphere-ionosphere interactions in the equatorial region.***

A specification of the global E-field is required to adequately understand the behavior of the charged and neutral species in the upper atmosphere. The E-field forces the ions to move in the $\mathbf{E}\times\mathbf{B}$ direction at high altitudes and in directions closer to the E-field direction at lower altitudes. The resulting plasma transport and ion-neutral chemistry affect the ionospheric composition and concentration, which, in turn, affect the neutral atmosphere dynamics by modifying the ion drag. These processes are further complicated by the fact that the ion-neutral collisions themselves drive currents that may modify the E-field and the resulting $\mathbf{E}\times\mathbf{B}$ drift motion of the plasma. To produce an adequate description of the ionosphere and thermosphere, it is therefore necessary to globally specify the E-field distribution. At the large spatial scales that are relevant to describing the global ionosphere, the magnetic field lines are electric equipotentials, and thus the E-field may be specified by describing the spatial distribution of electric potential. Small-scale structure that is superimposed on the large-scale E-field is also important. The task of describing the global ionospheric E-field may be conveniently divided into two parts: that pertaining to the specification at high latitudes, where the influences of ionosphere-magnetosphere coupling processes dominate, and that pertaining to middle and low latitudes, where ionosphere-thermosphere-mesosphere coupling processes dominate.

At high latitudes the ionospheric E-field is largely dependent on the nature of the magnetosphere-solar wind interactions, and interplanetary magnetic field and solar wind parameters tend to be the major variables affecting the electrostatic potential distribution. When the IMF is southward, a two-cell convection pattern is generally well defined, but the level of detail required to adequately specify the associated ionospheric densities is missing. When the IMF is northward, the variability of the convection pattern is much larger and the convection velocities are generally smaller than for the southward IMF case. This suggests that the underlying large-scale convection pattern may be disguised by the small-scale structure that is present in all cases. At low and middle latitudes, a specification of the E-fields is complicated by the existence of daily and longitudinal variations that are poorly understood. The relationship between the behavior of the ionosphere and thermosphere and the electrodynamics of the plasma can be quite well modeled, but prediction of the wind systems and E-field variations that can dramatically affect the bottomside ionosphere is not presently possible. A better understanding is required of the processes that determine the spatial and temporal characteristics of E-field penetration from high to low latitudes during ionospheric disturbances, including the establishment or breakdown of magnetospheric shielding effects.

A.1.13 Ionospheric Disturbances

The research objective is to understand the day-to-day variability of the large-scale ionospheric features and small-scale plasma density irregularities that affect radio wave propagation during magnetically quiet and disturbed times.

A multitude of structures populates various ionospheric regions at different times. Their spatial and temporal distributions are of interest in their own scientific context but are also of interest to communication and surveillance applications because of their impact on skywave signal channel characteristics. At mesoscale and macroscale (i.e., ~50-10^4 km) the interest has been in such phenomena as the auroral oval, the equatorial anomaly, the mid-latitude trough, the cusp, intermediate and descending layers, and polar cap patches. At smaller-scale sizes (centimeters to tens of kilometers) attention has been on plasma instabilities that play a role in the distribution of ionospheric irregularities. Through wave-particle interactions the instabilities and associated irregularities can influence currents and energize ions that ultimately populate the magnetosphere. Many processes (Rayleigh-Taylor, $\mathbf{E}\times\mathbf{B}$, current convective, and universal drift wave modes) depend on ionospheric structures and their density gradients as energy sources to drive the plasma to an unstable state. All of the high-latitude ionosphere and the nighttime equatorial region are susceptible to such processes. These regions are known to impair skywave performance when such instabilities and irregularity structures prevail. It is to be noted, however, that ionospheric disturbances are not always associated with instability mechanisms. They can be triggered by geomagnetic storms and attendant variations in E-fields, thermospheric winds, composition, and plasma density distributions.

Triggering mechanisms can also include gravity wave perturbations and day-to-day variabilities that can often escape identification with known cause-effect relationships. In fact, an underlying challenge (perhaps more fundamental than attempting to trace storm-time dynamics) is to define and specify quiet-time conditions (if such a classification truly exists) and their associated day-to-day variability. Herein lies the fundamental requirement for skywave performance characteristics in ionospheric controls of maximum usable frequencies, lowest usable frequencies, and frequencies of optimum transmission. These are link dependent and controlled by the details of E- and F-region characteristics as determined by seasonal, diurnal, and solar-cycle controls, and attendant day-to-day variability. Clearly, an understanding of all structures, laminar and disturbed, will provide a hierarchical perspective on all of the ionosphere and will develop insights into the processes that control and maintain the structures themselves, influence the coupling to other geospace domains, and modify the performance of communications and surveillance systems.

A.1.14 Ionospheric Scintillations

The research objective is to understand

- ***the thermosphere-ionosphere-magnetosphere interactions that control the formation and evolution of 10-km to 50-m electron density irregularities that cause scintillations.***
- ***the relationship between those irregularities and scintillation effects on specific systems.***

Spatial irregularities of ionospheric electron densities scatter satellite radio signals and lead to amplitude and phase variations. Amplitude scintillations induce signal fading and, when this exceeds the fade margin of a receiving system, message errors in satellite communications are encountered and loss of lock occurs in navigational systems. Phase scintillations cause Doppler shifts and may degrade the performance of phase-lock loops, such as in Global Positioning System (GPS) navigation systems. They may also affect the resolution of space-based synthetic aperture radars. The magnitudes of amplitude and phase scintillations and the temporal structure of scintillations need to be specified and predicted to provide support to operational communication and navigation systems.

The scintillation phenomenon is characterized by extreme temporal and spatial variability. The associated electron density irregularities are driven by complex, time-dependent ionospheric plasma instabilities. Research into the triggering mechanisms for the instabilities is crucial for achieving predictive capabilities. Scintillations are most severe in the equatorial region, where they often occur after sunset, and attain their maximum intensity around the peaks of the Appleton anomaly (15 degrees north and 15 degrees south latitude, magnetic). The scintillations have a large and poorly understood day-to-day variability, with active nights sometimes following (or leading) quiet nights with little apparent change in initial conditions. They are particularly severe during solar maximum conditions, and frequently occur during geomagnetically quiet periods.

At high latitudes, strong scintillation events are related to the macroscale plasma structures that become unstable near their moving boundaries. Under magnetically active conditions and IMF B_z southward orientations, such structures, known as polar cap patches, are convected from mid-latitudes through the dayside cusp into the polar cap and finally into the nightside auroral oval. It is first necessary to specify and predict polar cap patches and their trajectories based on IMF configurations. We then need to define plasma convection in the neutral frame of reference so that the growth time of plasma instabilities and relative amplitude of mesoscale irregularities may be derived in the nonlinear regime of the evolution of plasma instabilities. At mid-latitudes, weak to moderate levels of scintillation occur and maximize during the solar minimum period in a manner that still awaits explanation.

The physical conditions necessary for the onset of plasma instability in the equatorial region seem to be associated with the post-sunset enhancement of the eastward E-field and the presence of "seed" perturbations, provided by either geophysical noise or gravity wave activity. However, the manner in which these parameters control the day-to-day variability of scintillation remains unresolved. For the purpose of relating scintillations to plasma instabilities on a quantitative basis, it will be necessary to track these instabilities through the nonlinear regime and determine the saturation amplitudes of the irregularities with fast computer algorithms.

A.1.15 Neutral Atmosphere (Thermosphere and Mesosphere)

- ***The research objective is to understand the chemical, radiative, and dynamical processes that act to modify and redistribute energy and constituents throughout the upper atmosphere.***

The atmosphere above about 80 km is a weakly ionized, compressional, multi-constituent medium with a complex and variable morphology that is controlled by a variety of mechanisms, including direct solar heating and other important chemical, radiative, and dynamical coupling processes. Solar activity influences upper atmospheric variability directly by means of EUV/UV heating and indirectly by means of the magnetospheric sources of energy, momentum, and mass. Consequent variations in the neutral atmospheric state parameters (temperature, density, wind, and composition) have important effects on many operational systems. Direct effects include the perturbation of satellite trajectories in low Earth orbit. Indirect effects involve the response of the ionosphere to variations in neutral atmospheric composition and dynamics. For example, changes in thermospheric composition control ionization and recombination rates, whereas neutral winds act to redistribute the ionospheric layers both horizontally and vertically. Neutral winds can produce feedback on the magnetosphere-ionosphere electrical circuit by modifying the dynamo interaction. Also, neutral temperatures play a role in determining chemical reaction rates, which, in turn, affect all other parameters in the upper atmosphere.

Although sustained progress in understanding the upper thermosphere has occurred over the past decade and most of the important physical processes are known, we still possess only a preliminary climatology. Moreover, large errors regularly occur when too much reliance is placed on the accuracy of empirical models. This is due, in part, to the large intrinsic variability of the neutral upper thermosphere and its ability to support oscillations of all types and scales (gravity waves, planetary waves, and tides). Much less is known about the behavior of the lower altitude regions: the mesosphere and lower thermosphere/ionosphere (MLTI).

The MLTI is subject to strong forcings from both above and below, in the form of solar radiation; precipitating magnetospheric particles; magnetospheric electric fields; and currents, atmospheric waves of all scales, radiative transfer, and the transfer of important neutral constituents from the lower atmosphere. Many of the most important atmospheric processes in this region remain poorly characterized, including: the effects of breaking gravity waves; the variability of tides and planetary waves; the production, transport, and loss of species such as nitric oxide and atomic oxygen; radiation cooling under conditions of strong nonthermodynamic equilibrium; and heating by solar radiation, particle precipitation, chemical transformations, and auroral electric currents.

A.2 Model Development

The NSWP must support the continued development of models that specify and forecast the state of the solar-terrestrial system. The program must also foster the merging and integration of models developed for the different space weather regions. As the models are developed, they must continually be tested and validated against space weather measurements. This will necessitate both rapid access to existing ground- and space-based observing platforms as well as deployment of new facilities and satellites.

Different models are in different stages of maturity. Some are empirical, some are "physics based"; most are hybrids. The approach of the NSWP is to support the evolution from empirical models to coupled physical models. In the ideal situation, all models are self-consistently coupled so that changes in the driving forces of the system are communicated through the different regions of space. Finally, the physical models must not only be brought into existence but they must also be transferred into operational codes that will allow accurate space weather forecasts and nowcasts.

A.2.1 CME Models

CMEs produce dramatic effects in the solar wind that must be accurately modeled to predict the onset times and time profiles of solar wind disturbances at 1 AU (plasma, magnetic field, and energetic particle attributes, including strength of associated shocks, intensities of energetic particle events, flow speeds, densities, and magnetic field magnitudes and orientations). Such predictions should eventually be possible on a variety of time scales ranging from less than an hour to greater than several days. The optimum means of achieving this goal is through a combination of observations and models. The observations are required both to test the models and to provide the boundary conditions for model use in making forecasts. Of particular value in the modeling area for CME space weather effect predictions are the following:

- 3D MHD models of the ambient solar wind (see section A.2.4).
- 3D MHD models of CME-generated disturbance propagation in the solar wind from the Sun to beyond Earth's orbit. These models should strive to simulate the CME structure itself as well as the perturbation caused by the CME in the ambient interplanetary medium. They should ultimately be able to describe disturbance initiation and propagation from the base of the corona to 1 AU using realistic initial conditions for the ambient wind and realistic boundary conditions for the CME disturbance itself.
- Models of the CME-driven shock-related radio emission process. These models are needed to optimize the use of radio noise as a remote sensing device and as a diagnostic of approaching CMEs.

- Models of the CME initiation process that use realistic observable boundary conditions at the Sun to predict "injection" speed, mass, and intrinsic magnetic field attributes of the ejecta.
- 3D models of particle acceleration by CME-driven interplanetary shocks. Given a realistic model of the disturbance propagation (as in the second bulleted item above), these models should be capable of predicting the intensity and time history of the CME-associated energetic particle events at 1 AU.

A.2.2 Flare Models

The magnetic field plays a fundamental role in the production of flares and is the essence of several areas of flare modeling. First, because the coronal magnetic field cannot be observed directly, as yet, the only method for determining the field there is to observe it at the photosphere and use numerical modeling to extrapolate it into the corona. This method has had considerable success in matching observations from present magnetographs and the Yohkoh satellite. Because much higher quality data is expected in the next few years, magnetic extrapolation models must be extended to much higher numerical resolution. Second, the fundamental process by which magnetic free energy in the corona is released is believed to be magnetic reconnection. Recently, 2.5D models for magnetic reconnection have been successful in explaining observations of mass acceleration and heating associated with the magnetic energy release in chromospheric explosions. Solar flare reconnection, however, is intrinsically 3D. Rigorous models for 3D reconnection are the most important challenge to understanding flare physics, and to obtaining a physics-based model for flare prediction. Related to this, investigation of the microphysics that determines the site of reconnection in a particular magnetic field configuration is useful in assessing the potential for reconnection. These processes can generally be parameterized in MHD models to control the locations of the regions of maximum resistivity, and thus minimize the role of purely numerical diffusion.

Models relating to the processes that produce flare-generated transient UV, EUV, and x-ray bursts are potentially valuable for flare effect prediction because they can tell us something about the energetics of the flare and in particular about the potential for producing flare-generated solar energetic particles. Similarly, models of the processes that accelerate particles in flares and determine whether and where they are released from the flare site are useful in building forecasting schemes for this particular component of the SEP population.

The key modeling objectives for flare forecasting are thus the following:

- Development of 3D models for magnetic reconnection in active regions, including consideration of the processes that determine the distribution and magnitude of resistivity.
- Improvement of magnetic field extrapolation models based on photospheric field measurements, allowing for anticipated high-resolution magnetograph observations and eventually higher sensitivity full-vector magnetic field data.

A.2.3 Solar UV, EUV, and Soft X-Ray Models

Models of Earth's ionosphere and upper atmosphere rely on the solar 10.7-cm radio flux as a surrogate or proxy of the solar short-wavelength radiative input. The variation in the 10.7-cm radio flux, however, originates in active regions. Recent studies show that a significant contribution to the short-wavelength radiation emission levels comes from the dispersed fields of active regions and the weak network. This component of solar activity is not well represented by the 10.7 cm flux. The Ca II K index and He I 1083-nm equivalent width include contributions from active regions, as well as the weaker magnetic structures distributed over the entire surface of the Sun. However, better estimates of the short-wavelength radiative emission can be realized by using solar atmospheric models for different activity structures, such as sunspots, plages, active regions, and the network. In addition, understanding the physical basis for the variability and improving the development of reliable proxies are valuable.

The most promising research directed at this problem involves combining semi-empirical atmospheric models that fit the spectra of observed spatially resolved solar features, databases of line and continuum spectra computed in local thermodynamic equilibrium (LTE) and non-LTE, as appropriate, and analyses of the distribution on the solar disk of specific activity features from observations. This procedure yields a synthetic disk image, full-disk spectra, and the absolute full-disk irradiance in selected spectral bands. At the present time, the solar models are limited to lines formed at temperatures less than 10^5 K, that is, to the chromosphere up to the lower boundary of the transition region. Comparisons of the calculated Lyman-alpha irradiance, for example, with that measured by the Upper Atmosphere Research Satellite (UARS) show an agreement to within about 10%, indicating the potential of this analysis approach.

Specific modeling tasks include the following:

- Develop 3D models of the solar atmosphere that include the transition region and coronal lines formed at higher temperatures than are currently being used.
- Improve the solar spectrum calculations with the addition of line opacities in approximately 50 million lines, mostly in the UV, as well as other lines and continua from atoms, ions, and molecules. Improve non-LTE computations of metals continua, Fraunhofer lines, and the optically thin transition region and coronal lines.
- Develop additional models (e.g., for the penumbra), a finer distinction of modeled structures, and dynamical models that include flows and turbulent diffusion in order to better match the observed solar features and their spectral characteristics.

A.2.4 Solar Wind Models

Over the past two decades numerical models of the solar wind of various degrees of sophistication have been developed. The simplest of these are kinematic models that assume the magnetic field and velocity at the Sun and project them to 1 AU. Some of these models incorporate ad hoc descriptions of stream interaction effects. At a more computationally demanding and physically rigorous level are 2D and 3D MHD models that can in principle more accurately simulate stream structure. Solar observations, especially of the photospheric magnetic fields, can be used to specify the boundary conditions at the "source surface," although theoretical extrapolations or approximations are required to map these conditions to the ~20 solar radii (R_S) distance where the flow becomes truly radial and the speed is thought to be fully established. From a solar wind forecasting perspective, modeling efforts will eventually lead to a capability for predicting local solar wind conditions that can be used in magnetospheric and upper atmospheric models that depend on solar wind behavior, as well as in predictions of CME effects on the ambient interplanetary medium. Because these models rely on solar observations for their boundary conditions, the lead-time is potentially no shorter than the convection time from the Sun and is as long as a solar rotation if the solar magnetic field configuration is steady or slowly changing. Some examples of specific modeling activities of interest in this area are as follows:

- Development of 3D MHD models of the coronal acceleration region of the solar wind, which use realistic magnetic field configurations.
- Development of 3D MHD models of the solar wind extension into interplanetary space, which use realistic inner boundary conditions. These include using the critical "geoeffectiveness" parameters of plasma velocity and density, and vector magnetic field.
- Coupling of the above two models to determine an optimum proxy for specifying solar wind velocity prior to its free expansion into interplanetary space.

A key element in forecasting geomagnetic disturbances is the availability of solar wind and IMF data from the Lagrangian point (L1). Since the L1 point lies more than 200 R_E upwind from Earth, and since an L1 station is rarely on a streamline that hits the magnetosphere, there is a need to predict solar wind and IMF conditions at the magnetosphere from the L1 data. Existing models make such predictions using pure advection based on the assumption that all gradients are parallel to the Sun-Earth line. It should be possible to improve the accuracy of the predictions by computing the orientation of gradients from the L1 data and taking account of this information together with the propagation of the gradients relative to the wind. Two real-time L1 data stations are WIND and the Advanced Composition Explorer (ACE). Codes incorporating data from both stations should give accurate predictions most of the time. The extension of existing code to incorporate these aspects of the solar wind transit process should be completed and tested.

A.2.5 Magnetospheric Particle and Field Models

Magnetospheric models are needed to specify and predict the particles and fields in the magnetosphere and radiation belts, as well as the electrical currents that produce geomagnetic disturbances at Earth's surface. All magnetospheric models depend on knowledge of the solar wind, and the lead-time for magnetospheric predictions can only be as good as the corresponding lead-time for the solar wind inputs.

Currently, a magnetospheric model called the Magnetospheric Specification Model (MSM) is being used operationally to estimate fluxes of electrons and H^+ and O^+ ions in the distance range from L ~ 2 to nearly the magnetopause on the dayside and to about 15 to 20 R_E on the nightside. The MSM has at its core a particle drift code, with electric and magnetic field models that are driven by real-time data. The MSM can specify magnetospheric conditions on the basis of the Kp three-hourly planetary index of geomagnetic activity alone, but the quality of its output increases as its input database increases. The MSM is limited to providing nowcasts and retrospective analyses. However, the slightly more advanced Magnetospheric Specification and Forecast Model (MSFM), which is now in limited operational use, provides forecasts with a typical horizon of about 1 hour, as set by the availability of solar wind and IMF data from an L1 station.

The MSFM represents only one approach to numerical magnetospheric prediction codes. A principal shortcoming is the lack of quantitative, detailed self-consistency between the particle populations it numerically calculates and the magnetospheric magnetic field that it gets from a lookup table. Such self-consistency between plasma and magnetic field is the strength of global MHD simulations, which represent an alternative approach to numerical magnetospheric predictions. A principal shortcoming of global MHD simulations is their neglect of thermal drifts, which are important where field gradients are strong. Thermal drifts are explicitly calculated in the MSFM. Clearly a merger of an MSFM-like code (i.e., containing non-MHD physics) and a global magnetospheric MHD code represents a goal that should be set in order to advance toward greater capability in numerical space weather predictions. NASA has a plan, called the Quantitative Magnetospheric Predictions Program, to develop an operational numerical magnetospheric prediction capability based on integrating non-MHD physics into a global magnetospheric MHD code. At the same time the Department of Defense (DOD) is supporting the development of a particular version of a merger between an MSFM code and a global magnetospheric MHD code.

The present versions of the MSM and MSFM require accurate specifications of the electric and magnetic fields and the ionospheric conductance produced by auroral precipitation. One approach is to couple the MSFM to models of the ionospheric electrodynamics that assimilate data from ground-based magnetometers and radars, as well as from polar-orbiting satellites. Alternatively, semi-empirical models for E-fields and magnetic fields and auroral particle precipitation can be used. Models for E-fields and auroral precipitation are described in sections A.2.10 and A.2.8, respectively.

Various semi-empirical and theoretical models of the magnetospheric magnetic field are currently being developed. Semi-empirical magnetic field models are partly based on observations, but they also generally conserve magnetic flux and satisfy Ampere's Law. However, they do not explicitly relate currents and magnetic fields to plasma pressures, densities, or velocities. These models are usually designed to be user-friendly, and they run quickly on workstations. Theoretical models, which include the additional theoretical constraint of momentum conservation (and often conservation of mass and energy as well), can represent dynamical processes better, but they can run faster than real time only on the most advanced supercomputers or massively parallel machines, and they are not yet ready for operational use.

When the MSFM is successfully merged with a global magnetospheric MHD code, auroral precipitation E-fields and magnetic fields will be self-consistently computed. However, the semi-empirical models should continue to be refined and developed to validate and support the fully-coupled model.

A.2.6 Geomagnetic Disturbance Models

For some technical systems, it is not necessary to know the particles and fields everywhere in the magnetosphere. In some cases, it is sufficient to specify and predict the level of geomagnetic disturbance on the ground, or what is referred to as geomagnetically induced currents (GIC). A number of statistical algorithms are being developed to specify and forecast geomagnetic disturbances. These include an input-state space algorithm for the auroral electrojet (AE) index and more than one neural network algorithm for the magnetic disturbance storm time index (Dst). A statistical auroral electrojet predictor that specifies when, where, and how much the electrojet will intensify is being developed for use in making GIC warnings. These and similar algorithms that take the powerful statistical techniques that have been developed in the fields of nonlinear dynamics and artificial intelligence and use them to predict geomagnetic disturbance indices constitute a potentially rich source of useful specification and forecast products that can be transferred into operational service in the near term. Although prediction in the long term will be best done by physics-based numerical modeling, new techniques are under development to apply locally linear prediction filtering (of nonlinear phenomena) and deterministic chaos theory to characterize the magnetospheric response. Development of these and similar techniques could provide an alternative means for forecasting substorm activity through prediction of indices such as AE until the physics of substorm onset is better understood.

One deficiency all statistically based algorithms share is their poorly understood performance characteristics during extreme conditions, for which there are few data with which to fit or train them. Nonetheless, the mere fact that an algorithm is predicting out of range can have considerable forecast value. Regarding observational requirements, as a rule, these algorithms need real-time values of the index or quantity they predict, and some also need real-time upstream solar wind data.

A.2.7 Radiation Belt Models

Radiation belt particle populations have historically been specified by National Aeronautics and Space Administration (NASA) empirical models for inner and outer zone protons, called AP-8 Min and Max, and for inner and outer zone electrons, called AE-8 Min and Max, where Min and Max refer to phases of the solar cycle for which the models were designed. These models are based on data acquired before about 1990. All static models show various inaccuracies, especially in the South Atlantic anomalies and in the outer zone. Even in the more stable inner zone there is a deficiency in specifying >100 MeV protons and >10 MeV electrons.

Data from the Combined Release and Radiation Effects Satellite (CRRES) and Solar Anomalous Magnetospheric Particle Experiment (SAMPEX) satellites have demonstrated the extremely dynamic nature of the radiation belts and the inadequacy of the NASA AP-8 and AE-8 models. Outer zone relativistic electrons exhibit strong variations that are well correlated with the solar cycle, solar rotation, and solar wind speed. Inner zone protons can suffer sudden changes during magnetic storms and such changes can persist for months. This deficiency of the present models calls for research into dynamical models. Examples of such models have already appeared. The sudden creation by an interplanetary shock wave of a second inner belt has been successfully modeled. A neural network model based on Kp gives reasonably good predictions of the presence of relativistic electrons at geosynchronous orbit. Newer models of particle fluxes based on data from the CRRES and SAMPEX satellites are now becoming available. New CRRES radiation belt models which specify proton flux, electron flux, and total radiation dose are replacing the NASA models as inputs for specifying the radiation environment for satellite design engineers. The potential for improving and extending these and other models for operational purposes is great.

A.2.8 Auroral Models

An important element for both ionospheric and magnetospheric models is the ability to specify and predict the location and intensity of auroral precipitation. Current modeling efforts combine statistically based empirical models with known physics to produce reasonable assessments of inner magnetosphere dynamics and the resulting particle precipitation into the ionosphere. The MSFM provides the first numerical capability to follow magnetospheric particle fluxes and determine the precipitation into the auroral zone and an estimate of the time-varying electric field. Predictions of up to 1 hour are possible with solar wind data for input. However these models are missing good descriptions of time-varying, magnetosphere-ionosphere coupling and the resulting particle acceleration and field-aligned currents. The effects of the magnetospheric energy on the ionosphere can also be estimated with regionally based models that have no magnetosphere-ionosphere coupling.

A.2.9 Ionosphere Models

Because of the complicated nature of the ionosphere, there have been numerous approaches to ionospheric modeling over the years. These approaches include the following: (1) empirical models based on extensive worldwide data sets; (2) simple analytical models for a restricted number of ionospheric parameters; (3) 3D, time-dependent physical models including self-consistent coupling to other solar-terrestrial regions; (4) models based on orthogonal function fits to the output obtained from numerical models; and (5) models driven by real-time magnetospheric inputs. In an effort to achieve simplicity, some of the models have been restricted to certain altitude or latitude domains, while others have been restricted to certain ionospheric parameters, such as NmF2 and hmF2. Most of the models have been constructed to describe the climatology of the ionosphere and, in this regard, the models, such as the International Reference Ionosphere (IRI), have been very successful in describing the characteristic ionospheric features and their variations with universal time, season, solar cycle, and geomagnetic activity, as represented by Kp and Ap. More recently, the model development has focused on including the large-scale and medium-scale density structures in global simulations in a self-consistent manner. Efforts have also been directed toward modeling storms and substorms.

Global approaches to ionospheric weather and climatology include the Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIEGCM), the Time-Dependent Ionospheric Model, and the Field-Line Integrated Plasma model. Currently, the Parameterized Real-time Ionospheric Specification Model (PRISM) is being used to provide a near-real-time specification of the global ionosphere by starting with a parameterized physical model of the ionosphere and adjusting it to match near-real-time ionospheric data. The output of theoretically pre-calculated electron density profiles was parameterized to achieve sufficient computational speed. The near-real-time data ingested by PRISM are obtained from a network of ground-based sensors (bottomside soundings using digital ionosondes and GPS-based total electron content measurements) and space-based measurements from the suite of sensors on two Defense Meteorological Satellite Program (DMSP) satellites (in situ plasma data and precipitating ion and electron fluxes). PRISM is operational at the Air Force Weather Agency's 55th Space Weather Squadron (55 SWXS), providing global electron density profiles from 90 to 1600 km every 2 degrees latitude and 5 degrees longitude.

Critical parameters must be available either by means of measurements or models to improve ionospheric nowcasts. At high latitudes, the convection E-field and particle precipitation patterns must be known. Unfortunately, these 2-D patterns are needed as a function of time for dynamic simulations. It is, therefore, not a surprise that the bulk of the ionospheric modeling conducted to date pertains to climatology, because "empirical" or "statistical" E-field and precipitation models are appropriate in this case. Here, the empirical convection and precipitation patterns are held fixed for a 24-hour period, and diurnally reproducible electron densities are calculated. In the first few attempts to model time-dependent phenomena, such as geomagnetic storms, empirical convection and precipitation patterns were also adopted, but they were varied in time according to the variation of Kp with time. More recently, the time-dependent convection and precipitation patterns have been obtained by an ionospheric electrodynamic model driven by magnetometer, radar, and satellite data. With regard to the other ionospheric regions, the meridional wind is the critical parameter at mid-latitudes and the dynamo electric field is crucial at low latitudes. These parameters can be deduced by means of measurements of hmF2 or they can be calculated self-consistently using coupled ionosphere-thermosphere-electrodynamic models.

Among the first-principle models, deficiencies exist in both the topside and bottomside regions of the ionosphere. On the topside, the major problem exists at night and involves the plasmaspheric H^+ flux and its control of F-region heights and densities. Inability to accurately specify this flux is known to result in major errors (~>100%) in predictions of nighttime F-region densities. Until this problem is resolved, the relative roles of thermospheric winds and electric fields in the maintenance of the nighttime F-region will remain an open issue.

On the bottomside, it is necessary to specify the global distribution of upward-propagating tides and gravity waves, which is generally unknown. Major deficiencies in first-principle models also include inabilities to accurately specify the E-region and F1-region, including the distributions of intermediate, descending, and sporadic-E layers. These layers have gained attention because of their relevance to dynamo fields, their kinetic interactions with thermospheric winds, their enhanced conductivity and associated controls of E-region current systems, and their potential role as a tracer of wind-shear nodes and tidal components. Model deficiency in specifying these layers stems from inabilities to accurately specify NO, NO^+, and metallic ion populations along with forces due to zonal and meridional winds.

It is important to develop nested-grid, adaptive-grid, and nested-model approaches so that density structures of various scales can be self-consistently included in global simulations. In the short term, continued improvement in empirical electron density models is required, based on the new databases. For the long term, it is important to further develop coupled physical models. In addition, computationally fast empirical-numerical hybrid models will eventually be needed in order to develop a real-time forecasting capability. As part of this effort, multi-site data taken in real time will be needed for ingestion into the forecast models.

A.2.10 Ionospheric Electric Field Models

At high latitudes the ability to specify the global potential distribution lies in four areas: analytical or semi-analytical models driven by interplanetary parameters; adaptive numerical models driven by observations; data assimilation techniques driven by observations; and global magnetospheric models driven by interplanetary parameters. Evidently a predictive capability for the high-latitude potential distribution lies in improvement of the analytical or semi-analytical models and the refinement of global magnetospheric models. Immediate improvement of the present E-field nowcasting capability may be accomplished by improvement in data assimilation techniques and in the refinement of the adaptive models. The results from data assimilation procedures need to be quantified in a manner that makes comparison and integration into analytical models more straightforward.

At low and middle latitudes, a specification of the E-field is largely available from statistical analysis of data sets from incoherent-scatter radar sites rather sparsely distributed around the globe. Incorporation of these latest data sets into a global E-field model has not yet been undertaken. Work continues on the effects of high-latitude phenomena on the low-latitude ionosphere, with quantitative estimates of the penetration and disturbance effects to be expected in the near future to allow transition to a forecast model. Accurate specification of the longitude variations requires a wider distribution of measurements that are not presently available. The height of the F-region peak density and the distribution of ion concentration about the dip equator, are sensitive functions of the $\mathbf{E}\times\mathbf{B}$ drift motion of the plasma. It is thus possible that a description of these plasma properties may serve as a proxy for the $\mathbf{E}\times\mathbf{B}$ drift motion. In general, advances in this area are currently hampered by the lack of contiguous data sets that would allow accurate assessment of daily variations and their possible sources.

The goal of achieving some convergence in the present specification of the high-latitude potential distribution from each technique should be achieved in the near future. Results from global numerical models can now be compared with observations, and we may expect refinements in the models to occur in response to such comparisons. As a far-future goal, we should expect a convergence in the specification of E-fields from all these techniques and an increase in the efficiency of global numerical models, allowing their more frequent use. Models now generally provide a specification of the high-latitude potential distribution for a rather coarse profile of interplanetary parameters. The challenge is to provide a more continuous nowcast and forecast capability and the appropriate methodology to evolve the pattern from one state to the next.

A.2.11 Ionospheric Disturbance Models

Currently, ionospheric models do not incorporate ionospheric disturbances that affect the propagation and transmission of radio waves. These disturbances are associated with phenomena such as spread-F, sporadic E, polar cap patches, intermediate and descending layers, and traveling ionospheric disturbances. Ionospheric disturbances can result from such processes as plasma instabilities, auroral precipitation, meteors, geomagnetic storms and substorms, thermospheric winds, and gravity waves. Physics-based models that account for the development and evolution of these disturbances are required to achieve a full predictive capability. After such models have been developed, they must be integrated into the large-scale ionosphere models, such that the large-scale models set the conditions under which the smaller-scale disturbances will develop. These coupled models will enable predictions about the likelihood of ionospheric disturbances at a given place and time.

A.2.12 Ionospheric Scintillation Models

A global climatological model of scintillation, WBMOD, is available. The model was initially developed from scintillation observations with the Wideband satellite and phase screen theory of scattering. The initial model was found to be deficient because of poor temporal and spatial coverage. These limitations arose from the Sun-synchronous orbit of the Wideband satellite and the limited number of observing stations. The WBMOD model has recently been upgraded by infusing time-continuous equatorial scintillation data from geostationary satellites and scintillation data obtained from the HiLat and Polar Bear satellites in the auroral/polar cap region. The upgraded WBMOD (UWBMOD) model specifies scintillation for any radio wave propagation path between the ground and a satellite above 1000 km and at any frequency above 100 MHz. The inputs to the model are the day number, universal time, sunspot number, magnetic index, locations of the receiver and the satellite, frequency of satellite transmission, and phase detrend interval. The model outputs are the amplitude scintillation index, defined as the ratio of the standard deviation of intensity fluctuations to the average signal intensity; phase scintillation index, defined as the standard deviation of phase fluctuations over a specified detrend interval; and phase spectral strength and phase spectral slope, which define the phase structure of the scintillating signal.

UWBMOD is a climatological model and it fails to reproduce the extreme day-to-day variability of scintillation. As such, it is of limited use for real-time operational support and is useful only for long-term planning purposes. In order to improve its usefulness, the model needs to be driven by scintillation data from a network of stations. Because the frequency range over which intensity scintillation can be extrapolated is limited to the weak-scatter domain, multi-frequency data will be necessary. From the operational standpoint, the model needs to provide support to systems in the very high frequency (VHF) to GHz range of frequencies; 250 MHz transmissions from communications satellites and 1.2 to 1.6 GHz transmissions from GPS satellites may be exploited. The optimum number of sensors is dictated by the spatial dimensions of scintillation structures, their motions and lifetimes. The real-time, data-driven UWBMOD, developed in the interim, will provide a nowcasting capability for scintillations.

The later goal is to develop a physics-based model for the purpose of forecasting scintillation. Such a forecast model will be based on existing first-principle electron density models that incorporate: the physical processes leading to the formation of macroscale (several hundred kilometer) structures, including polar cap patches and equatorial plasma bubbles; further structuring to mesoscale and smaller scales (a few kilometers to tens of meters) by plasma instabilities; determination of the saturation amplitude of mesoscale structures; and radio wave scattering theory that computes scintillation for the propagation of signals from satellites through such turbulent media. The physics-based model should be developed in a phased manner. It needs to be focused on the equatorial region where scintillations are most severe. The next area should correspond to the polar region, and finally the focus should be shifted to the mid-latitude region. Plasma instability computations will require physical inputs. Critical needs are measurements of E-field components in the F-region, and plasma drift in the neutral frame of reference. Some of these sensors are currently available on the ground and onboard the DMSP satellites.

A.2.13 Neutral Atmosphere Models (Thermosphere and Mesosphere)

The appropriate modeling tool for the study of atmospheric density structure is the class of numerical TIEGCMs which can self-consistently calculate density perturbations and neutral wind systems on a global, 3D, time-dependent basis from physical principles.

As a first step in thermospheric nowcasting, empirical or semi-empirical models, exemplified by the Mass Spectrometer and Incoherent Scatter (MSIS) model, have been continuously improved and extended over the years. These models provide a critical first-order validation of any operational model and, indeed, can be used as such where high spatial resolution or time-dependency is not an issue. It is important to continue the development of these models that enable different data sets to be quantitatively reviewed and intercompared. Several operational models of thermospheric density and temperature, currently based on such semi-empirical models, reflect the mean behavior of the thermosphere as described by the large bodies of data from the various previous experimental programs. The semi-empirical or hybrid models use analytical functions to fit to randomly selected subsets of the available data, and spectral coefficients are generated that can be used conveniently to reconstitute thermospheric densities and temperatures as a function of space, time, and geomagnetic and solar activity levels.

The most important limitations of current numerical models are related to the accuracy of the time-dependent parameterizations used for the upper and lower boundary conditions. For example, the E-field distribution at high latitudes is a key factor in determining the magnitude of thermospheric response to geomagnetic activity. Three separate approaches are being used to lift these limitations. First, attempts are being made to lower the lower boundary of the TIEGCM to altitudes below the mesosphere to enable more self-consistent calculations of the important dynamical structures. Second, more rigor is being applied to calculations of the topside parameters (heat fluxes, currents, etc.), with the ultimate goal of generating a coupled magnetosphere-thermosphere-ionosphere model. Third, more systematic approaches are being used to develop improved empirical representations of boundaries, as in the assimilative mapping of ionospheric electrodynamics model, which uses disparate data sources to derive improved E-field distributions.

The fully coupled thermosphere-ionosphere models being developed for nowcasting and forecasting will use a variety of prescriptions and parameterizations based on geophysical and solar indices to describe the thermospheric energy inputs and solve the coupled governing equations discussed earlier to calculate all the thermospheric state variables (temperature, density, composition, and wind) on a global time-dependent grid. These models are being validated, and results are encouraging, particularly at F-region altitudes where Dynamics Explorer satellite data have been available to constrain and test the formulation.

A.3 Observations

Users of space weather information are concerned with both the background environment and the time of arrival, intensity, and duration of space weather disturbances as they manifest themselves at specific locations. The variations occur on time scales from minutes through days to years. To have a complete picture of the environment from the present into the future, forecasters need observations from key locations beginning with the origin of the disturbances at the Sun and continuing along their propagation routes into the near-Earth environment.

Eventually, a complete suite of observational sensors will provide this information on a continuing basis. However, in the near term, many sensors will be developed and deployed to provide observations that will support research into several areas: helping to improve the understanding of the physics of space weather, providing information to improve space sensors, and defining the requirements for observations to support operational models. This section describes the observations required to meet these needs.

A.3.1 Solar/Solar Wind Observations

CME. Investigations along the following lines should prove fruitful in improving our ability to predict CME-related disturbances in the solar wind and the associated energetic particle events:

- Develop techniques useful for understanding and predicting solar wind disturbances using soft x-ray images of the Sun such as provided by Yohkoh and the Solar and Heliospheric Observatory (SOHO), in anticipation of the Solar X-ray Imager (SXI) x-ray monitoring spacecraft series. This will enhance the x-ray observations currently being made by the Geostationary Operational Environmental Satellite (GOES).
- Study and assess radio capabilities for tracking solar wind disturbances in interplanetary space from the Sun to the Earth, including observations of both radio bursts and the interplanetary scintillation technique.
- Optimize coronagraph capabilities for studying the behavior of CMEs as a function of radial distance.
- Maintain ground-based coronagraph observation activities to provide a measure of global solar CME activity levels, and to increase the database for investigations of solar cycle variations of CMEs.
- Investigate the utility and capabilities of a solar wind monitor placed near Venus or Mercury orbit for predicting solar wind disturbances near Earth.
- Maintain an L1 or equivalent upstream monitoring capability for carrying out the above investigations and for maintaining at least a 1-hour forecast capability for major geomagnetic storms.
- Develop an EUV magnetograph capable of measuring coronal magnetic fields and test it on a spacecraft mission.

Solar Flare. Several missions can greatly improve our understanding of the flare process if we are able to take full advantage of them. In particular, SOHO provides line-of-sight magnetograms with much higher spatial resolution than previously available from the ground. In combination with Yohkoh, the SOHO observations greatly increase our understanding of magnetic structure in the corona. SOHO affords a unique opportunity to observe flares into the 2000 maximum from optical through soft x-ray wavelengths.

Technology developments are also under way that could constrain some of the models of flare energetics and improve our ability to predict the space weather consequences of an event on the Sun. In particular, the technology for imaging spectroscopy of hard x-rays with spatial resolution of less than 2 arc-seconds is now available. The current maximum provides an opportunity for applying this new technology to obtaining observations of many solar flares. Such observations could revolutionize our understanding of the basic problems of flare particle acceleration and heating.

Additional new technologies are poised to improve our understanding of the crucial magnetic field configuration in active regions and its relation to the larger scale magnetic field structure in the corona. The Flare Genesis project, consisting of an 80-cm solar telescope, was launched in December 1995 from the Antarctic. Flare Genesis was designed to obtain full-vector field observations above the atmosphere using a system of filters, thus leading to breakthroughs in our understanding of flare energy buildup and release. If Flare Genesis is successful in attaining its science objectives, balloon-borne vector magnetographs should be flown throughout the Solar Maximum.

These new missions and technologies notwithstanding, ground-based observation is the only likely option in the near future for continuous monitoring of the solar magnetic field. Present-day vector magnetographs are relatively insensitive; however, recent demonstrations of the use of infrared (IR) telescopes and magnetographs show their promise for obtaining measurements of the full-vector fields with much greater accuracy. This technology should be pursued vigorously and, if successful, developed for transition to an operational capability.

Existing routine observations can also be applied in new ways to the forecasting activity if the most recent understanding is exploited. For example, most flare forecasting is performed, at present, on the basis of the instantaneous structure of the photospheric and chromospheric magnetic, velocity, and photon emission intensity fields. By following the temporal evolution of these quantities, it should be possible to improve the accuracy of the predictions. For example, it may be possible to detect changes in magnetic shear leading up to a flare and to utilize those observations for forecasts. In addition, it is of special interest to predict flare intensity and duration. At present, this is done primarily by statistical tables that attempt to relate flare intensity and duration to other observable properties. These relationships need to be studied and tabulated much more accurately in order to decrease the high number of false alarms.

The observational goals pertaining to flare diagnosis and forecasting can be summarized as follows:

- Extend the SOHO and Yohkoh observations through the current solar maximum and expedite their utilization in models pertaining to flare-related space weather effects.
- Execute a flare mission for the current maximum. A mission such as NASA's High Energy Solar Spectroscopic Imager (HESSI) will utilize advanced high-resolution x-ray technology.
- Pursue the development of balloon-borne magnetographs like those in the Flare Genesis project, and assess their potential for operational use during the next solar maximum.
- Develop full-disk IR magnetograph technology for ground-based (and possibly space-based) monitoring of the full-vector solar magnetic fields.

Solar Radio Noise. Discrete solar radio bursts are detected and reported in real time by the Radio Solar Telescope Network (RSTN) operated by the Air Force and collocated with solar optical observing facilities worldwide. Plans call for RSTN to be replaced or augmented by the Solar Radio Burst Locator (SRBL), which will not only measure burst levels but also locate the solar position of the microwave source.

Data analysis and interpretation efforts, which employ new observations such as x-ray images from Yohkoh, are needed to investigate the nature of the sources of radio noise and their relationships with other features and events. Observational studies of the cause of radio noise should attempt to determine whether noise enhancements are precursors or byproducts of other significant releases of energy in the solar atmosphere. These studies could be undertaken immediately using currently available data.

Solar Wind. The numerical models of the solar wind need to be extensively compared with observations before they are incorporated into forecasting tools and tested operationally. Solar observations, especially of the photospheric magnetic fields, are required to provide the boundary conditions at the "source surface," although theoretical extrapolations or approximations are required to map these conditions to the ~20 R_S distance where the flow becomes more nearly radial and the speed is thought to be fully established. Currently, full-disk magnetograms are obtained routinely (e.g., daily) at observatories such as Wilcox Solar Observatory, Big Bear Observatory, Mt. Wilson Observatory, and the National Solar Observatory at Kitt Peak. Archives of interplanetary data at the National Space Science Data Center (NSSDC) have become widely available and could be used in conjunction with the magnetogram data to assess a given model's accuracy. The necessity of observing the photospheric fields more frequently as a part of model validation and application tests remains to be explored, as do other means of observationally determining the global solar wind inner boundary conditions. The time is ripe for experimentation with solar wind models, both to test them in retrospective data comparisons and to try predictions related to the generation of the primary "geoeffectiveness" parameters: velocity V, vector magnetic field B, and dynamic pressure ρv^2 that are observed at the L1 point by various spacecraft such as WIND and ACE. Ulysses observations currently provide a valuable 3D view of heliospheric magnetic field and solar wind structure, which will improve the source surface models.

From another perspective, interplanetary scintillation (IPS) measurements in principle provide a means by which coronal holes and stream interaction regions can be remotely sensed. As with their use in CME detection, these data require interpretation of a line-of-sight integration through the solar wind. Nevertheless, to the extent that these can be used to monitor the solar wind near its source, they are regularly available data that should not be overlooked. The IPS data should be considered as complementary to in situ plasma data, but of course interplanetary field perturbations can only be inferred. On the other hand, recent observations suggest that the heliospheric current sheet can be remotely detected using this method.

A number of actions can be undertaken in the observational area to enhance our solar wind knowledge and our use of it in space weather systems:

- Upstream monitors providing at least V, B, and solar wind density can be maintained to both test solar wind forecasting models in retrospective analyses such as those described above and to make ~1-hour forecasts and nowcasts.
- IPS data from appropriately located spacecraft should be made routinely available for analysis and operational use. International efforts to improve IPS techniques should be supported and the results evaluated.
- The full-disk magnetic field should continue to be regularly monitored to both validate models and attempt long-lead-time predictions of solar wind behavior using the models. In addition, methods should be developed to determine observationally the full-disk vector B field on a regular basis (e.g., with IR magnetographs), because this forms the basis for many of the potential forecasting model boundary conditions.
- Methods for determining the solar wind velocity near the Sun from remote observations need to be developed, including those based on full-disk magnetic field observations.
- The Solar Probe mission should be developed and used to learn more about the solar wind origin and acceleration, and its connection to the solar magnetic field structure.

A.3.2 Magnetospheric Observations

For operational nowcasting and forecasting, continuous, real-time data are crucial. Space-based measurements include upstream solar wind and IMF data; particle and field data from at least four well-positioned geosynchronous satellites; particle data from the suite of GPS satellites; and particle, magnetic field, electric field, and imaging data from low Earth orbit (LEO) polar orbiters. Currently, LEO operational satellites include both the DMSP and National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellite (POES) systems, which will eventually converge to form the joint National Polar Orbiting Environmental Satellite System (NPOESS). Assets currently in geosynchronous orbit include the GOES 8 and 10 satellites, carrying magnetometers and energetic particle instruments, and several satellites carrying Department of Energy environmental plasma and energetic particle instruments. Ground-based systems include instruments for observing surface magnetic field data that adequately cover low-, middle-, and high-latitude regions (for example, as described in The National Geomagnetic Initiative, published by the National Research Council, National Academy Press, Washington, D.C., 1993); the existing and planned radar arrays; and ionosonde and riometer stations. All these measurements have an important role to play in an effective operational forecasting capability.

Operational measurements must be available in real time if they are to be of use for prediction. Real-time data access will be important for both ground-based and satellite-based data sources. Operational space weather prediction of high-latitude phenomena requires an upstream monitor of solar wind conditions. The ACE satellite became the first operational monitor, and this must be followed by continuous operational monitoring of the IMF and solar wind parameters. All numerical space weather models ultimately require solar wind information to function in the predictive mode. The space environment sensors on the DMSP and NOAA POES satellites provide an especially valuable resource for constraining the present-generation models and will continue to be useful for future models as well. Improvement of the freshness of the data is necessary for predictive capabilities. Other fleets of operational satellites should be utilized in the future to provide critical data for constraining space weather models. One source of especially useful data could be the GPS constellation of satellites, which could provide data on the source population temperature and other moments of auroral particles prior to acceleration by field-aligned potentials, parameters of particular use in the modeling of magnetosphere-ionosphere coupling.

Observations for attacking the science issues and observations for providing operational drivers for space weather models are overlapping but different. During the period leading up to and through the solar maximum, a large number of research satellites have been and will be launched that can provide critical data for investigating key science issues. NASA's POLAR and WIND satellites, combined with the Japanese Geotail mission, will answer basic questions on a global scale of energy input, storage, and release relative to magnetic storms and substorms. The Fast Auroral Snapshot (FAST) satellite will investigate auroral processes on microscales and mesoscales. The Ørsted satellite will make very accurate measurements of the near-Earth magnetic field, which will be useful for the study of external currents. Put in the context of the auroral images from POLAR, these measurements will be used for addressing the 5-km-scale description of aurora desired by the customer base. Continuing these missions through the more active conditions typical of the solar maximum will ensure that the physics learned fits not only moderate to active conditions but also the extreme conditions that can be the most devastating for space weather-related problems. Continuous monitoring of the high-latitude regions by the DMSP and NOAA POES satellites and by ground-based techniques such as incoherent scatter radars, HF radars, magnetometers, and riometers provides complementary information to satellite missions and is an essential component of the research database needed to explore and define the physical processes. Extension of ground-based facilities to the center of the polar cap with the Relocatable Atmospheric Observatory augments the current longitudinal-chain measurement capability significantly. This complements the Super Dual Auroral Radar Network (SuperDARN) chain of HF radars that will monitor simultaneously auroral zone electrodynamics over 7 hours of local time. The Automated Geophysical Observatories (AGOs) will provide information about magnetic and auroral conditions in the Southern Hemisphere

An important future thrust for magnetospheric observations is the validation of techniques for space-based imaging of the magnetosphere. In addition to existing techniques for multispectral imaging of the aurora, the technology exists to image the ring current, plasmasphere, inner plasma sheet, and possibly ionospheric ions. Many of these concepts will be validated as part of NASA's Imager for Magnetopause to Aurora Global Exploration (IMAGE) satellite program. Other future research satellites of importance include a dedicated radiation belt satellite and a satellite in the IMP-J orbit to monitor the near-Earth solar wind and tail regions.

A.3.3 Ionosphere/Thermosphere Observations

Electron Density. The most critical need for the calculation of ionospheric electron densities is a specification of the time-dependent model inputs on a global scale (i.e., specification of the convection and precipitation patterns, meridional neutral winds, and dynamo E-fields). Also, for validation purposes, global measurements of the electron density distribution are required. The inputs and electron densities are needed for a range of geophysical conditions, including quiet and disturbed periods for different seasonal and solar cycle conditions. Ultimately, multi-site measurements from a globally distributed network of relatively inexpensive instruments operating in real time are required for forecasting purposes. Coordinated multi-instrument measurement campaigns will also be needed to address unresolved physics issues.

In the near term, progress in the physical understanding of coupling processes and time delay mechanisms can be achieved by exploiting the comprehensive databases recently acquired as part of Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) and Geospace Environment Modeling (GEM) campaigns. These databases include multi-site measurements and data from a variety of instruments (magnetometers, coherent and incoherent scatter radars, satellites). Because the largest perturbations and the greatest uncertainties in density calculations occur during geomagnetic storms and substorms, the near-term observational emphasis should be on these phenomena. However, there are still important unresolved issues connected with the creation, transport, and decay of electron density structures, and multi-instrument measurement campaigns are required to resolve them. In addition, it seems certain that more LEO receivers on spacecraft like GPS-Met will be launched for meteorological purposes, but will also be potentially very useful for determining ionospheric vertical density profiles by the use of inversion algorithms.

Ionospheric Electric Field. For advancement at high latitudes, the observational requirements are clear. We require the maximum possible coverage of the high-latitude region with specification of the F-region ion drift or electric field. This need is met in part with radar arrays that may be augmented in the near future. In this area there is a real synergism between the capabilities of ground-based arrays to provide good temporal resolution with less than global coverage and spacecraft systems to provide almost global "snapshots" at given times. An ideal satellite configuration, for adequate constraint of the models, places sensors in at least two and preferably four local time planes with multiple spacecraft in each plane. Such a configuration, together with ground-based sensors, would dramatically advance our ability to determine the nature of the temporal and spatial distribution of the potential, and to begin a meaningful parameterization of its evolutionary properties.

In the long term, the Relocatable Atmospheric Observatory (RAO) will provide invaluable data for resolving problems that have plagued our community for almost 30 years. For example, although E-fields have been measured since the early 1960s, there is still a major disagreement on the configuration of the high-latitude convection pattern when the interplanetary magnetic field is northward. The combination of data from the RAO and the DMSP satellites should resolve this issue.

At middle and low latitudes the need for monitoring the $\mathbf{E}\times\mathbf{B}$ drift of the plasma is paramount. The spatial scales of interest are such that this could be rather easily accomplished with a low-inclination spacecraft. The use of ground-based measurements to describe the height of the F-peak will continue to make important contributions in this area. However, access to a data set from a satellite in equatorial orbit would allow the association between $\mathbf{E}\times\mathbf{B}$ drift motion and the nighttime stability of the ionosphere to be quantitatively established.

Ionospheric Disturbances. Among the requirements is global, long-term (10-30 day), around-the-clock observations that by their very definition are guaranteed to capture quiet and storm-time conditions and associated transitions in the growth and recovery phases of associated disturbances and their inter-hemispheric manifestations. This will permit an accurate empirical specification of the weather and climatology of E, F_1, and F_2 characteristics. In this regard, archives exist with sufficient campaign data (e.g., in the CEDAR database) to carry out a systematic quantitative evaluation of empirical and first-principle models and determine levels of accuracy and inadequacies in model prediction capabilities as a function of season, solar epoch, local and universal time, geographic and geomagnetic domains, and levels of disturbance. With this perspective, the existing ionosonde database (with more than 50 stations currently active worldwide) can provide heights and densities of the E- and F-regions along with specification of dominant intermediate and descending layers. The F-region densities will define the temporally and spatially dependent condition of the ionosphere in its quiet, transitional, and disturbed states, and the measurements of F-region heights, through servo-analysis, will provide an indirect observation of meridional winds at all local times over a broad range of mid-latitude sites. Ionosondes also provide direct measures of sporadic-E as well as range and frequency of spread-F. Augmentation of these observations with incoherent scatter radars (for E-fields and F-region winds), Fabry-Perot interferometers (for dawn/dusk F-region winds), and satellites of opportunity, e.g., DMSP and NOAA POES for specification of high-latitude inputs, will provide significant gains. Future programs can build on more complete specification of the ionosphere-thermosphere system and controlling forces. Promising opportunities include the Arizona Airglow Experiment (GLO), Midcourse Space Experiment (MSX), Advanced Research and Global Observing Satellite (ARGOS), and Thermosphere-Ionosphere-Magnetosphere Energetics and Dynamics Mission (TIMED) programs and a recently proposed upper F-region satellite at low inclination focused on topside profiles and scintillation data during conditions of equatorial spread-F.

Ionospheric Scintillations. Effects of scintillation on some operational systems, notably GPS satellite navigation systems operating at 1.2-1.6 GHz frequencies have not been determined. It is generally recognized that GPS navigation systems are vulnerable in the polar and especially in the equatorial region during the solar maximum period. In the equatorial region the irregularity structures are highly elongated in the north-south direction and are discrete in the east-west direction with dimensions of several hundred kilometers. With such spatial distribution of irregularities, we need to determine how often a GPS receiver fails to provide navigation aid with the available constellation of GPS satellites. It is recommended that GPS receivers acquiring amplitude and differential phase at a high data rate (50 Hz) be deployed to assess the effects of scintillation on the performance of GPS navigation systems in the equatorial region. Such measurements will also be helpful in the design of satellite-based cellular telephone systems using L-band frequencies.

Observations are also needed to establish the survivability of MILSTAR satellite systems using frequencies in the K_a band (20-40 GHz) and the UHF band (250 MHz). K_a-band transmissions are not affected by the ionosphere but are very vulnerable to rain and fog in the equatorial region. On the other hand, 250 MHz systems will be able to withstand the effects of rain but suffer outages from ionospheric scintillation.

In view of the extreme spatial and temporal variability of scintillation, immediate deployment of a network of ground-based scintillation sensors is recommended. Sensors need to cover the frequency range (250 MHz to 6 GHz) used by operational systems. Geostationary satellite transmissions of 250 MHz and GPS satellite transmissions at 1.2-1.6 GHz may be utilized by these sensors. The current climatological model of scintillation may be adapted to ingest the multifrequency scintillation data to provide a real-time-data-driven scintillation model.

From an operational standpoint, the forecasting and specification of equatorial scintillation is a major requirement. From a physics point of view, the temporal and spatial variability of scintillation in the equatorial region remains unresolved. There is general agreement that the interaction between thermospheric neutral wind and the ionized species critically controls the E-field at F-region heights in the post-sunset period, and thereby controls the onset of plasma instabilities and scintillation. Whether the instability is inhibited by the meridional wind on a day-to-day basis or it requires a finite-amplitude seed perturbation from gravity waves is not known. Overall, there is a need to monitor the thermosphere-ionosphere interactions on a short temporal and spatial scale. An equatorial satellite with altitude between 600 and 700 km and orbital inclination of about 30° carrying a modest number of sensors is required to monitor this interaction. The sensors should include an ion drift meter, vector electric field instrument, phase coherent radio beacons at L-band and VHF frequencies, and instruments to measure neutral wind and ion/neutral composition. With an orbital period of 90 minutes, the satellite will be able to monitor the formation of plasma bubbles and their scintillation effects on beacon transmissions. It will also support studies on thermosphere-ionosphere interactions at low latitudes and provide physical inputs to the physics-based model of scintillation.

Neutral Atmosphere. The neutral upper atmosphere is a data-poor domain by comparison with the lower atmosphere. In fact, the existing database is still insufficient to provide a full climatology of thermospheric state parameters as a function of altitude, universal time, local time, latitude, longitude, season, solar activity and geomagnetic activity. Important pieces of this climatology certainly exist, but careful experimental work is still needed to provide a complete quantitative description. Semi-empirical models, such as MSIS, may be used for rough estimates of thermospheric parameters. The accuracy of such models, however, is still quite limited; for example, mean thermospheric densities are modeled to accuracies of only 15% at best, with errors of factors of two or more occurring at high latitudes and/or for geomagnetically active periods. Some of the problems can be traced to spatial- and temporal-resolution limitations, some to instrument calibration limitations, and some to limitations in spatial coverage. Clearly, these models will need to be greatly improved through the ingestion of new, carefully calibrated, global-scale data sets. Similar considerations apply for the numerical, hybrid, or stripped-down numerical codes, which all require more extensive, well-calibrated global-scale data sets for validation and testing. The basic observational needs are for measurements of thermospheric and upper mesospheric density, wind, temperature, and composition to accuracies of better than 5%. Careful attention to spatial and temporal coverage will be required to aid in the specification of the thermospheric and mesospheric waves of importance (gravity waves, planetary waves, and tides). This latter challenge will require the systematic deployment of airglow imagers, lidars, HF radars, and specialized satellite techniques.

The thermosphere is driven by solar EUV heating. Currently, however, the ground-based proxy indices for solar radiative fluxes are inadequate. Therefore, it will be of central importance to develop a long-term, reliable monitoring method to measure the direct solar EUV fluxes impinging on the upper atmosphere. This will require a long-term commitment to deploy a satellite instrument or series of instruments. Also, sustained observations of thermospheric structures at high geomagnetic latitudes will be needed from satellites, the RAO, and other sites, to determine the nature of the inputs and atmospheric response to geomagnetic activity. This effort would be greatly helped by the recommended high-inclination, highly elliptical satellite designed to investigate high-latitude electrodynamics.

Finally, the development of new experimental means of monitoring thermospheric compositional changes from ground and space will be very advantageous. It is clear that a major limitation of current thermospheric and ionospheric models relates to the ability to predict composition of such critical species as atomic oxygen, nitric oxide, and carbon dioxide.