

## SECTION 4

## SPACE WEATHER--A NEW CHALLENGE FOR METEOROLOGISTS

## INTRODUCTION

Information about weather has become increasingly popular in recent years. This escalation in interest is due in part to improvements in communications and packaging. The ability to pinpoint each day's most important weather events and present them as riveting news stories makes for compelling entertainment. However, perhaps the most important reason for the recent increase in weather awareness in the general population is that, despite our seemingly successful efforts to control our environment, our lives are in many ways as sensitive to weather as they have ever been. Space weather is poised to undergo a similar surge in interest. The existence of weather in space and its potential impacts have been known for some time. However, real impacts have been limited, and the general population has been largely unaware of them. That is about to change.

During the current solar minimum, the application of technologies which are vulnerable to space weather have exploded in the commercial and consumer sectors. When the sun becomes increasingly active near the turn of the century, space weather can be expected to interfere with daily activity in ways that are different from terrestrial weather, but can be equally as obnoxious and can occasionally pose threats to human health and property. It is not unreasonable to expect space weather information to become part of a routine flight weather briefing for aircraft operations so that aircrews will know when and where their communications and navigation systems may not work as expected. We may even see space weather information in television weather reports to let the populace know when they may experience difficulty getting their high-tech systems like cellular phones to work properly. Understanding space weather and its impacts, and communicating that information to potential customers poses a new challenge to meteorologists. The following will acquaint meteorologists with some important aspects of that challenge.

This section begins with an explanation of the basics of space weather and its impacts. The roles of the sun, the interplanetary medium, and the upper regions of the Earth's atmosphere (the magnetosphere and ionosphere) will be discussed, followed by examples of how space weather interferes with operations and can damage or destroy components or systems. With that background, an interdepartmental effort to improve our capability to observe and forecast the space environment, called the National Space Weather Program, will be discussed.

## SPACE WEATHER AND ITS IMPACTS

Space Weather Primer

"Space weather" refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health. Space weather is similar to terrestrial weather in at least one aspect--its source of energy is the sun. However, while terrestrial weather is driven by radiative energy from the sun, space weather responds to both radiative and particle energy. Variations in solar output may affect long term climatological trends but have not been shown to impact daily terrestrial weather. On the other hand, the variations in the sun's radiation and particle emissions trigger rapid and often dramatic change in the space environment. Several solar processes cause variations in the sun's emissions:

» *Solar Wind.* Continuous particle emissions form a low energy plasma, which comprises the solar wind. As the solar wind moves outward from the sun, it interacts with the Earth's magnetic field. This process creates the magnetosphere, a tear-drop shaped region which is compressed to a distance of five to ten Earth radii on the daylight side of the Earth and stretched on the nighttime side to distances sometimes exceeding the orbit of the moon (See Figure 4.1).

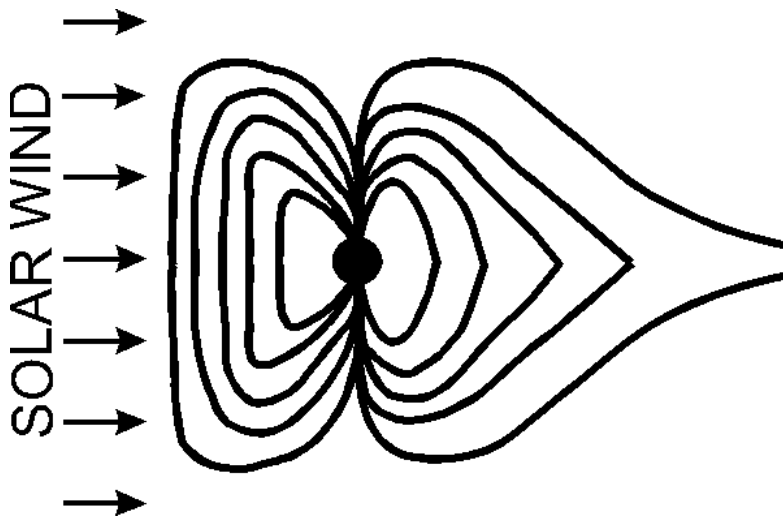


Figure 4.1 Interaction of Magnetosphere and Solar Wind

» *Sunspots.* Areas of strong magnetic field on the surface of the sun are cooler than the surrounding solar surface and appear darker. These visible features serve as an indicator of solar activity, and they are often the site of solar flares. The number of sunspots follow an 11-year cycle. The last solar maximum occurred in 1989, and solar minimum occurred in 1996 (See Figure 4.2).

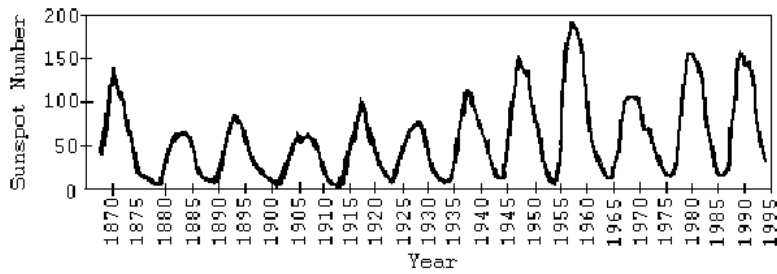


Figure 4.2 Plot of Annual Sunspot Number

» *Solar Flares.* Short-lived (minutes to hours), intense bursts of energy, solar flares radiate throughout the electromagnetic spectrum, from gamma and X rays through the visible range to radio waves. Visible as bright spots on the surface of the sun, flares can also be detected as bursts of radio noise.

» *Coronal Mass Ejections.* Violent releases of bubbles or tongues of gas, coronal mass ejections can suddenly accelerate up to a billion tons of matter into space at up to two million miles per hour, twice the normal speed of material released from the sun.

» *Prominences.* Visible as dark filaments, prominences are clouds of solar material suspended above the surface of the sun by the solar magnetic field. Prominences eventually erupt, releasing solar material into space.

» *Coronal Holes.* Open field lines in the sun's magnetic field, coronal holes are long-lasting (months-years) features which are visible in the X-ray region of the spectrum. They allow the outflow of high velocity solar wind.

Within 30 minutes of a major solar flare, energetic protons released during the flare can shower the Earth. Some of these particles can be captured in the magnetosphere and move downward along the field lines, triggering a proton event.

Within 1 to 4 days after a flare or eruptive prominence, a cloud of matter and magnetic field can reach the Earth, buffeting the magnetosphere and causing a geomagnetic storm. These storms, which last for several days, are characterized by a worldwide disturbance in the Earth's magnetic field, causing it to vary rapidly in direction and intensity. Through processes which are not well understood, storms disrupt the equatorial regions of the ionosphere, causing intensification of normally occurring spatial irregularities in electron density (scintillations). Geomagnetic storms and increased ultraviolet emission from flares can also heat the Earth's upper atmosphere, causing it to expand upward.

Substorms occur when charged particles are captured by the magnetosphere and then release their energy, a process characterized by visible aurora and development of intense currents in the ionosphere--the atmospheric layer underlying the magnetosphere. Substorms usually last a few hours, originating near local midnight and spreading into both the evening and morning sectors.

### Space Weather Impacts

In terms of impacts on people and society, space weather stands in a unique and curious juxtaposition with terrestrial weather. Terrestrial weather affects people directly and dramatically, and society has applied technology to alleviate its impacts. Space weather, on the other hand, has historically had little impact on daily human life. It was only when we began using technology on a large scale and/or in sophisticated ways that we felt the impacts of space weather. Several types of systems are affected by space weather:

» *Satellites.* Upward expansion of the atmosphere during geomagnetic storms or in response to enhanced ultraviolet emissions from the sun increases the density of the atmosphere at low earth orbit altitudes. This process, in turn, causes an increase in drag on satellites, affecting orbital parameters and complicating the use of data from satellites whose missions require precise knowledge of the position of the satellite. In the worse case, the increase in drag can cause premature reentry of satellites, shortening their orbital life. Satellites are also vulnerable to the effects of energetic particles. Very energetic particles penetrate electronic components causing spurious electronic signals which can result in erroneous (and often deleterious) commands or bad data from an instrument. During geomagnetic storms, satellites traveling through an environment of somewhat less energetic particles develop differential charges on different areas and materials on the spacecraft. The charge can build to a point where arcing occurs, and sensitive components can be damaged.

» *Power Systems.* When magnetic fields move about in the vicinity of a conductor such as a wire, an electric current is induced into the conductor. Power transmission lines are susceptible to this type of current induced by dramatic changes in ionospheric currents that occur during geomagnetic storms. Power surges produced by these induced currents can cause power network failures and damage equipment in power generation plants and transmission systems. In the past, this phenomenon has caused millions of dollars in damages and deprived millions of people of commercial electrical power for several hours. Over recent decades, power systems have become more interconnected, used more complex controls and technologies, and increased the practice of transferring power over large distances. While these changes have made power more affordable and reliable under normal circumstances, they have also increased the vulnerability of the systems to disruption and damage by space weather effects.

» *Navigation Systems.* The very low frequency radio signals used in systems such as LORAN and OMEGA are affected when solar activity disrupts their wavelengths. Changes in the ionosphere caused by proton events, solar flares, or geomagnetic storms can cause positional errors as large as several miles. Ionospheric conditions also affect radio waves from Global Positioning System (GPS) satellites. Normally, the signals from GPS satellites can be used to calculate very accurate positions. However, changes in the ionosphere can refract and slow GPS radio waves, introducing significant errors in position. In addition, GPS receivers can experience a loss of signal lock when the signal traverses an ionospheric disturbance (scintillation).

» *Communications Systems.* Radio-wave communications over a broad range of frequencies are affected by space weather. High frequency (HF) communications are more routinely affected because this frequency depends on reflection from the ionosphere to carry signals great distances. Ionospheric irregularities contribute to signal fading, and highly disturbed conditions can absorb the signal completely and make HF propagation impossible. Higher frequency radio signals, such as ultrahigh frequency, are often used for communications which pass through the ionosphere as they are relayed by satellite. Properties of these signals can be altered by ionospheric conditions to the extent that they can not be accurately received.

» *Manned Space Flight.* The flux of very high energy particles can increase several orders of magnitude during intense solar flares and can also increase to dangerous levels during large geomagnetic storms. The Earth's atmosphere and magnetosphere provide adequate protection at ground level from these particles,

as all but the most energetic cosmic ray particles are absorbed. However, in space, the penetration of high energy particles into living cells can lead to chromosome damage and cancer. Large doses can be fatal immediately. The greatest risk is to astronauts performing extra-vehicular activity, spacecraft in high inclination orbits, and crews and passengers on high altitude aircraft flying in the polar regions.

#### IMPROVING SPACE WEATHER SUPPORT

Meeting the needs for space weather support is extremely challenging. The vast volume of the environment in which space weather occurs and the lack of *in situ* observations make specifying the current state of the weather difficult and forecasting its future state out to a few days nearly impossible. Interactions between regions of the space environment complicate the problem. For example, a particular location of interest in the ionosphere changes in response to the ionospheric conditions around it, to magnetospheric conditions, and to radiation directly from the sun. But the magnetosphere, meanwhile, is responding to both the solar wind and other particle and electromagnetic solar emissions, and variations in those phenomena are caused by events on the sun.

A robust suite of observations from the ionosphere and magnetosphere would allow for timely forecasts of some important events which impact operations. The ability to carefully observe and monitor conditions on the sun and characterize in detail the nature of solar emissions would allow forecasters to broaden the range of events for which they could provide timely warnings and forecasts. However, the ability to meet all space weather requirements would necessitate timely and accurate forecasts of events on the sun.

#### Current Capabilities

Operational space weather support is provided to civilian customers by NOAA's Space Environment Center (SEC) in Boulder, CO. The 50th Weather Squadron (50 WS), located at Falcon Air Force Base, CO, supports military space weather requirements. Information on products and capabilities of these organizations is available in Appendix A (for SEC--under National Weather Service and the Office of Oceanic and Atmospheric Research) and Appendix B (for 50 WS--under United States Air Force, Space Environment Services). A more detailed, although somewhat dated, explanation of the entire space environment support system is given in the OFCM's *National Plan for Space Environment Services and Supporting Research, 1993-1997*.

#### Plans for the Future--The National Space Weather Program

A few years ago members of the space science community recognized the need for improving the nation's ability to specify and forecast space weather. They also recognized the potential for significant improvement in that ability if a concerted effort were made to capitalize on research efforts planned and underway. Because space weather operations and space science research efforts spanned several agencies of the federal government, the Office of the Federal Coordinator for Meteorology (OFCM) was asked to facilitate an effort to develop an interagency space weather program. The result was the National Space Weather Program (NSWP), which was instituted in August 1995 with the chartering of a program council to oversee the NSWP and the adoption of the National Space Weather Program Strategic Plan.

The overarching goal of the NSWP is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts within the next 10 years. Participating agencies include the following:

- » The Departments of Commerce and Defense, which support research and include organizations that provide operational services.
- » The National Science Foundation and the National Aeronautics and Space Administration, which support and/or conduct research in the space sciences.
- » The Departments of Energy and Interior, which operate sensors which collect space weather data and conduct some related research.

Providing timely, accurate, reliable space weather forecasts will require several elements of a system, including comprehensive observations, coupled with physics-based models of the various regions of the space environment, and an educated community of producers and users of space weather information. The recently published National Space Weather Program Implementation Plan addresses these elements in detail and lays out a roadmap for meeting NSWP goals. The implementation plan recognizes the importance of research early in the program and is heavily focused on that element. Other elements are addressed in somewhat less detail.

To provide some organizational structure to an extremely complex undertaking, the implementation plan divides the research element into two dimensions. First, research is conducted in three areas--physical understanding, model development, and observations.

- » *Physical understanding* involves increasing our knowledge of the physical processes controlling the space environment. This area could best be thought of as basic scientific research.
- » *Model development* is a common way of expressing the physical understanding derived from basic research. Models provide a "deliverable" from the research process which can be adapted to support operations.
- » *Observations* encompass several thrusts--to provide data for improving physical understanding, to help determine what data will be required by operational physics-based models, and to develop and improve the technology of observing systems.

Secondly, the NSWP Implementation Plan divides the space environment into three regions.

- » *Solar/Solar Wind* includes coronal mass ejections, solar activity/flares, solar and galactic energetic particles, solar UV/EUV/Soft X rays, solar radio noise, and solar wind.
- » *Magnetosphere* includes magnetospheric particles and fields, geomagnetic disturbances, and radiation belts.
- » *Ionosphere/Thermosphere* includes the aurora, ionospheric properties, ionospheric electric fields, ionospheric disturbances, ionospheric scintillations, and the neutral atmosphere.

For each of these areas a detailed time line was developed showing what research observations will be needed, what research-grade models will be developed to express the understanding of the physical processes at work, what operational models will be implemented based on the research-grade models, and what operational observation systems will be needed to support those models.

The implementation plan also prioritizes NSWP efforts by suggesting areas for near-term emphasis, discusses potential education efforts, and provides information on program management such as OFCM management structure, non-federal involvement, metrics, and agency roles and responsibilities.

Finally, the implementation plan addresses the difficult issue of moving technology from the laboratory or academic community into the operational environment. There are many aspects of this issue, which fall under the general heading of "technology transfer" or  $T^2$ --building and deploying long-life operational sensors, moving data where it is needed in real time, using operational databases, etc. However, the plan focuses on one of the tougher issues which will be an early and constant challenge during the program--converting research-grade models into operational models. The plan suggests employing rapid prototyping, a process which provides immediate feedback to a development team as they iteratively test implementation concepts in a quasi-operational environment.

Figure 4-3 depicts the overall scheme of the NSWP. The two dimensional nature of the research effort is shown producing new capabilities which proceed through a technology transfer ( $T^2$ ) process into the operations environment where continuous observations support coupled, physics-based models. This model output is used to produce tailored products which support various missions.

In July 1996, the National Science Foundation awarded \$1.3 million to support 23 research projects associated with the NSWP. With detailed research requirements well documented, the focus of the NSWP will shift, in the coming years, toward moving new technology into the operational environment.

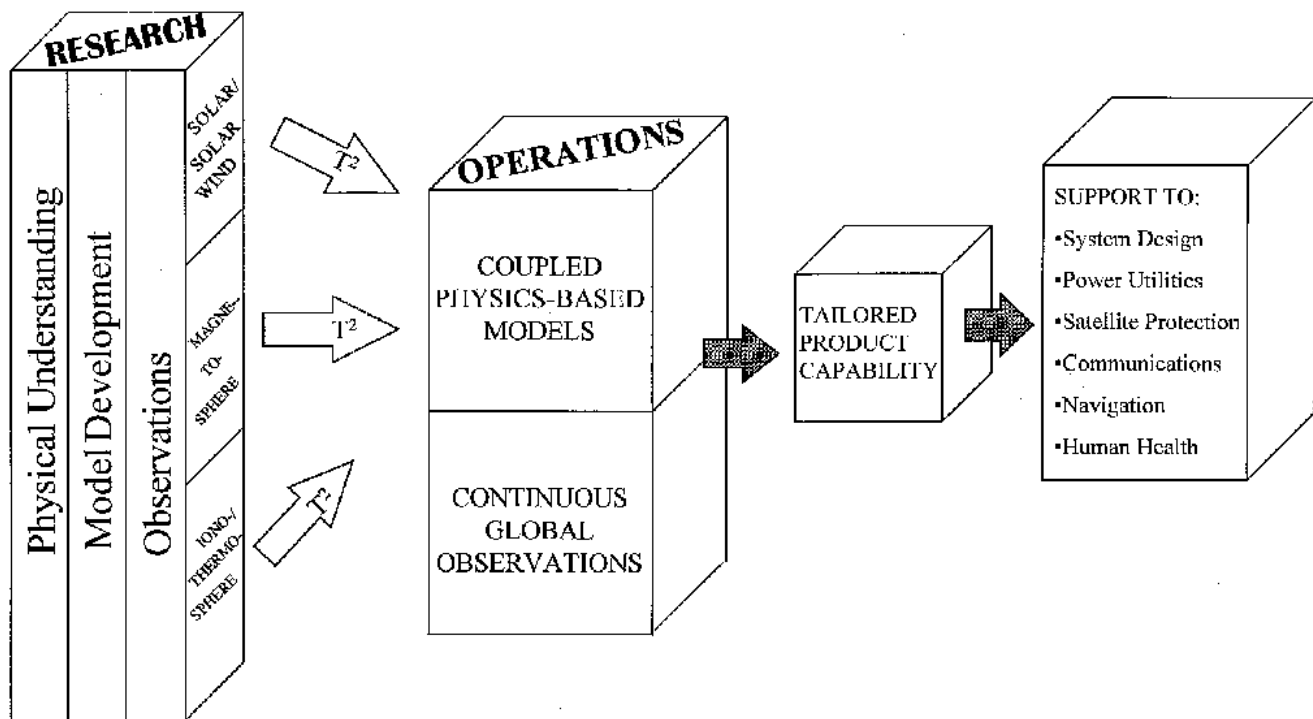


Figure 4.3 National Space Weather Program Roadmap

*This section was prepared by Colonel Jud Stailey, USAF, who is assigned to the OFCM as the Assistant Federal Coordinator for the Air Force and Army affairs. In addition to serving as the Executive Secretary to the National Space Weather Program Council, Committee for Space Environment Forecasting, and the Working Group for the National Space Weather Program, Colonel Stailey serves as the Secretary for the Working Groups for Climate Services and Meteorological Information Management as well as the coordinator for the Interdepartmental Hurricane Conference. Colonel Stailey joined OFCM in 1995 after serving for three years as the Commander of the Air Force Combat Climatology Center, Scott AFB, Illinois.*

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