Long-Term Solar-Terrestrial Observations

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Long-Term Solar-Terrestrial Observations report presents the results of an 18-month study of the requirements for long-term monitoring and archiving of solar-terrestrial data. The value of long-term solar-terrestrial observations is discussed together with parameters, associated measurements, and observational problem areas in each of the solar-terrestrial links--the sun, the interplanetary medium, the magnetosphere, and the thermosphere-ionosphere. Some recommendations are offered for coordinated planning for long-term solar-terrestrial observations.

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Long-Term
Solar-Terrestrial
Observations

Long-Term Solar-Terrestrial Observations

Panel on Long-Term Observations
Committee on Solar-Terrestrial Research
Board on Atmospheric Sciences and Climate
Commission on Physical Sciences,
　　Mathematics, and Resources
National Research Council

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COMMITTEE ON SOLAR-TERRESTRIAL RESEARCH

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1
Introduction

In principle, solar-terrestrial research deals with the direct irradiation of the earth's upper atmosphere by the full spectrum of electromagnetic radiation and with the transport of particles and fields from the sun, through the interplanetary medium, to and through the magnetic field and atmosphere of the earth (NRC, 1981a). However, with the advent of satellite-based observing systems, attention has focused on the solar-terrestrial environment as an enormous plasma "laboratory" in which at different places and different times a rich variety of plasma processes are demonstrated. The sun is the only star close enough for such detailed scientific research. Researchers in this cosmic laboratory muster the latest and best instruments to gather data from this laboratory to solve the problems each process poses. From the perspective of research into space plasma physics, solar-terrestrial data gathering and the data themselves are most valuable when they lead to the discovery of new processes or advance our understanding of known processes, thus enhancing the value of ongoing national space-related operational services.

Space plasma physics lies within the older and broader field of solar-terrestrial science. The interest of solar-terrestrial science is the description and understanding of a large number of environmental features and processes that characterize the sun-earth system. These include the full range of the sun's electromagnetic emissions (especially the variable short- and long-wavelength components), all

manifestations of solar activity, and the variable and structured fluxes of particles and fields that make up the solar wind, which with solar and galactic cosmic rays fills interplanetary space. They include the magnetosphere with its many particle populations, current systems, and dynamical behavior. They include also the ionosphere and thermosphere, which are the terrestrial recipients of the sun's electromagnetic emissions and particle fluxes, the latter having been greatly modified in transit and in interactions with the geomagnetic field, and the upper atmosphere. Solar-terrestrial science focuses on the links and interfaces of a dynamic chain extending from the core of the sun to the surface of the earth. Through the difficult challenges they present to science to understand the earth's environment in space and through their effects on communications, power networks, defense operations, and possibly weather, the variations of these interlinked processes affect life on earth. Especially in informationally networked and space-faring societies, the daily as well as longer term cyclical variations of the interlinked solar-terrestrial spheres have significant national consequences. Long-term solar observations have been conducted by several agencies, and federally funded as part of a national policy, over many decades. Long-term observations that bridge changes in measurement technology of decades and that compare satellite measurements and ground-based measurements in competition for funds, and research needs against operational national service needs, pose difficult funding problems and give rise to uneasy compromises in practice.

In the fall of 1985, the Committee on Solar-Terrestrial Research (CSTR) created a panel to study the requirements for long-term monitoring and archiving of solar-terrestrial data. The panel comprised specialists in all four areas that constitute solar-terrestrial science: the sun, interplanetary medium, magnetosphere-thermosphere-ionosphere, and upper atmosphere. It interviewed many individuals from the solar-terrestrial monitoring and data archiving communities, along with administrators and directors from appropriate government agencies. It circulated nearly 500 questionnaires to obtain information and opinions from the broader community to learn which observational data should be considered essential over the long term to support the operational and research needs of solar-terrestrial science.

During a period of decreasing budgets, the CSTR is concerned, on the one hand, over threatened or actual termination or reduction of a number of solar-terrestrial observations that have been

conducted over many decades and form the basis for operational national services used by many federal agencies and private industries, and, on the other hand, with the necessity for acquiring data essential for new research, some of which will require continued observations over the long term.

Noting the absence of a comprehensive evaluation of observational needs and a scientific rationale against which the scientific importance and net cost of any one data stream for both research and operational services could be evaluated in comparison with the whole body of needs, the CSTR gave a general charge to the panel:

1. Identify measurement needs for research on solar-terrestrial phenomena requiring long-term observations.

2. Prepare a report (after an 18-month study period) to (a) identify areas of research requiring long-term data records, (b) identify measurements needed, and (c) specify quantities, their precision, accuracy and dynamic range, frequency, and duration.

Chapter 2 of this report summarizes the panel's principal findings, and the panel's recommendations follow in Chapter 3. A separate section listing the critical observational needs by area is presented together with the scientific rationale for each area. The recommendations are defended in Chapters 4, 5, and 6 in terms of this explicit scientific rationale and the multifold uses of current and long-term solar-terrestrial observations for continued operational solar-terrestrial forecasts and services.

Finally, in Chapter 7 the panel addresses the question of setting priorities among the critical set of observations during periods of low or declining scientific budgets. Here the most important criterion is the recognition that the field must allocate funding to support new research at the same time that it is acquiring the high-priority data sets over the long term. New research may begin with the measurement of a new quantity, or with retrospective analyses on a cyclically varying interacting series of processes that have been acquired over a term of decades. Since budgets will always be limited in the ever competitive fields of science, the choices in solar-terrestrial physics must be carefully delineated and, once made, continually reviewed for changing relevance and priorities.

2
Principal Findings

The Panel on Long-Term Solar-Terrestrial Observations has reviewed the needs for solar-terrestrial observations over the long term, elucidated the scientific rationale in each area of solar-terrestrial research, examined the uses of the data, and compiled a comprehensive list of critical observational data streams.

The panel recognized early in its deliberations that the data acquisition needs for long-term research would not be satisfied by limited periods of special campaigns or experiments. The scientific rationale calls for the investigation of cyclical behavior, which varies from over a few days, for flare behavior, to the 27-day period of solar rotation, to 11- and 22-year and even longer cycles and into historical and paleoclimatological periods recorded in exotic records such as tree rings and ice cores. New insights based on limited observations must be verified over the range of these cycles.

Also assuming overriding importance is the finding that the current long-term observations, many by single observatories or even individual scientists, have been incorporated into many operational applications, forecasts, and services that satisfy important national needs, such as worldwide communications and navigation systems, transmission lines for oil, gas, and electricity, geological prospecting for raw materials, global environmental change, lifetime of earth-orbiting satellites and spacecraft, and even the physical safety of astronauts and commercial airline travelers over polar routes. These

essential applications of solar-terrestrial observations must be considered, and in many instances they will become the drivers for establishing needs for long-term solar-terrestrial observations. The panel determined that all areas of solar-terrestrial research should be evaluated simultaneously, using similar criteria, in order to delineate the observational and data needs of each area.

Finally, the panel recognized that the state of the art of solar-terrestrial science is not advanced enough to specify an "optimal" set of interrelated observations, nor would the national scientific budget allocations support an "optimal" set. Therefore the panel endeavored to set down a procedure for establishing priorities for observations and data streams both to support new research and to maintain long-term observations.

The panel has completed its charge to the best of its ability, but with the recognition that this report is a beginning, a base for a continuing process to refine and sharpen the comprehensive list of observational needs and priorities as the field of solar-terrestrial science advances. The panel has attempted to apply similar criteria to the measurement needs of each area, but at the same time to view them as an interacting whole. In each case, the measurement needs have been justified in terms of an explicit scientific rationale that is as complete as the time and resources of this panel permitted. The scientific rationales and related measurements should be viewed as a formulation subject to improvements and later revisions.

The panel also finds that data acquisition—i.e., making observations year after year as required—is insufficient to ensure the health and vitality of solar-terrestrial research and operational services. Equally important is the need to plan and budget for processing and archiving the data acquired, and for ensuring that these data are preserved in a form readily accessible and available to users over long periods. This is especially important because of the retrospective nature of analyses of variable solar-terrestrial data, collected and preserved for analysis over multiyear cycles. It is noted that daily analyses of most solar-terrestrial data streams are made for operational services to meet short-term research objectives and national applications, forecasts, and services. Thereafter, the data are processed and archived for retrospective research.

The need to ensure the planning and budgetary commitment to data and information services is of such importance that the panel has recommended that the standing committee designated to oversee the setting of priorities for long-term observations also direct

its oversight to the quality, viability, preservation, and accessibility of long-term solar-terrestrial data. A certain percentage of each agency's budget will need to be designated to provide data accessibility for long-term solar-terrestrial research. Arrangements, such as those of NASA, to set aside a period of up to two years for the principal investigators to prepare scientific papers from particular research projects can be made. But the responsibility to contribute complete data in usable form for long-term retrospective research is essential. Its inclusion in a research plan should be required as a prerequisite to funding, and the fulfillment of this responsibility should be subject to oversight by the recommended committee. Just as in many areas of physics, the worldwide cooperative nature of solar-terrestrial science makes this commitment imperative. This same standing committee would be charged with responsibility for reviewing and recommending overall scientific priorities, since both new research and long-term observations will continue to be funded from the same pot.

The justification for the recommended standing committee relies on the need for and the value given to the data by science and society. The panel finds that long-term solar-terrestrial observations are essential for the following reasons:

1. *Interdisciplinary applications.* The sun is the most accessible member of a central class of stars. What we learn about it applies to the whole class. The sun fixes a point on the curve linking all classes, extending our knowledge to stars generally. For example, the sunspot and magnetic cycles best document the behavior of magnetohydrodynamic dynamos. Understanding the solar dynamo and the ways by which the magnetic energy generated thereby is converted into high-energy particle and electromagnetic emissions opens the door to understanding these processes in planetary, stellar, and galactic settings.

2. *Relevance to society.* The impact of solar irradiance at various portions of the electromagnetic spectrum, and of particles and fields transported from the sun, disturbs the fabric of industrial and information societies in many significant ways. The integrity of worldwide communication and navigation systems depends on solar-terrestrial forecasts. Large magnetic storms induce damaging voltage transients on high-voltage lines and corrosive currents on pipe lines, and accelerate orbit decay of low-altitude satellites. Protection from the damaging solar ultraviolet radiation is provided by stratospheric ozone, the concentration of which is also affected by solar proton

events. As advanced societies move increasingly into space, accurate forecasting of space "weather" (i.e., the short-term variability of the space environment), including the probability of extreme events based on continuous monitoring of a number of solar-terrestrial indices, becomes increasingly important.

The panel finds that long-term solar-terrestrial observations are valuable for the following reasons:

1. *To establish a solar-terrestrial climatology.* Since the sunspot cycle, the solar magnetic cycle, and the solar secular variation occur on decadal time scales, long-term solar-terrestrial observations are needed to (a) establish the baseline values for the solar-terrestrial system, (b) characterize statistically changes in the solar "seasons" (the sunspot and magnetic cycles), (c) characterize statistically long-term secular variation, and (d) guide and validate the work to uncover the physical determinants of long-term solar-terrestrial variations.

2. *To support space environment forecasts.* Continuously gathered data are used in preparing forecasts for operations both in space and on earth for research campaigns, communications, commerce, and defense. These data streams support retrospective solar-terrestrial research.

3. *To specify space weather conditions and the state of the solar "seasons" for particular events.* Continuous monitoring permits placing data taken in campaigns and for special purposes in the context of the prevailing space weather and solar cycles.

4. *To provide the data base for statistical syntheses, correlative studies, case studies, and serendipitous discoveries.* Solar-terrestrial research must compensate for the data sparsity inherent to the field by taking a statistical approach to global synoptic studies. Expanded data archives are needed to build statistical montages of solar wind structures and magnetospheric structures for the full range of determining conditions. Further, continuous monitoring provides a constantly expanding inventory of phenomena to carry out increasingly rigorous correlative studies and increasingly fruitful case studies, and to ensure an ever-increasing opportunity for new and important discoveries.

The panel finds that long-term solar-terrestrial observations have suffered from terminations, discontinuities, and delays in compilation and are threatened with more of each. Actual or threatened discontinuations of long-term data streams have occurred in the solar, interplanetary, magnetospheric, ionospheric, and thermospheric

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components of solar-terrestrial research with little consideration of the scientific merit or priorities of such observations. Over the last decade, there has been a substantial decline in the number of installations used for long-term monitoring of solar-terrestrial parameters. Unless steps are taken to prevent it, the decline is apt to continue.

The panel finds that observational programs undertaken or perceived by funding authorities to be undertaken for a specific mission or campaign cannot be justified or supported thereafter as a long-term observational program. A scientific rationale for long-term observations must stand on its own.

Taken together, these findings call for the following actions:

1. Define the critical long-term observations for each link in the solar-terrestrial chain.

2. Promote interagency and international institutionalization of planning, coordination, management, scientific oversight, and joint or shared funding in accordance with a scientific rationale clearly justifying the needs for long-term solar-terrestrial observations for both operational and research goals.

3

Recommendations

In response to the call for action, this report makes one primary recommendation and five implementing recommendations.

PRIMARY RECOMMENDATION

The panel has identified a set of observations to specify the links that couple the sun to the earth (see Chapter 6). Most are already widely used in solar-terrestrial research. A diachronic record of the list of observations would serve the most basic needs of solar-terrestrial research and operational national services. *The panel recommends that these long-term solar-terrestrial observations be taken continuously*, through interagency and international cooperative planning and cooperative programs. To facilitate this recommendation, the panel proposes a method to prioritize the list when budgets will not support the entire list.

Circumstances peculiar to long-term observations unintentionally jeopardize even a minimal record of solar-terrestrial observations. The following recommendations address how to implement the primary recommendation in the face of these circumstances.

Note: See Appendix for a list of definitions used in this report.

IMPLEMENTING RECOMMENDATIONS

1. *The panel recommends that a body be established, composed of independent, knowledgeable scientists, to be responsible for overseeing the overall scientific priorities based on consideration of new research and long-term solar-terrestrial observational needs for both operational and research goals, and for evaluating the quality, viability, continuity, preservation, and accessibility of long-term solar-terrestrial data.* This body could be a subcommittee of the Interagency Coordinating Committee for Solar-Terrestrial Research (ICCSTR), CSTR itself, or some standing subcommittee under CSTR, the Committee on Space Environment Forecasting of the Office of the Federal Coordinator for Meteorological Services and Supporting Research, or some other appropriate committee.

Traditionally regarded as interdisciplinary, long-term solar-terrestrial research has its programs, funding, and data sources spread over several agencies. Many problems in obtaining and maintaining long-term solar-terrestrial data, such as technological advance and institutional change, recur periodically, and their resolution therefore requires a continuing interagency and international coordinated planning effort. The standing committee would respond to evolving scientific knowledge and technology, while guiding the processes keeping scientifically important, long-term data sets available and useful. The tasks of this committee could include: set priorities as required under varying circumstances; recommend arrangements to continue valuable data sets that are in danger of disappearing; evaluate the performance of the archival agencies; determine critical non-redundant parameters, station locations, and measurement strategies for data collection; and oversee the vital processes of data processing, archiving, and accessibility to researchers. (Note that this recommendation is similar in many respects to recommendations 2 and 7 in *Solar-Terrestrial Data, Access, Distribution, and Archiving* (NRC, 1981b) and to recommendation 4 of the NRC Status Report 1985 of the Committee on Geophysical Data, Solar-Terrestrial Physics Section (NRC, 1986a).) Agency plans to terminate existing solar-terrestrial observations should be provided for review by this committee to meet the priorities of solar-terrestrial science under the given budget limitations.

2. To ensure uniformity of diachronic data sets, *we recommend that sufficient overlap between old and new instruments and measurement methods occur to provide adequate cross-calibration. We recommend further that if a new reduction technique is implemented,*

it be designed to minimize the change in the algorithms that generate output parameters from input data. Such steps should be coordinated by individual agencies and scientists with the new oversight committee on a timely basis. The same criteria as applied in setting priorities for long-term observations will be applied in determining whether uniformity can be ensured, or the data set terminated.

3.   *We recommend increased review and evaluation of efforts to acquire, catalog, disseminate, and analyze archived, historical, and proxy data.* Many of our most important insights into the long-term behavior of solar-terrestrial linkages have come from studies of archived, historical, and proxy data. This is because, unlike astronomers, solar-terrestrial scientists have only one system to observe, and unlike laboratory physicists they cannot carry out controlled experiments. Therefore, to extend the continued measurement of the solar-terrestrial system's behavior, solar-terrestrial scientists must evaluate critically archival data sets, historical anecdotal accounts, and solar activity tracers in tree rings, ice cores, and lunar samples. The new committee is charged with the responsibility to evaluate and set guidelines to deal with the problems of nonstandard long-term solar-terrestrial data. Specific examples of current interest include analysis of carbon-14 anomalies in tree rings, cataloguing historical auroras and sunspots from western and oriental sources, and microfilming pre-IGY U.S. magnetograms (archiving them at the National Geophysical Data Center (NGDC)).

4.   *We recommend that agencies and organizations explore ways to continue the high-priority long-term observations through a program of unmanned satellite and space station observing systems, particularly add-on instrumentation attached to scheduled spacecraft and free-flyer missions.*

5.   *We recommend that the new committee recommend, and national and international agencies designate and fund, national agencies, such as the NOAA-operated World Data Center and National Geophysical Data Center, to collect, archive, and prepare accessible data sets to support research in solar-terrestrial science over the long term.*

6.   Since the long-term data requirements identified by this panel pertain in most cases to global parameters of the solar-terrestrial system, and since both ground-based and satellite observations are essential to achievement of the desired result, *we recommend that the acquisition and archiving of specified long-term data sets be coordinated and conducted as the U.S. commitment to the various international organizations (the World Meteorological Organization and its World Data Centers and the International Committee of Scientific*

Unions) that plan and conduct global solar-terrestrial data collection and research. These organizations should be encouraged to review and support the critical set of solar-terrestrial observations through coordinated international cooperative programs, with added observations as required by each nation, and to support the role of the World Data Center for long-term solar-terrestrial observations.

4
The Value of Long-Term Observations

This chapter reviews in some detail the reasons why long-term solar-terrestrial observations are important. One point peculiar to solar-terrestrial science should be noted at the outset. The field expanded enormously at the onset of the space age. Consequently, the number of solar-terrestrial parameters monitored increased dramatically around 1960. Solar wind speed and magnetic field are prime examples. Barely two 11-year solar activity cycles and one 22-year solar magnetic cycle have elapsed since satellite monitoring of solar-terrestrial data began. Monitoring of many key parameters began even later, for example, accurate observations of the total solar irradiance from space. Thus while accumulating data on solar wind streams and shocks and short-term solar-terrestrial events are beginning to provide part of a systematic solar-terrestrial climatology, the solar cycle dependences of many solar-terrestrial linkages and their intercycle variability are as yet unknown.

A succinct summary of the value of long-term solar-terrestrial observations may be stated as follows. Each of these points is expanded in the remainder of this section. Long-term solar-terrestrial observations permit the following:

1. Characterizing periodic (cyclical) processes of the solar-terrestrial linkages over all time scales.

2.   Documenting secular changes in solar-terrestrial phenomena.

3.   Characterizing significant short-lived events important to solar-terrestrial coupling, such as solar flares, solar proton events, coronal transients, interplanetary shock waves, and magnetic storms.

4.   Promoting understanding of magnetospheric structure based on spacecraft probes of limited duration.

5.   Characterizing statistically solar-terrestrial linkages.

6.   Developing techniques for solar event warnings and space environment forecasts.

7.   Evaluating campaign or mission data in the context of long-term changes.

8.   Studying correlations of solar-terrestrial linkages.

9.   Developing data bases for case studies.

10.   Facilitating serendipitous discoveries.

11.   Capturing and recording rare events, e.g., comet passages.

1.   *Long-term observations are needed to characterize and understand the behavior of periodic phenomena in the processes of the sun to quantify their interactions with the interplanetary media and the magnetosphere and atmosphere of the earth.* The chain of linkages starts at the sun. The first link, solar activity, exhibits a quasi-11-year cycle. There is also a 22-year solar magnetic cycle and a 27-day cycle of corotating solar wind structures. Coronal hole observations and solar wind monitoring illustrate the point. Even before the space age, magnetic storms recurring after one solar rotation implied long-lived streams of solar particles. Having no visible solar portals, they were said to emanate from M (magnetic) regions. From spacecraft, particle and field instruments detected the solar streams and x-ray detectors observed the coronal holes from which they issued. Now the main solar-terrestrial links producing recurring storms can be monitored directly, and their solar cycle behavior understood in terms of changing coronal morphology.

The solar cycle dependences of some key solar-terrestrial links have not been established. Figure 1 compares the variations in the interplanetary magnetic field strength and the Zurich-observed sunspot number R_z over two solar cycles, numbers 20 and 21. Is this the pattern of a 22-year wave, or is there no regular pattern?

The total solar irradiance ("solar constant") is another example of a key parameter that should be measured continuously over one or more solar cycles. Figure 2 shows a plot of the total solar irradiance measured by the Active Cavity Radiometer Irradiance Monitor
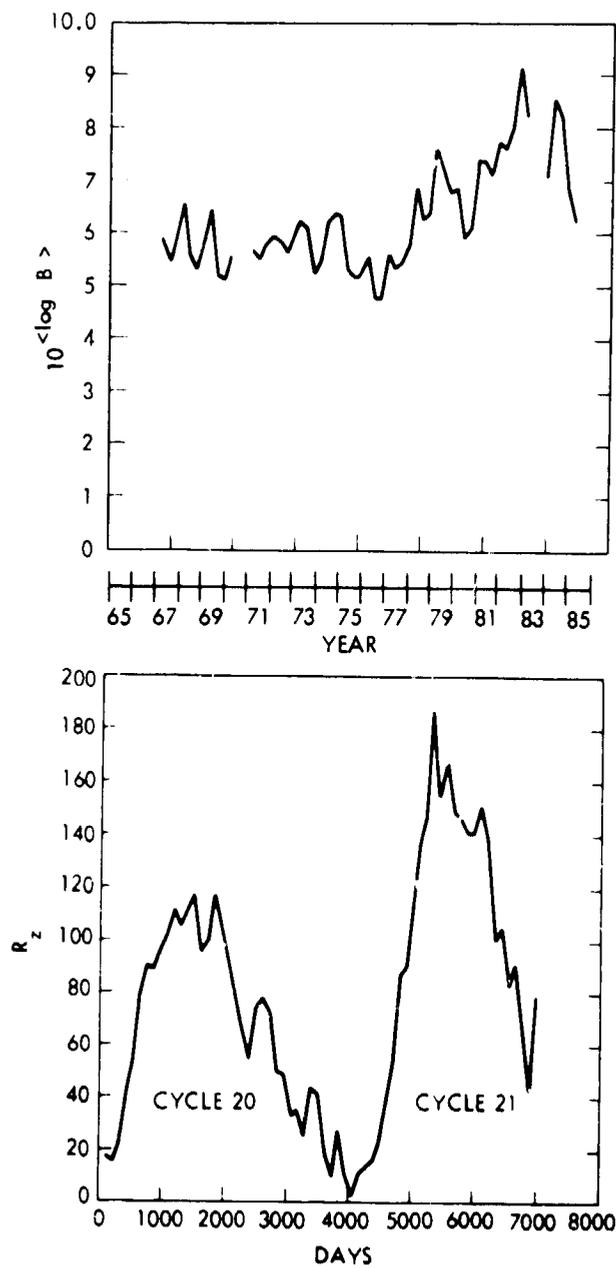
FIGURE 1 Variations in interplanetary magnetic field strength B and the Zurich sunspot number R_z. (Reprinted, by permission, from Slavin et al., 1986. Copyright ©1986 by the American Geophysical Union.)

(ACRIM) on the Solar Maximum Mission spacecraft. The downtrend seen between 1980 and late 1985 is mainly due to a real solar irradiance decrease, as demonstrated by bottoming out of the curve in 1986, and by the close correspondence in year-to-year trends recently pointed out from comparison with a similar set of measurements from the Nimbus-7 satellite. These results indicate that the sun is about 0.1 percent dimmer at activity minimum than at maximum.

The measured long-term decrease in total solar irradiance is remarkable, since it is in the opposite direction expected from studies of sunspot blocking. Further study of these variations, which appear to be caused mainly by evolution in area of bright photospheric magnetic faculae, is of fundamental interest. The time scale and probably also the amplitude of the irradiance modulation would have been significantly larger during extended periods of depressed activity such as the Maunder and Spörer minima in the seventeenth and fifteenth centuries, and might have played a role in determining the climatic cooling recorded at those times. An important advance in the analysis of the relationship between solar variability and atmospheric response has occurred with the work of Labitske (1987) and Labitzke and Van Loon (1988). They showed that by sorting atmospheric data according to the phase of the quasi-biennial oscillation of equatorial stratospheric winds (the QBO) clear correlations with the 11-year solar cycle emerged. For 30-mbar temperatures above the North Pole they found a 20°C increase from solar minimum to solar maximum for the west phase of the QBO.

There are two magnetospheric examples of long-term periodic phenomena of considerable interest. During the last decade, plasma detectors have been developed and flown that measure directly the low-energy ($\leq$20 keV) ion mass composition and charge state in the magnetosphere. As the measurement history of this newly discovered solar-terrestrial variable grows, it begins to reveal a marked, apparent solar cycle variation. Figure 3a shows strong apparent solar cycle variations in O^+ density at 6.6 R_E. Singly charged oxygen in the magnetosphere originates in the atmosphere, not the solar wind. Measurements of O^+ are therefore of major diagnostic value. A confirmed solar cycle variation in O^+ density would expose a solar cycle dependence of global magnetosphere-ionosphere coupling. Unfortunately, the relationship between ion composition and smoothed sunspot number has only been determined for part of one solar cycle. Moreover, this relationship has only been systematically examined in the middle magnetosphere region. The observed large changes in
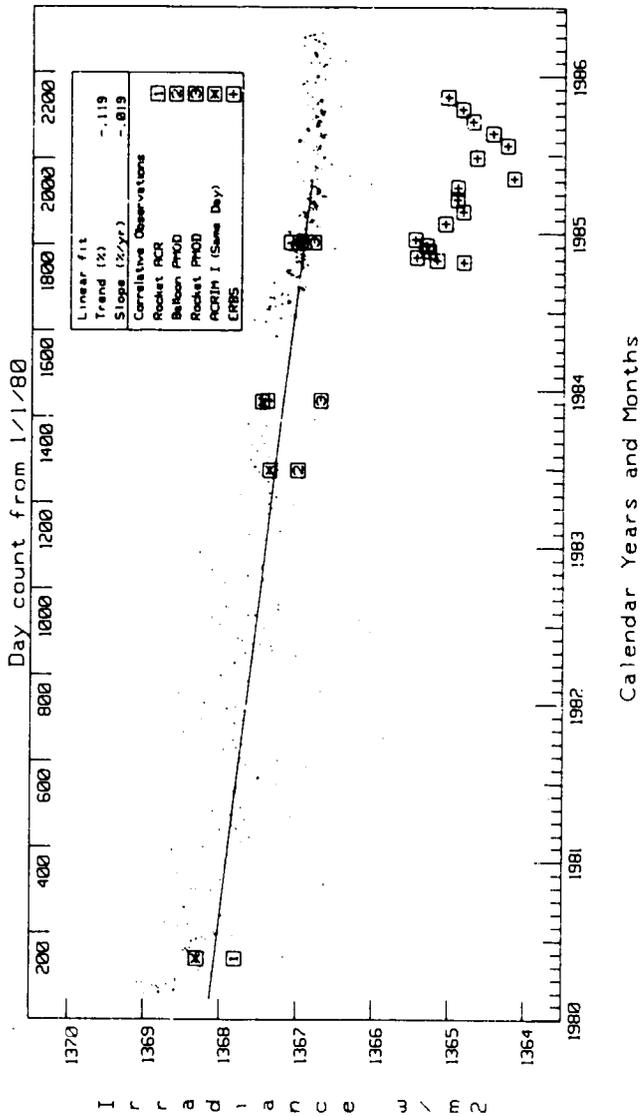
FIGURE 2 Time series of SMM/ACRIM I daily mean results for the period from 1980 to mid-1986. Standard errors of the daily means increased from 0.0001 to 0.0005 percent from 1981 through 1983 because of a much lower rate of data acquisition during this period of "wobbly" spin stabilisation of the SMM spacecraft. The linear least-squares fit shown has a slope of −0.019 percent per year. (Extended to mid-1986 and reprinted, by permission, from Willson et al., 1986. Copyright ©1986 by the American Association for the Advancement of Science.)

ion composition may be both causes and effects of solar cycle solar-terrestrial changes. The variations of O^+ density are plausibly due to ionospheric chemistry and scale height effects related to the variation of solar extreme ultraviolet (EUV) over the 11-year solar cycle. In this sense the variations are an effect. But also, these variations can be the cause of a wide variety of mass- and charge-dependent plasma effects in the outer magnetosphere. It is important to maintain a record of plasma composition over several solar cycles in order to understand the implications of possible plasma compositional changes.

Observations at geosynchronous orbit since 1979 have revealed major variations in the flux of relativistic electrons. As shown in Figure 3b, they were nearly absent during the last solar maximum, they were abundant during the subsequent decline, and now their intensity has diminished again as solar minimum has passed. There initially appears to be a strong solar cycle dependence. When at their maximum intensities in the magnetosphere, these electrons precipitate and deposit significant amounts of energy into the atmosphere at 40- to 60-km altitude. This upper atmospheric energy source could be an important link in the solar-terrestrial system, communicating the sun's long-term variability to the middle atmosphere through modulating lower D-region ionization and upper stratospheric ozone chemistry. It is important to learn more about the long-term behavior of this particle population.

2. *Long-term observations document secular changes in solar-terrestrial phenomena.* Successive solar activity cycles differ, and there appears to be a supercycle covering typically eight to ten 11-year cycles.

Sunspot cycles 19, 20, and 21, which peaked in 1958, 1968, and 1980, respectively, illustrate intercycle differences. The first exhibited the highest recorded sunspot number (Figure 4), and the second exhibited the largest declining-phase peak in geomagnetic activity (Figure 5). Figure 1 also shows a striking difference in the behavior of the solar wind magnetic field at 1 AU during cycles 20 and 21. This is important because the magnetic field couples the solar wind to the magnetosphere. Moreover, the yearly averaged solar wind magnetic field correlated well with geomagnetic activity in cycle 21, but in cycle 20, solar wind speed dominated the correlation. The second peak in geomagnetic activity was strong in both cycles. However, in the first, recurring solar wind streams caused most of the activity, and in the second, non-recurring events had the greater effect.
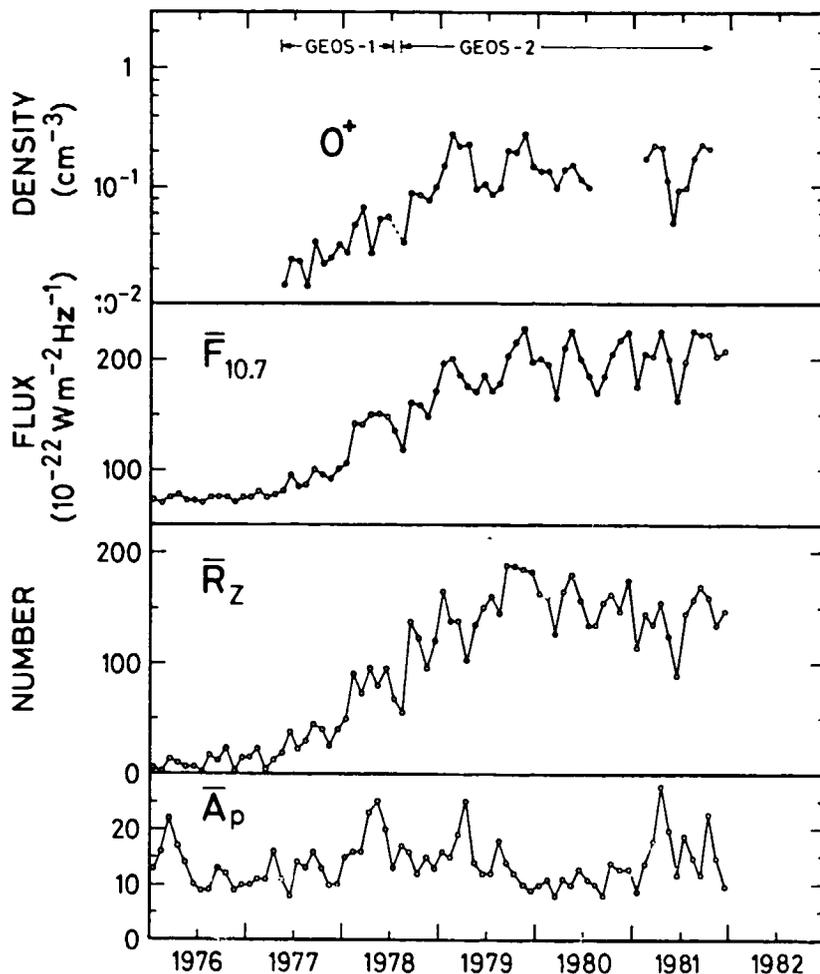
FIGURE 3a   The apparent correlation of O^+ density present at 6.6 R_E in the energy range 0.9 to 15.9 keV with the proxy indices of solar activity $\bar{F}_{10.7}$ and $\bar{R}_z$. Note the lack of correlation with the geomagnetic index Ap. (Reprinted, by permission, from Young et al., 1982. Copyright ©1982 by the American Geophysical Union.)

As seen in Figure 4, over sufficiently long-time scales, the supercycle modulation dominates intercycle differences. Geomagnetic activity follows solar activity. Figure 6 shows the present supercycle's rise, peak, and incipient decline in one geomagnetic activity index. The steady rise in the minima of the 11-year wave implies that the

HIGH ENERGY ELECTRONS

DAYS FROM 1 JAN. 1979
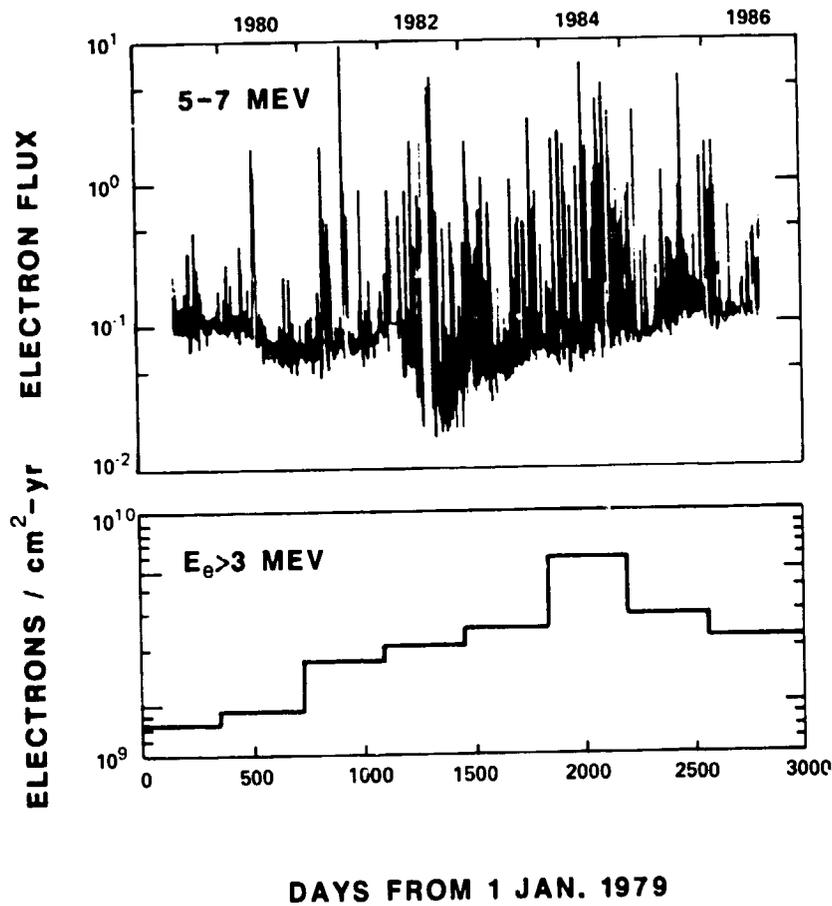
FIGURE 3b (top) Daily averages of 5- to 7-MeV electrons measured on board spacecraft 1979-053 and spacecraft 1982-019 at geostationary orbit from mid-1979 to late 1986. The background flux level in the top panel is determined by galactic cosmic ray fluxes reaching the geostationary orbit altitudes, while the spiky increases are due to magnetospheric electrons. (bottom) The background-corrected yearly averaged fluxes of electrons with energy 3 MeV measured by the geostationary spacecraft are shown. A long-term flux variation on a solar cycle scale is indicated. (Adapted and reprinted, by permission, from Baker et al., 1987. Copyright ©1987 by the American Geophysical Union.)
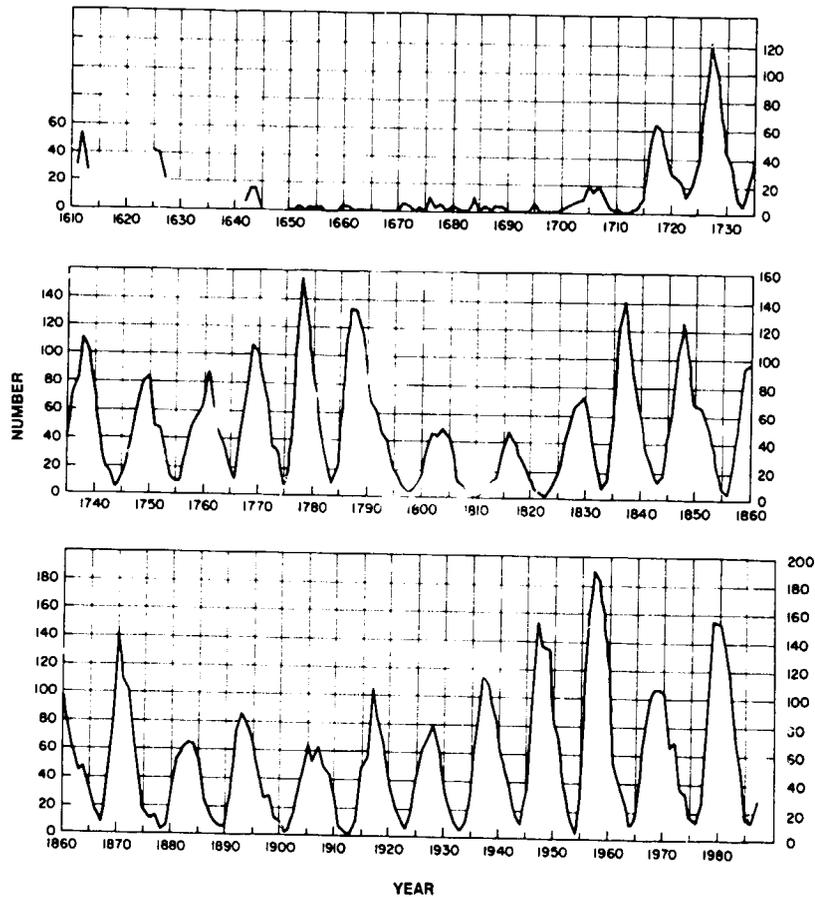
FIGURE 4 Annual mean sunspot numbers, 1610-1987. Cycle 19 (peak year 1958) exhibited the highest sunspot number on record (from Eddy, 1978, as revised through 1987 by author, courtesy of J.A. Eddy).

two-solar-cycle record of in situ solar wind data contains few if any instances of conditions that typified the minimum of 1901.

In the past the supercycle wave has evidently meandered outside of the range of its current cycle. Figure 7 shows a 1000-year overview of past solar activity. It combines direct, archived, historical, and proxy data. It reveals occasional intervals when solar activity virtually ceased for several cycles. Since the Maunder Minimum, only the lull at the beginning of the nineteenth century approaches deep
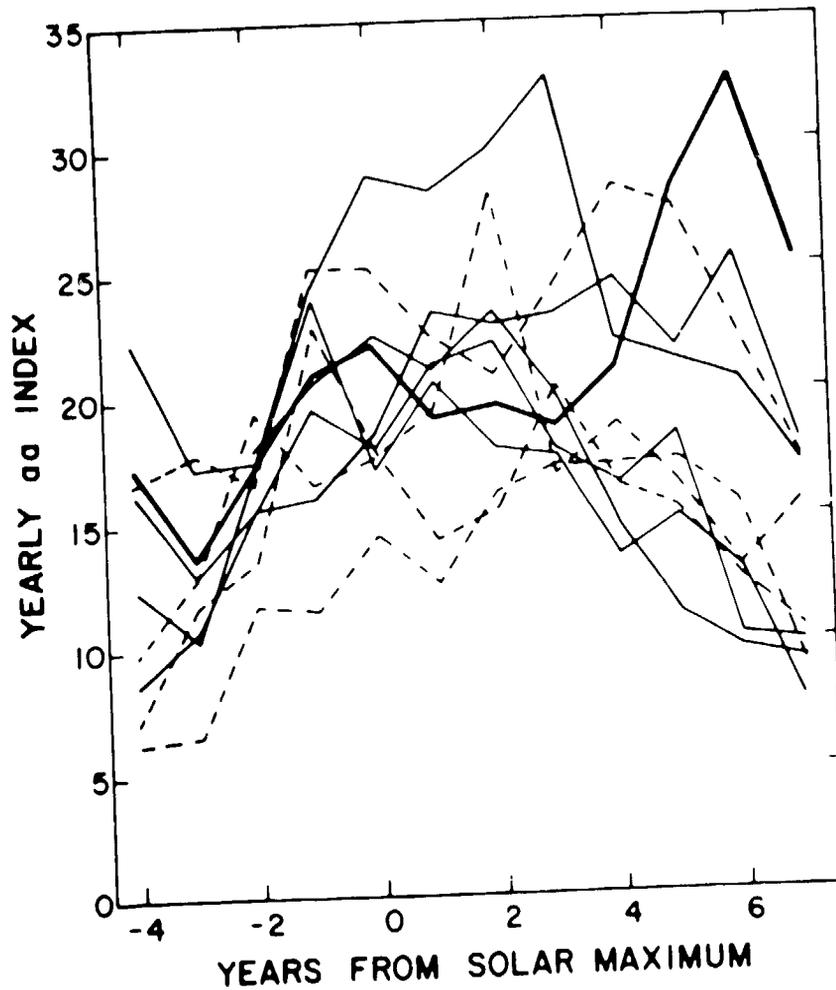
FIGURE 5 Geomagnetic variability during cycles 11 through 20. Odd-numbered cycles are drawn with light solid lines, even cycles with dashed lines, and cycle 20 with a heavy solid line. Cycle 20 exhibited the larges. .ak in geomagnetic variability during the declining phase of the solar maximum during this period. (Reprinted, by permission, from Gosling et al., 1977. Copyright ©1977 by the American Geophysical Union.)

quiescence. Based on the reconstructed solar record for the last millennium, the sun is overdue for a period of prolonged inactivity.

The examples demonstrate that long-term solar-terrestrial data records are incomplete. We could add examples showing the lack
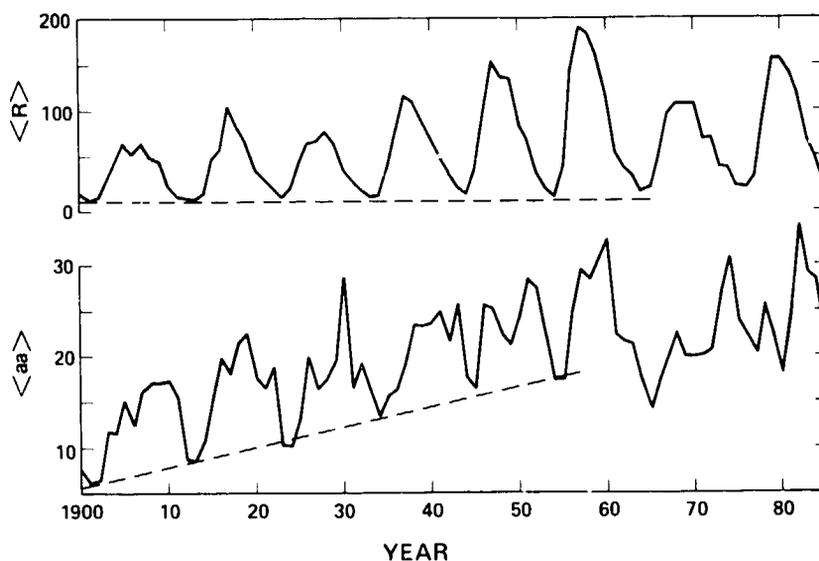
FIGURE 6 Variations in yearly means of sunspot number R and the aa index of geomagnetic activity. (Adapted and reprinted, by permission, from Feynman and Crooker, 1978. Copyright ©1978 by Macmillan Magazines Ltd.)

of data on the solar cycle and secular dependences of solar oscillations and magnetism, coronal structure and transients, solar wind structure and transients, modes of solar wind-magnetosphere coupling and the magnetospheric response, magnetosphere-ionosphere coupling, upper atmospheric response, solar cosmic ray ion production, and galactic cosmic ray modulation. The sunspot record reveals the intercycle and supercycle variations in the primary solar-activity link. Geomagnetic and auroral records extend far enough to expose the same long-term components in the terrestrial link. Intercycle variability characterizes the shorter records that exist of ground-based proxy data on solar ultraviolet (UV), and solar and galactic cosmic rays.

Some crucial links can be monitored only from spacecraft: solar x rays, EUV, UV radiation, the solar wind, and its magnetic field. Others discovered by spacecraft—coronal holes, field-aligned currents, and thermospheric temperature—admit to ground monitoring. The behavior of these links has been documented for two solar cycles or less. Some links are unknown or uncertain—the processes that produce the solar magnetic field, solar flares, coronal transients, the solar wind, the coupling between the solar wind and
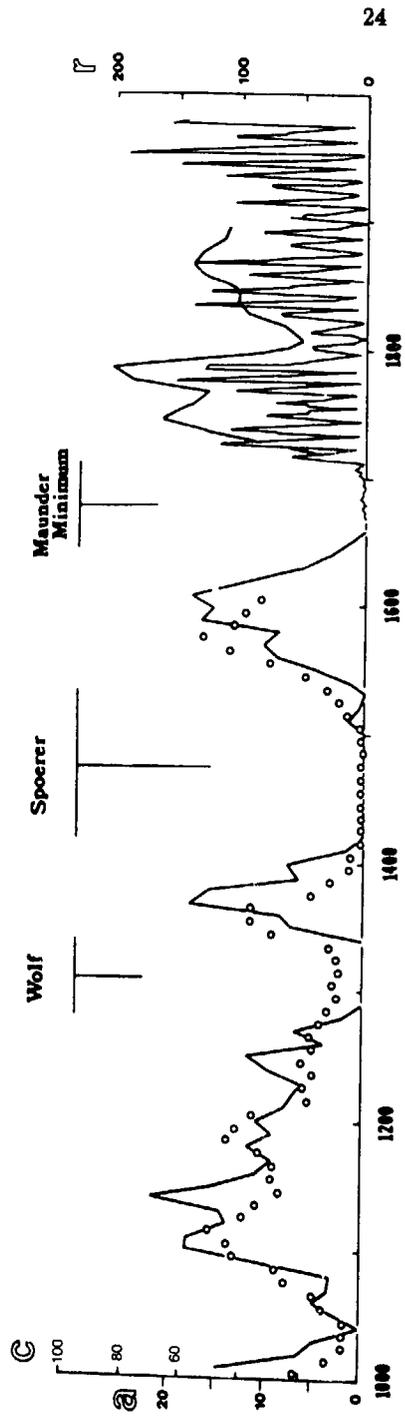
FIGURE 7   Three indices of solar activity compared as a function of time for the period since AD 1000. The observed annual mean magnetic number (r, scale at right) is shown by the thin line beginning in AD 1650, with pronounced 11-year cycles visible after about AD 1700. The heavier curve (c, scale at left) extending from AD 1000 to AD 1900 is a proxy sunspot number index derived from measurements of tree ring ^{14}C. Open circles (a, scale at left) are an index of the occurrence of northern hemisphere aurorae, another measure of solar activity, in sitings per decade. The three independent indices confirm the existence of significant long-period changes in the level of solar activity, including three prolonged periods of depressed behavior labeled as the Wolf, Spoerer and Maunder Minimum (from National Research Council, 1986b).

the magnetosphere, and the couplings between the magnetosphere, ionosphere, and thermosphere. New observations are needed to document all crucial solar-terrestrial links. For these the records have yet to begin.

3. *Continuous observations accumulate data on short-lived, basically unpredictable events important to solar-terrestrial coupling, such as solar flares, solar proton events, coronal transients, interplanetary shock waves, and magnetic storms.* Multiple samplings are needed to establish the basic physics of these phenomena. The need is double because they not only vary inherently but may also exhibit intercycle and supercycle differences. As data accumulate and understanding matures, data requirements evolve. To be most effective, new generation observations also should be continued on a long-term basis.

Solar proton events illustrate this class of phenomena. Interest in solar proton events has increased in recent years because they give an opportunity to analyze the perturbed middle atmosphere in a kind of "natural laboratory" experiment. By simultaneously observing particle events and related changes in ozone abundance, such experiments can test complex interactions affecting ozone. Ozone depletions in nine solar proton events have been identified. The mechanisms rely on HO_x and NO_x catalytic reactions that destroy ozone. Both short-term (1 day or less) and long-term (1 week or more) ozone responses have been observed. HO_x radicals are mostly responsible for ozone changes above the stratopause, while NO_x production effects become important below that level. Some ozone depletions observed between 50 and 60 km are significantly larger than predicted values, and there is a further need for research in this area.

Solar proton events show solar cycle variations and considerable intercycle differences. During solar cycle 20 there were enough events to have an influence on the chemical balance of the middle atmosphere. There is a need to determine the long-term influence of solar proton events on the overall chemical structure of the middle atmosphere.

Studies of interplanetary shock waves, current sheets, hydromagnetic waves, and turbulence rely predominantly on the slow, steady accumulation of data on many events to determine the statistical properties of their behavior and to determine statistically their global structure and their relation to solar structure. Figure 8 illustrates this class of studies by an important result obtained through a superposed-epoch analysis. The figure shows the structure of the

heliospheric current sheet, that wavy quasi-equatorial skirt that circles the sun and separates particles and fields that come from the northern and southern hemispheres. To reveal the density and compositional structure across this sheet even crudely as in the figure required eight years of continuous solar wind data, which yielded only 23 crossings sufficiently isolated to be judged usable. The heliospheric current sheet is a major structural solar wind feature. The example makes the point that very long, continuous data records are needed to build up a picture of the structure and behavior of solar wind features.

Magnetic storm data exemplify deficiencies in characterizing important, short-lived solar-terrestrial events. Magnetic storms, the longest known and largest of the terrestrial links, vary in kind and strength. There are suddenly commencing storms, gradually commencing storms, and storms with positive and negative interplanetary magnetic field north-south components perpendicular to the ecliptic—the main coupling parameter. To characterize a storm adequately requires solar wind, magnetopause, tail, ring current, auroral zone, and ground-magnetometer data. Dependent on favorable spacecraft alignments coinciding with a storm, full storm captures are infrequent. Accumulating samples for comparative studies is correspondingly slow.

4. *Accumulating and archiving in situ magnetospheric data permit constructing global pictures of magnetospheric structure at specific activity levels by fitting together pieces of the picture acquired at different times and places when such levels occurred.* The only way known at present to establish the three-dimensional structure of the magnetosphere is to take in situ observations with spacecraft that probe its interior features and map its boundaries. But the dynamic magnetosphere moves and changes while being measured. To construct a snapshot of global magnetospheric structure, researchers must piece together a global montage out of small views seen by spacecraft at random times and places when the magnetosphere happens to be in a specified condition. Thus magnetospheric science must adopt a statistical approach to global synoptic studies. Continuous in situ magnetospheric monitoring and archiving are indispensable for the purpose.

Important studies of this type have been completed. The bow shock and dayside (but not nightside) magnetopause have been mapped for several (but not a complete set of) solar wind conditions. The average position and shape of the tail's neutral sheet and
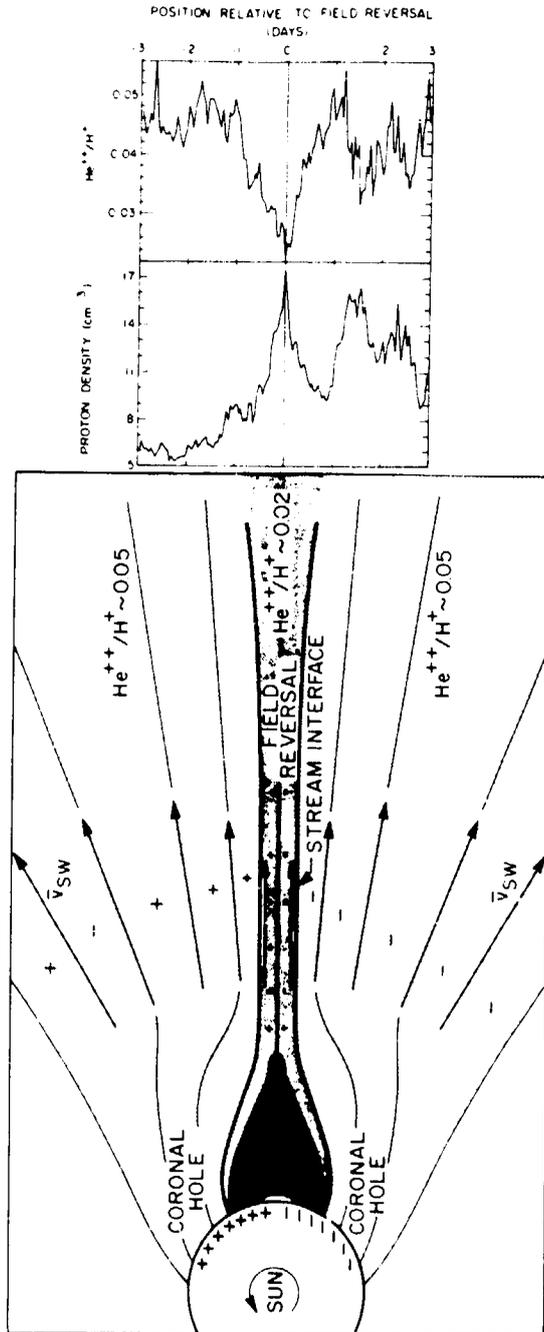
FIGURE 8 The meridional structure of the heliospheric current sheet determined from a superposed-epoch analysis of 23 events garnered from 8 years of solar wind data. (Reprinted, by permission, from Gosling et al., 1981. Copyright ©1981 by the American Geophysical Union.)

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their seasonal variations have been charted, but deviations from the averages imposed by the external magnetic field, substorms, and fluting remain unresolved. The variations of average field strength down the tail and across the tail from top to bottom and from side to side have been determined. However, the tail data have not yet been assembled into an explicit, statistically determined, three-dimensional, global empirical model of the magnetic structure of the tail. Data from low-altitude, polar-orbiting satellites have been binned to reveal the patterns of high-latitude electric fields and field-aligned currents that reflect global magnetospheric dyramics. However, maps based on other important binning strategies have yet to be compiled. Finally, similar incoherent-radar observations of the high-latitude ionosphere have been montaged into full local-time auroral zone maps of conductivity and electric fields for different levels of magnetospheric activity.

The Tsyganenko-Usmanov empirically determined, mathematically explicit model of the magnetosphere's magnetic field illustrates the statistical approach to global synoptic studies. The model combines a set of analytic representations of magnetospheric current systems with a power series expansion that was tailored to fit the spatial variation of the field that remained when the analytically determined contributions were removed. The data that were fit to the model were the accumulated magnetic field measurements from the IMP and HEOS spacecraft. The parameters that specify the analytical expressions and the coefficients of the expansion were determined by minimizing residuals between the calculated field and the statistically averaged field. The parameters were determined for different activity levels as measured by the geomagnetic index Kp. The resulting model gives a spatially continuous representation of the magnetic field for different activity levels that is valid from about 6 R_E to 20 R_E—the range covered by the spacecraft. This type of model is especially valuable because it permits calculating the three components of the electric current everywhere in the domain of validity. This capability opens the door to empirical studies of magnetospheric dynamics and empirical determinations of the spatial distribution of field-aligned currents in the magnetosphere, complementary to the maps obtained with data from low-altitude, polar-orbiting satellites.

Figure 9 shows contours of field-aligned currents obtained with the Tsyganenko-Usmanov model and projected onto the equatorial
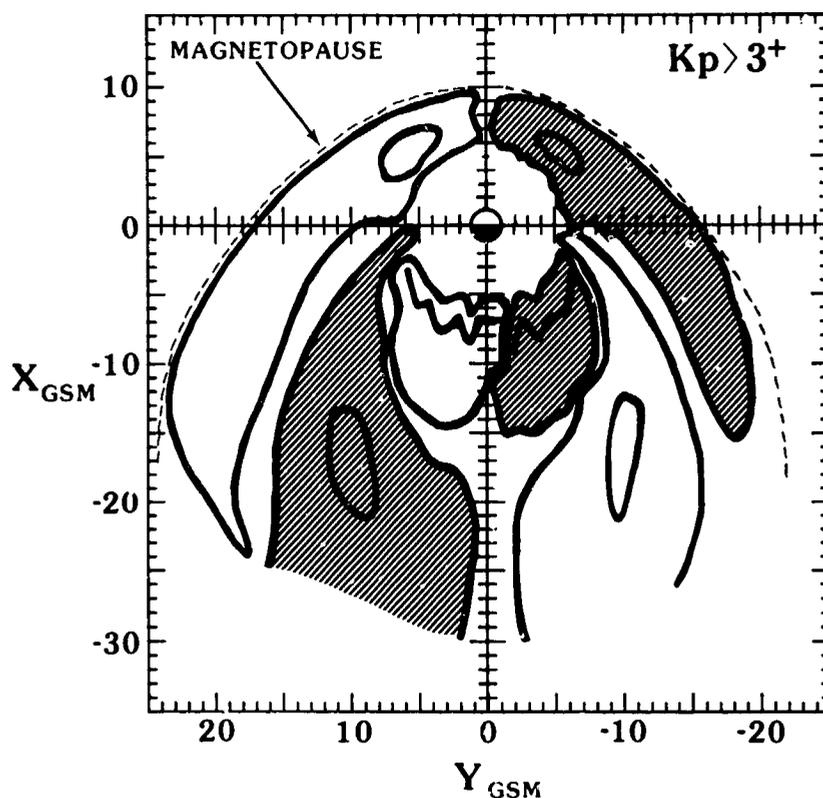
FIGURE 9 An equatorial cross-section of the magnetosphere showing the equatorial crossing points of the field lines carrying field-aligned currents as determined from the Tsyganenko-Usmanov model. Hatched areas indicate field lines carrying current toward the northern polar ionosphere, while unhatched areas indicate the opposite polarity. (Reprinted, by permission, from Elphic et al., 1987. Copyright ©1987 by the Johns Hopkins University Press.)

plane. A moderately active, equinox situation is depicted. The result locates two magnetospheric source regions for a current system that at low altitudes had been assumed to be continuous and reveals a prominent new system not previously identified from low-altitude observations. The result demonstrates the value of constructing montages (in this case an analytical montage) out of data accumulated from continuous magnetospheric monitoring. More such data are needed. The model should be extended to be valid inside of 6 R_E and outside of 20 R_E and to give more reliable results for rare index values where there are few data.

5. *The statistical characterization of solar-terrestrial linkages establishes (1) the baselines against which to detect changes from known or suspected causes and (2) the risk factors for space activities.* Long, continuous records of data on solar-terrestrial linkages permit determining their averages and their distributions about the averages, the frequency and range of extreme values, and the normal correlations between them. These statistics can be used to assign probabilities that some known or suspected agent has affected the solar-terrestrial environment, for example, the close passage of a comet or anthropogenic sources of waves or contaminants. Large solar flares, major magnetic storms, and intense substorms can be dangerous for humans in space, damaging to spacecraft, and disruptive to communications. The August 1972 series of storms dramatized the point by spraying the moon with lethal doses of solar cosmic rays near the time of the Apollo missions. Large storms are rare, but potentially very hazardous. Hurricanes are an appropriate meteorological analog. As any meteorologist can recite the names of the famous killer hurricanes, the monster magnetic storms are well-recalled by solar-terrestrial researchers: September 1859, February 1872, February 1957, and August 1972 to identify the most famous. But there were many more nearly as large. Extreme value statistics can be applied to solar-terrestrial data on extreme events to enable risk assessments for space activities. The analyses become more reliable as the length of the record and the number of events grow. The need for reliable risk estimates will become increasingly important as people become more dependent on space communications and monitoring satellites and as observatories, laboratories, stations, and colonies move into space.

6. *Continuously monitoring the solar-terrestrial environment enables techniques to be developed for solar event warnings and space environment forecasts.* As noted above and as is relevant again here, spacecraft operations and lifetimes can be affected seriously by changes in spacecraft environment. Earth-based communications, power, and transportation networks, as well as spacecraft, experience failures caused by voltages induced by magnetic storms. Active experiments and scientific campaigns are initiated when continuous-data monitors indicate favorable conditions. Flare monitors give one- to two-hour proton event warnings and one- to two-day magnetic storm warnings. At its Lagrangian station, ISEE-3 gave one-hour shock-arrival warnings and two-hour substorm warnings. Ground magnetic observatories together with polar-crossing

and geosynchronous spacecraft continuously monitor the state of the magnetosphere. Their data could provide reasonably comprehensive magnetospheric, ionospheric, and thermospheric forecasts.

7. *Continuous observations are needed to support studies, campaigns, and missions that require data to specify the solar-terrestrial environment and to place their results in the context of long-term changes.* Solar flares, solar proton events, solar 10-cm radio flux, the solar wind magnetic field (y and z components), and geomagnetic indices (aa, AE, Ap, Dst, Kp) typify routine observations and indices used to characterize the state of the solar-terrestrial environment. They are used to bin data (for example, quiet, moderate, and active according to the level of Kp) and to compare new and old results pertaining to the same environmental conditions.

To give an example, the value of the data taken by the Ulysses spacecraft will be greatly enhanced if long-term solar and solar wind observations are extended continuously through the Ulysses mission. The solar and solar wind states should be specified to relate Ulysses data to a particular solar-cycle phase and solar-activity condition.

8. *Continuous observations provide data bases for correlative studies of solar-terrestrial linkages.* The subject of solar-terrestrial relations is founded on observed correlations between indices of solar, geomagnetic, and auroral activity. Correlative studies between different long-term data sets continue to be important as new data sets grow and their relations to older sets are tested. The indefinite correlation between the solar wind magnetic field and the sunspot number shown in Figure 1 is a case in point.

More commonly, continuous long-term data are correlated against short-term measurements, for example to see how they depend on magnetic activity or the orientation of the solar wind magnetic field. The dependence of the asymmetry in polar cap convection on solar sector polarity and the related Svalgaard-Mansurov effect are instances.

The earth's thermosphere and ionosphere are known to respond dramatically to solar and auroral activity. Middle atmosphere ozone changes have also been attributed to variable solar UV fluxes and to intense solar proton bombardment. It is not known how deep into the atmosphere the variable effects of solar activity penetrate. Nonetheless, the venerable subject of sun-weather relations comprises a body of possibly important, though still inconclusive, correlations between

weather and climate parameters and long-term solar-terrestrial parameters. Eleven-year, twenty-two year, and supercycle signals have been reported. As yet no convincing causal mechanism has been found. Nonetheless, the possibility of a sun-weather connection gives reason to monitor the solar constant, solar UV, and solar particle fluxes continuously.

9. *Continuous observations provide data bases for case studies of solar-terrestrial linkages.* The experience of tropospheric meteorology tells us that synoptic analysis of data from a sufficiently dense network of stations is needed to reveal the structure and behavior of the atmosphere's storms and calms. It is difficult to apply this lesson to solar-terrestrial weather processes in the absence of a dense network of fixed, continuously monitoring stations. The field relies instead on accidental, favorable alignments of spacecraft coinciding with an event of the type to be studied. Individual researchers initiated the systematic application of this procedure in the early 1970s, but it was formalized in the late 1970s under the International Magnetospheric Study (IMS) Program as Coordinated Data Analysis Workshops (CDAWs). By 1987, the eighth CDAW was in progress.

The concept escalated recently under the Polar Region and Outer Magnetosphere International Study (PROMIS), which obtained as complete a set as possible of coordinated global magnetospheric measurements. PROMIS incorporated VIKING and DE-1 auroral imaging sequences, along with ISEE-1 and -2 plasma sheet measurements, plus IMP-8 upstream data and a variety of geostationary orbit and ground-based information. The program produced approximately three months of highly coordinated information that will provide a rich research data set. The program illustrates the benefits of coordinated data collection and especially demonstrates the importance of continuous data records in order to understand the global solar-wind-magnetosphere-ionosphere system.

There is also a growing trend in thermospheric, ionospheric, and mesospheric research to organize measurement periods into global campaigns, such as GISMOS (global incoherent scatter measurements of substorms), GTMS (global thermospheric mapping study), and CEDAR (Coupling, Energetics and Dynamics of Atmospheric Regions). These campaigns gather continuous data for preselected time periods, and they are designed to study certain geophysical phenomena. Solar-terrestrial indices are important for these campaign studies because they are used to characterize energy and momentum inputs into the thermosphere and ionosphere. In certain cases,

predictions of enhanced solar or geomagnetic activity are used to coordinate intensive data-taking periods and alert other stations to opportunities for additional measurements. The indices are also used to organize and characterize data in the analysis phase. These campaigns are often designed to observe during various phases of the solar cycle to determine differences in global structure and differences in the response to auroral activity.

10. *Although by their nature discoveries are unpredictable and are therefore difficult to use in priority assessment, it is well recognized that routinely monitored data are capital that yield discoveries as interest.* The sunspot cycle and its geomagnetic echo are century-old examples. The Maunder Minimum, recurrent magnetic storms, and the Svalgaard-Mansurov effect were discovered, not predicted. The discoveries of the Io decametric emission and the Antarctic ozone hole emerged from studies of accumulated routine synoptic data. As the inventory of continuously monitored data increases, so does the likelihood of serendipitous discoveries.

An excellent example of a serendipitous discovery was the discovery of the 11-year variation of the cosmic ray intensity in antiphase with sunspot activity by S. Forbush. In this case, data were taken with carefully calibrated detectors over a number of years. The initial goal was to study short-term variations, but because good data taken over a long time were available, the previously undiscovered longer-term variations were found.

The variation of the cosmic ray intensity as measured by neutron monitors is illustrated in Figure 10. The large 11-year variation is caused by the "modulation" of the cosmic rays by the solar wind. The serendipitous discovery is the difference between the cosmic ray maximum centered on the 1965 sunspot minimum and the one centered on 1975. The finding illustrates another point of relevance. A recent theory of the modulation of cosmic rays by the solar wind suggests that the difference is due to the different sign of the solar magnetic field at successive sunspot minima. If this were correct, the general nature of the variation between 1965 and 1975 should repeat itself with a 22-year period. To verify this prediction, and clarify our understanding of a variety of solar-terrestrial effects of cosmic rays, we need to continue the neutron monitor measurements for at least 22 more years.

A final significant observed effect to emerge unpredicted from analyzing long data records also illustrates the importance of geomagnetic indices. In a recent careful study of the correlation of the

27 day averages
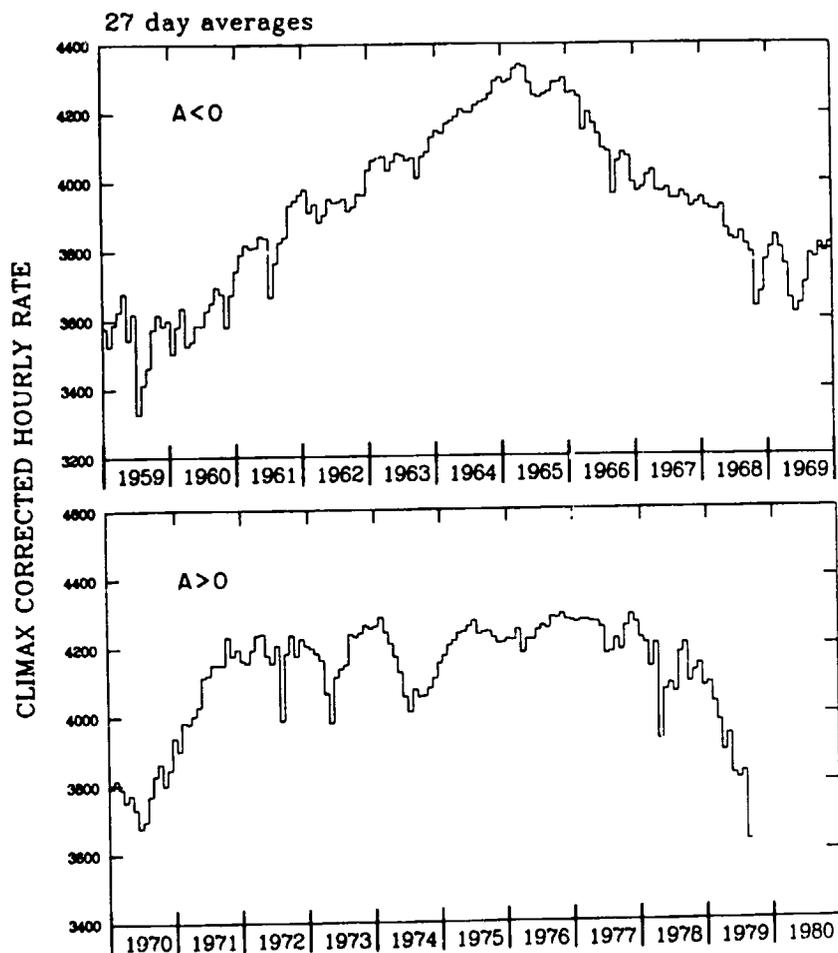
FIGURE 10   Counting rate of the Climax Neutron Monitor (courtesy of J.A. Simpson).

geomagnetic aa index with the counting rate of the Mt. Washington neutron monitor, Shea and Smart (1985) found that the correlation was quite significant and negative (-0.86) during the years around the 1965 solar minimum but that it was much smaller and insignificant (<0.16) during the 1975 solar minimum. This effect was initially very puzzling to observers but may be shown to be a natural consequence of current theory, if one takes the aa index to be a measure

of disturbances in the solar wind at the earth but not at high heliographic latitudes. This extremely important analysis, which sheds light on the whole question of cyclic variations in the solar-terrestrial system, would be impossible without the availability of long-term geomagnetic indices.

11. *Continuous monitoring and archiving captures and stores observations of rare events for future analyses.* In 1910, the earth passed through the tail of Halley's Comet. Several times per century auroras are seen at extraordinarily low latitudes (for example, Mexico City in 1859 and Bombay in 1872). As the field of solar-terrestrial research matures, its ability to analyze and understand unique and rare events like these grows. Reciprocally, data on such events are useful to measure the field's maturity by testing its theories in extreme limits and under unusual conditions. In this capacity, monitoring and archiving of solar-terrestrial data play a role similar to sky surveys and plate archives in astronomy.

5
Problem Areas in Long-Term
Solar-Terrestrial Observations

The Committee on Solar-Terrestrial Research solicited the panel's study after identifying a number of problem areas in maintaining high-quality, viable, and maximally useful long-term solar-terrestrial observations. Instances of endangered, threatened, and actually discontinued long-term solar-terrestrial observations are easily cited. In many of these instances, the observational program began as, or was perceived as stemming from, a *campaign- or mission-oriented view of the purpose of the observations. That these observations contributed to the goals of long-term solar-terrestrial research and to fulfilling the scientific rationale for continuous monitoring, as described in the previous section, normally entered minimally if at all into considerations about long-term funding.* It is clear in retrospect that the solar-terrestrial community cannot expect continuation of observational programs perceived by funding authorities as a specific mission or campaign. The need for long-term solar-terrestrial observations must be established in a periodically revised scientific rationale from the beginning, together with criteria for eventual termination or replacement of given observations. Other issues addressed include the general decrease in solar-terrestrial monitoring, the problem of optimizing long-term solar-terrestrial observations for solar-terrestrial climatology, the successor problem in maintaining diachronic observations in small-unit operations, and the need for intercalibration when one variable supplants another.

TYPICAL PROBLEM CASES IN EACH
SOLAR-TERRESTRIAL LINK

The Sun

The high-quality satellite measurements of the total solar irradiance begun in 1978 may suffer discontinuity if the next launch of the ACRIM instrument must wait for the UARS mission in the early 1990s, which is the present plan. By precluding intercalibration of old and new ACRIM monitors, the discontinuity would be serious. A strongly recommended solution is to incorporate total solar irradiance measurements as a standard part of GOES missions, which have programmatically planned continuity. Also, continued operation of the ERB on the Nimbus-7 well into solar cycle 22 is urged.

Monitoring of solar ultraviolet flux variations will require a major effort in development of stable spectrometers, detectors, and standards to attain the precision limits of a few percent over the solar cycle that are required, for example, to study ozone trends. Figure 11 illustrates the gaps in the UV data and the large calibration uncertainties. In the important region for ozone studies, between 150 and 300 nm, few useful data were available before about 1976. Calibration errors in the data since then are still several tens of percent and thus are often inadequate to discern atmospherically important solar cycle trends.

Delays in reflight of the SUSIM shuttle experiment until 1992 mean that the major instrument in the area of UV solar irradiance studies will be inoperative for at least five years. In the EUV below Lyman alpha, Figure 11 shows that, since the termination of AE-E measurements about seven years ago and the retirement of E. Hinteregger at the U.S. Air Force Geophysical Laboratory, essentially no useful data of any kind are available, and at present no regular measurements in the EUV are planned.

Solar monitoring at the Sacramento Peak, Mt. Wilson, Stanford, and Big Bear observatories has been threatened with discontinuities. Each of these observatories provides unique data on solar chromospheric and coronal activity, and together with KPNO they constitute the backbone of U.S. solar monitoring capability at present. The Ft. Davis radio spectrograph, which provided the only high-resolution swept-frequency information on meter wave solar disturbance in the United States, has been shut down. Support for continuance of the Ottawa 10.7-cm solar flux measurements is
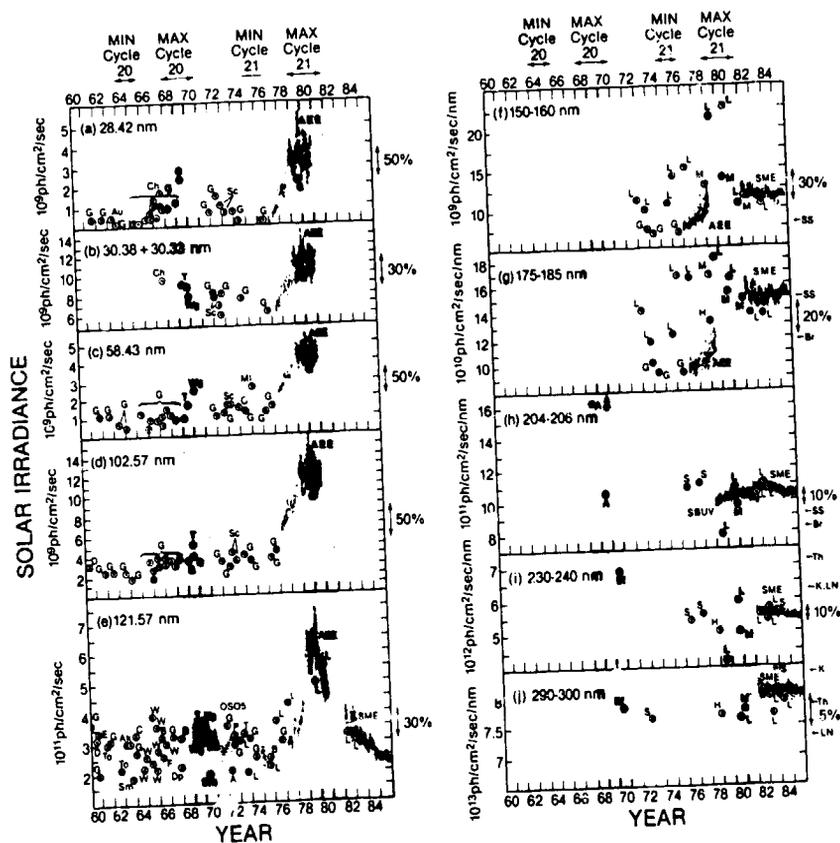
FIGURE 11   Measurements from satellites and rockets of ultraviolet irradiances during solar cycles 20 and 21. (Reprinted, by permission, from Lean, 1987. Copyright ©1987 by the American Geophysical Union.)

precarious. Both the Culgoora, Australia, solar radio interferometer measurements and the U.S. Clark Lake meter-decameter solar imaging have been discontinued.

Interplanetary Medium

Interplanetary field and plasma monitoring decreased substantially in 1982 when NASA made a post-launch decision to move ISEE-3 from its Lagrangian station, where it had provided continuous data on the solar plasma streaming toward the earth. IMP-8,

providing less than 50 percent coverage, was also threatened with de-activation, which would have left no near-earth solar wind monitor. The situation will not improve until the launch of the WIND space-craft, which is one of the two recently approved U.S. complements to the International Solar-Terrestrial Program (ISTP). The impor-tance of the WIND spacecraft to solar-terrestrial science is difficult to overstress.

Magnetosphere

Long-term magnetospheric studies suffer from the lack of contin-uous solar wind data. They also suffer from the lack of coordinated multispacecraft missions to build a data bank of synoptic analyses on which to base global magnetospheric studies. The situation will improve when the ISTP program is launched.

Auroral Electrojet

Auroral electrojet (AE), a ground-based geomagnetic index, is the prime monitor of substorm activity. NOAA first assumed the responsibility to compile it and provided a record that begins in 1966 but stops in 1975. The World Data Center C2 in Japan subsequently took over responsibility for providing the index, but it is not a high-priority task. The records for 1976-1977 are missing; the delay between measurement and publication of AE is three years; and there is no long-term commitment to continue providing it.

Thermosphere-Ionosphere

Operating since October 1981, the solar Mesosphere Explorer spacecraft ceased making measurements late in 1986 while still per-forming flawlessly. Although it continues to monitor solar UV ir-radiance, the opportunity to monitor the solar cycle dependence of mesosphere parameters was lost.

Airglow observations from Fritz Peak Observatory in Colorado began in the 1950s, and thermospheric temperature and winds have been measured since 1968. This station, providing important infor-mation on the long-term chemical and dynamic structure of the meso-sphere and thermosphere, was closed by NOAA in 1985. Ground-based ionosonde and polarimeter data, plus indirect satellite imagery data describing the state of the ionosphere, are being taken by the Air Force for real-time operational purposes and subsequently archived

at the Air Force Environmental Technical Applications Center and the National Geophysical Data Center, but not processed for long-trend studies.

GENERAL DECLINE

Comparing the number of entries in two directories listing the stations that monitor the sun-earth environment (MONSEE Directories 1 and 2), Shea and Allen (1985) found a general, global decrease between 1976 and 1984 (Figure 12). Their report shows the percentages of change over this interval in the number of stations gathering solar/interplanetary, ionospheric, flare-associated, geomagnetic, auroral, cosmic ray, and airglow data. All declined except the number of flare-associated monitors, which rose because of newly opened U.S. Coast Guard OMEGA stations. The number of geomagnetic observatories dropped by 14 percent worldwide and by 33 percent for U.S.-sponsored stations. Since the Shea and Allen finding, the Air Force has discontinued its mid-latitude chain of geomagnetic observatories, and the U.S. Geological Survey is contemplating closing its geomagnetic observatories at Barrow, Alaska, and Newport, Washington. Some solar-terrestrial environment monitoring stations have closed to make room for fewer, more efficient replacements. Others fell to pruning efforts that left the field healthy. But many closings have terminated useful measurement records and damaged the ability of science and the space enterprise to benefit from long-term solar-terrestrial data.

THE DATA OPTIMIZATION PROBLEM

There is a discontinuity at the interface between the data gathering and archiving enterprises and the scientific user community. The result is a less than optimal data resource establishment to serve the needs of solar-terrestrial research. The present World Data Centers were established as part of the IGY. Their holdings and basic management policy are based on the IGY precedent, namely, to collect and store all data that bear on the great unknown—the upper atmosphere and outer space. The meteorological roots of NOAA, which manages the U.S. operations in climatic, oceanographic, and geophysical data, fortunately foster a policy of treating solar-terrestrial phenomena like weather, which should be continuously monitored and archived. NOAA's National Geophysical Data

WORLD-WIDE STR MONITORING STATIONS

	NUMBER OF SENSORS	
	1976	1984
SOLAR/ INTERPLANETARY	219	182
IONOSPHERIC	368	293
FLARE- ASSOCIATED	159	206
GEOMAGNETIC	295	254
AURORA	66	52
COSMIC RAYS	107	105
AIRGLOW	28	21

PERCENT CHANGE 1976 THROUGH 1984
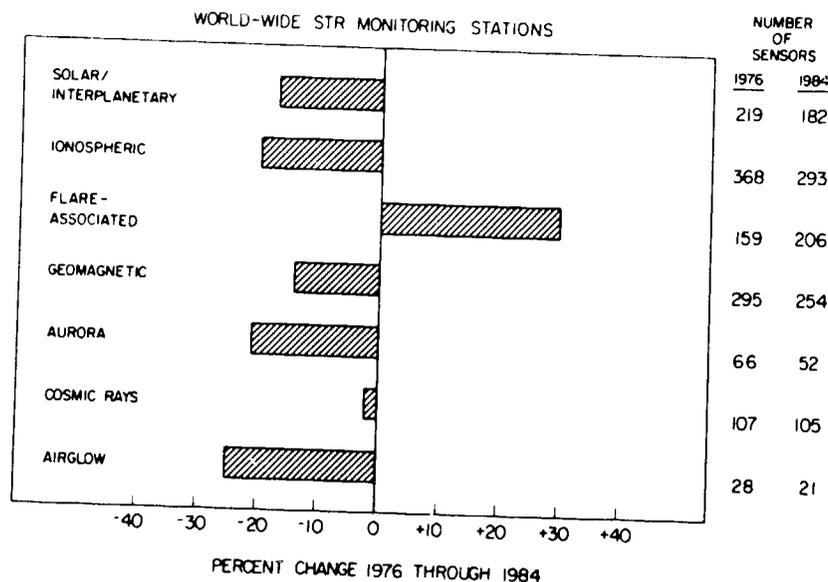
FIGURE 12   Relative change in the number of operational worldwide solar-terrestrial monitoring sensors between 1976 and 1984. The actual number of sensors is given on the right side of the figure. (Reprinted, by permission, from Shea and Allen, 1985.)

Center (NGDC) holds an extraordinarily valuable solar-terrestrial data archive, and provides indispensable data products and services to the solar-terrestrial community. Unfortunately, there is a tendency to regard the current solar-terrestrial observations and monitoring stations to be fixed like atmospheric weather elements and monitoring stations. But solar-terrestrial science is comparatively young. *The optimum combination of solar-terrestrial observations and data gathering strategy is yet to be determined.* The need to determine that strategy is greatest for long-term solar-terrestrial research, because of its critical reliance on archived data. *One of the highest priority tasks of the recommended standing advisory body on long-term observations should be to review the existing data resource structures and recommend how to optimize them for retrospective research.*

THE DATA RECORD SUCCESSOR PROBLEM

At a time such as the present, when funds for research are scarce at universities and government laboratories and in private industry, it is difficult for individual institutions to set aside funds to support

measurement programs that are likely to bear fruit only on time scales of decades and longer. We believe that some benefit might be derived from public, broad recognition of this need, and one of the recommendations of this report is a move in that direction. Organization of a special session at the American Geophysical Union general meeting for this purpose would seem also to be a beneficial move. It is to be hoped that such steps will increase the likelihood that policy-makers in university, government, and private industry research sectors will respond to this need by taking steps to groom key successors and provide resources that will ensure continuing, ongoing synoptic observation programs.

At the same time, it is unrealistic to expect that such a policy will in itself be sufficient to solve the problem of continuing all the key data bases that the solar-terrestrial research community relies upon. Qualified personnel and facilities are available in the United States to carry out such programs if the financial commitments, which must ultimately come out of research budgets at NSF, NASA, NOAA, and DOD, can be made. The broadly felt need for such data bases must then be reflected in policy at these agencies primarily responsible for research support in solar-terrestrial research. Several avenues are available that do not seem to have been explored so far. For example, a precedent exists within the agencies such as the NSF for relatively long-term support commitments to "multiuser facilities." More systematic review and support procedures for such facilities are currently under consideration at the NSF. It appears that such facilities (e.g., National Geophysical Data Center at NOAA or NCAR) could include centers charged with acquisition and archiving of solar-terrestrial synoptic data for multiuser dissemination. Although such commitments would certainly not be open-ended, they might be made for time scales of four to five years that could prove useful in attracting quality personnel to this task at universities or government laboratories or in industry.

A second possibility is for the agencies to support such synoptic data bases through contracts to private industry in those cases in which universities or government laboratories are unable or unwilling to carry out work perceived by the solar-terrestrial research community to be of broad importance. One mechanism that could prove useful in this respect is the Small Business Innovation Research (SBIR) program in which a fraction of all NSF, NOAA, NASA, and DOD research funds is set aside for work by small businesses performed on solicited research tasks defined to be of importance to

these agencies. Continuous support for approximately three years at a time can be obtained in this manner. The advantage of this approach is that support for these tasks, since it is set aside by law, does not compete directly for university research grants within these agencies.

A third option, which by no means obviates the previous two, is an agreement by all funding agencies that a certain fixed percentage of each research and operational budget provide for data processing, archiving, and retrieval-oriented data bases under national and international guidelines. This function would be subject to peer review by the recommended standing committee.

COMPATIBILITY PROBLEM

When existing long-term indices are upgraded or replaced, great care must be taken to ensure that the new index can be clearly related to the old over what is frequently a wide and heterogeneous range of applications. For instance, the Ottawa 10.7-cm ($F_{10.7}$) flux has been used worldwide since about 1947 as a general indicator of magnetic activity, together with the Zurich sunspot number, R_z. Empirical relations between $F_{10.7}$ and satellite drag, for instance, form the main basis of NASA predictions of spacecraft lifetime.

Any planned discontinuation of the $F_{10.7}$ measurements requires at least a several-year cross-calibration against the Air Force RSTN network of microwave receivers, to ensure that such correlations can be maintained. It would be desirable over the long term to replace the proxy microwave data with continuous space measurements of the varying UV, x-ray, and particle fluxes that are actually responsible for changes in the upper atmosphere. However, it must be recognized that no working physical model of the upper atmosphere yet exists that could be used to calculate reliably the satellite drag from observed variations in these primary fluxes. Until such a practical model is developed, a continuing need will exist for the proxy microwave data.

6
Solar-Terrestrial Parameters and
Associated Measurements

The panel presents in this chapter the current understanding of the major solar-terrestrial parameters and associated state-of-the-art measurement capabilities needed over the long term for a vital program of solar-terrestrial research and to support national operational solar-terrestrial forecasts and services. This chapter fulfills the specific charge to the panel insofar as the resources and time available permitted.

Since a major part of solar-terrestrial research is devoted to the necessity of characterizing statistically and in terms of physical processes the variable nature of the sun and the huge plasma bubble formed by the solar wind streaming outward and encompassing the earth, long-term observations demand significant portions of the total solar-terrestrial budget. Yet sufficient funding for new research, for preserving and making easily accessible the data records resulting from continuing observations, and for technology development to improve the state-of-the-art of measurement, analysis, and operational services, must be provided from any given budget.

The panel concludes that competition for funds for long-term solar-terrestrial observational programs is an integral part of this field of science; albeit that the multidecade time periods involved, exceeding the useful life of many measurement systems, render this problem more intractable than most. Therefore the panel has chosen

to go beyond the presentation of a static list of high-priority measurements needed today and to recommend that a standing committee of independent scientists be established to review continually the priorities for long-term solar-terrestrial observations, provide quality standards and peer review for the data records created, and provide scientific guidelines for interagency, international cooperative observing programs through which long-term solar-terrestrial observations are acquired. (Implementing Recommendation No. 1)

Within this framework, the following list of the major solar-terrestrial parameters and associated state-of-the-art measurement systems is presented as a near-optimal statement of currently known needs, with recognition that the entire program cannot be funded and maintained over long time periods. Indeed, long-term solar-terrestrial observations will always require an interagency and international cooperative approach. Even then, a selection must be made within the constraints of all the budgets involved, and with a recognition of the independence of each budgetary agency to pursue its primary mission.

The panel discusses in Chapter 7 of this report the role of the recommended standing committee for the ever-present priority decisions that must be made each year to continue, change, or terminate observational programs. The overriding thesis of this approach is that the costs and rationale for long-term solar-terrestrial observations must be planned and presented up front by the solar-terrestrial community, and accepted as an agency responsibility by participating agencies. It will take time for this policy to be implemented, but the alternative is yearly pleading that solar-terrestrial science requires special consideration to continue poorly planned and poorly coordinated programs.

Major solar-terrestrial parameters are identified in a sequential list below, numbered from 1 through 16, each of which is subsumed under the appropriate link in the chain of cause and effect from the sun to the earth. This outline, it is hoped, will make clearer the listing of associated state-of-the-art measurements that follow.

In the main body of this chapter, the major solar-terrestrial fields of study, i.e., the sun, interplanetary medium, magnetosphere, and thermosphere-ionosphere, serve as section headings. Under each heading is a discussion of the scientific rationale for the major parameters and critical observations desired. This is followed by subordinate paragraphs, one for each numbered parameter, under which the measurement systems desired are identified.

THE SUN: PARAMETERS AND QUANTITIES
TO BE MEASURED

Scientific Rationale

Variations of the total solar radiative output have now been demonstrated at the level of up to a few tenths of a percent over all time scales between minutes and years. There is new evidence for a modulation synchronized with the activity cycle. One key set of measurements that must be obtained from satellites is radiometry of the total solar irradiance. Continuous daily measurements with a precision at least equal to that now achieved are necessary to track the rapid fluctuations and provide data sets from which the slower changes can be studied. Independent measurement sets from separate spacecraft, such as those obtained from the Nimbus-7 and SMM data obtained concurrently since 1980, are absolutely necessary to interpret the solar cycle modulations at the 0.1 percent level. The amplitude of such trends and their phase relative to the solar cycle are critical inputs to models of climate on time scales on the order of a hundred years.

The radiometers flown typically have time constants of seconds. These data should not be degraded in time resolution, since they are also very useful in studies of possible secular variability of the five-minute oscillation models. This information can yield results of great value on slow structural changes in the solar interior that would help us to understand solar luminosity variations over climatologically interesting time scales.

A second key set of satellite measurements involves spectrophotometry of the solar EUV and UV fluxes. Short-term fluctuations at $\lambda \leq 0.25$ μm are now reliably measured and have been shown to correlate with the rotation and evolution of active regions to within errors in the areas and photometric contrast of plages and network. Measurements of the precision and time resolution obtained from the ongoing SBUV experiment on Nimbus-7 need to be continued. Monitoring of the EUV below Lyman alpha, which has been discontinued since the last AE measurements in 1981, needs to be reinstated. Both of these data bases are important from the standpoint of understanding processes with relatively short time scales in the ionosphere, thermosphere, mesosphere, and stratosphere. A program of less frequent but more precise measurements to determine the slow solar cycle variations in the EUV and UV needs to be carried out by shuttle instruments such as SUSIM, since it is difficult

to preserve the calibration stability of UV photometers on satellites for years. The long-term precision of these measurements must be in the 5 percent range, and at least one good set of measurements per year is required.

Full-disc integrated fluxes of hard and soft x rays provide one of the basic diagnostic tools for the recognition of flares, their importance classification, and statistical studies of the physics involved in, e.g., particle and plasma acceleration. A continuous record of these fluxes with 1-s resolution is required, as is currently obtained from the GOES satellite.

Full-disc imaging of the sun in soft x rays provides the most effective method of tracking the evolution and rotation of coronal holes and studying the magnetic structures in the low corona. One good picture per day with spatial resolution of a few arc seconds is sufficient. It would be desirable to obtain and archive pictures more often (one per minute) during flares and filament eruptions, although the priority is not as high.

Studies of the evolution of the outer corona on time scales of hours, and the ejection of coronal transients, require monitoring of the K-corona in white light from a satellite-borne coronograph, such as the coronographs that have been flown on OSO-7, Skylab, P78-1, and SMM. In the absence of coronal transients, only one picture per day need be archived.

A daily white light image of the photosphere is required to provide the data to determine the sunspot number for studies of solar rotation from spots as tracers, for studies of active region influence on the total solar irradiance, and for statistical studies of active region properties. The spatial resolution required is 1 to 2 arc sec, obtainable with a small photoheliograph. The image scale must be sufficient to identify the smallest spots, to calculate the spot number, and to measure the umbral and penumbral areas of the larger spots for the irradiance studies. Rotation studies require care to avoid distortion in the optical system.

Full-disc H-alpha images provide the location of filaments and prominences (and the phenomenology of their eruptions) and also the main observations to study the location and morphology of flares. Spatial resolution of 1 to 2 arc sec is adequate and can be achieved on a full-disc image with a small, automatic photoheliograph used with a birefringent filter. Only one image per day needs to be archived unless a flare or other eruption is under way.

Studies of the photospheric velocity field, in particular changes

in the sun's differential rotation, will require daily full-disc Doppler measurements at the spatial resolution used at Mt. Wilson, or at least at the lower resolution used at Wilcox Solar Observatory. These measurements are important for long-term studies of the relationships between solar rotation and the magnetic activity cycle. Solar cycle variability of the plasma Doppler rotation rate and the sunspot rotation rate has been demonstrated over the past several solar cycles. The behavior of such solar cycle rotation variations could provide important clues to the mechanism behind the magnetic solar cycle and help predict its amplitude and phase. Shears in photospheric velocity within active regions have been related to flare occurrence, and a long-term data base is needed to study such a correlation.

A daily magnetogram with a few arc seconds spatial resolution provides the basic information required to study the solar magnetic field's morphology and polarity. From the photospheric data, harmonic analyses are carried out for information on slow trends in the global field, on its mapping into the corona, and on the evolution of active regions. These data are central to studies of the flare mechanism and of the processes leading to liberation of magnetic energy in filament eruptions.

Twenty-four-hour full-disc coverage in swept frequency meter waves and microwaves provides the most direct information on plasma waves in flares and on particle acceleration. Only data taken during flares and eruptions need to be analyzed.

In the absence of reliable daily EUV and UV flux observations over extended periods, the most directly useful information on the variation of these fluxes still comes from continuous coverage at 10.7-cm (or 11 cm) microwaves. Daily average fluxes need to be archived for this purpose. Progressively more use is being made of empirical models to estimate the EUV and UV fluxes based on the location, area, and brightness of CaK plage regions. Such models require CaK filtergrams of spectroheliograms on a daily basis. These should be made with a few arc seconds spatial resolution and sufficient image scale in order to compute area and coordinate measurements. Useful information for this purpose also comes from daily measurements of the full-disc integrated CaK and HeI 10830 line flux measurements, which provide a closer approximation to the variation in the UV continuum and in the EUV HeI and HeII resonance lines than does the 10.7-cm flux.

Until a reliable x-ray imager is placed in orbit, the only good information on the location and evolution of coronal holes will be

provided by spectroheliograms in the HeI 10830 line (on the disc) and from FeXIV 5303 line coronal observations (at the limb).

Long-Term Observations Needed

State-of-the-art measurement needs related to the sun are listed below.

1. *Total Solar Radiative Output*
- Radiometry of the total solar irradiance from satellites and rockets requires daily monitoring and several good measurements per year at a long-term reproducibility equal to or better than the present precision achieved by ACRIM and ERB.

2. *Solar Spectral Irradiance (especially, EUV and UV)*
- Spectro-radiometry of the solar EUV and UV flux from satellites and rockets. One good measurement per year at a long-term reproducibility of 10 percent or better around 250 nm (e.g., SUSIM) and daily monitoring (e.g., Nimbus-7 SBUV).

Substitutions are required until satellite systems are operational to measure solar spectral irradiance. These are the most critical ground-based measurements.

- Daily full-disc 10.7-cm radio flux, or equivalent microwave flux well-calibrated to the $F_{10.7}$ scale (e.g., Ottawa).
- At least one good CaK full-disc image per day at a spatial resolution of a few arc seconds (e.g., Mt. Wilson, BBSO, NSO). Full-disc integrated CaK and HeI flux measurement.
- At least one good white-light full-disc image per day at a spatial resolution of a few arc seconds (e.g., Mt. Wilson, BBSO, NSO). Also reduction to produce daily sunspot number.

3. *Solar Particle Outputs*
- Full-disc integrated x-ray flux monitor in hard and soft x-rays with 1-s time resolution (e.g., GOES).
- At least one full-disc x-ray image per minute. Only one image per day needs to be archived, except during eruptions (e.g., the x-ray imager currently planned by the National Oceanic and Atmospheric Administration and the National Aeronautics and Space Agency, with additional funding by the U.S. Air Force).

Substitutions are necessary to measure solar particle and fields outputs until the satellite systems are operational. These ground-based measurements are as follows:

- One good HeI 10830 image per day at a few arc seconds spatial resolution (e.g., NSO).
- One good FeXIV image per day at a few arc seconds spatial resolution (e.g., NSO).
- At least one K-corona image per hour. Only one per day needs to be archived, except during transient events (e.g., SMM).
- Full-disc H-alpha imaging at a spatial resolution of about 1 arc sec, with a repetition rate of 1 image per 10 s or better. Only one image per day need be archived unless a flare or other eruption is under way (e.g., BBSO, NSO).
- Twenty-four-hour full-disc swept-frequency meter wave coverage with a few seconds time resolution (e.g., Clark Lake).

4. *Behavior of Solar Magnetic Field and Solar Rotation*
- At least one good magnetogram per day at better than 5-arc sec spatial resolution. Desirable also to have one at low spatial resolution (e.g., NSO).
- Daily full-disc Doppler data at a spatial resolution of roughly 10 arc sec or better (e.g., Mt. Wilson).

THE INTERPLANETARY MEDIUM: QUANTITIES TO BE MEASURED

Scientific Rationale

The solar-terrestrial system is in essence a huge bubble of plasma in the interstellar gas, with the sun near its center, and the earth some distance away. This bubble is created by the radial supersonic outflow of plasma (solar wind) from the sun and its interaction with the interstellar medium that encloses it. The solar wind is a supersonic, superalfvenic, strongly ionized flow that transports plasma, magnetic field, angular momentum, and energy to the earth's magnetosphere, and beyond, to the furthest reaches of the solar system, where its momentum is balanced by the inward pressure of the interstellar gas, magnetic field, and cosmic rays. Spacecraft traveling currently well beyond the orbit of the farthest planet still have not detected the boundary of the wind.

Interplanetary parameters have been monitored in situ for two solar activity cycles and one solar magnetic cycle. These measurements document a two-decade actual history of the interplanetary

medium. The coverage of some parameters was minimal. Even in the best cases, the coverage shows frequent, often large gaps. Nonetheless, these measurements solidly inaugurate an important long-term data record. For the monitored cycles, the basic solar cycle variations and intercycle differences of many interplanetary parameters have been determined. Their statistical characteristics and intercorrelations have been studied. The essential structure and the range of variability of solar wind streams, flare-driven blast waves, and coronal mass ejections are becoming known, as are the properties of solar wind discontinuities, waves, and turbulence. The data set is a resource that is still being extensively mined. It has been and continues to be indispensable to coordinated data analysis efforts aimed at constructing global pictures of how solar-terrestrial parameters are linked.

For the following reasons, it is important to continue in situ interplanetary monitoring. Although solar cycles follow long-term trends, one cycle differs markedly from the next; within certain constraints, each unfolds a unique history of the locations, timing, and strengths of the signatures of solar activity. Thus long-term solar-terrestrial research is inherently an historical science. Continuous monitoring is needed to document this history.

Because all interplanetary linkages were not monitored over the two decades of in situ measurements and because the coverage for all parameters was incomplete, the solar cycle variations of important elements of the interplanetary medium have not been established. Further, while the gross characteristics of solar wind streams and transients have been determined, much remains to be learned through accumulating additional observations that present these features in a wider range of sizes, intensities, orientations, and intercept paths to survey their three-dimensional structures. Thus, continued monitoring is needed to establish and verify the solar cycle dependences of the interplanetary solar-terrestrial links and to characterize adequately the norm and the range of the structures that solar wind streams and transients present.

Intercycle differences cannot be distinguished from a 22-year solar magnetic cycle variation until another solar magnetic cycle is sampled. Further, to determine the secular variation of the solar-terrestrial links requires continuous data over many cycles. Continued monitoring is needed to establish the intercycle, the solar magnetic cycle, and the secular variations of the interplanetary solar-terrestrial links.

The solar wind is the primary motive force for virtually all magnetospheric processes. Synoptic studies of magnetospheric dynamics must therefore have available solar wind measurements. Changes in solar wind parameters precede changes in magnetospheric behavior. Hence, magnetospheric space weather forecasts need continuous solar wind measurements. Continuous monitoring is needed to provide continuous solar wind data for ongoing magnetospheric research and space operations.

The interplanetary solar-terrestrial links include the processes at the sun that generate the solar wind, the solar wind itself, and the processes at the interface with the earth's magnetosphere. They carry many variable solar inputs, such as energetic particles and shock waves, from the sun to the earth and form central links in the chain of cause and effect connecting the sun to the earth.

Therefore the long-term observations of the interplanetary medium critical to the study of solar-terrestrial relations consist of measurements of those parameters that carry information about variability of energy and momentum flux from the sun to the earth, and those additional measurements that enable us to understand better the propagation of these variations. Hence, from this point of view, the most important primary physical parameters must be those that characterize the local structure of the solar wind.

Long-Term Observations Needed

State-of-the-art measurements discussed for the interplanetary medium are listed below.

5. *Average Mass Flux, Flow Velocity, Density, Ram Pressure, Pressure, Temperature, and Heat Flux for Dominant Species (Protons, Helium Nuclei, Electrons), and Composition*

- Plasma detectors to measure local values of the mass flux, flow velocity, density, composition, and temperatures at a temporal resolution of at least one measurement per 5 min.
- Measurement of turbulence parameters, on an hourly basis, to determine effects on momentum and energy flux.
- Radio measurements of interplanetary scintillations, spacecraft tracking, radio bursts to provide average velocity and turbulence measurements integrated along the line of sight, and some remote magnetic-field and density data. The first two of these can be carried out inexpensively from the ground. Systematic measurements with daily averages reported would be most useful.

- Geomagnetic indices aa, Kp, AE, and Dst should be maintained as a high priority, providing important proxy determinations of various solar wind parameters from ground-based measurements.

- Neutron monitor and muon detector observations of cosmic ray variations (solar cycle modulation and Forbush decreases) provide ground-based information on changes in solar wind conditions, such as the level of turbulence and the presence of shock waves. Such data now extend continuously over several solar cycles. For these reasons, the major ground-based neutron monitors and muon detectors should be maintained.

6. *Magnetic Field Vector*

- Direct spacecraft measurements of the magnetic field vector at the same time resolution as for the plasma data—every 5 min.

- Radio monitoring to record radio bursts caused by energetic electrons propagating along the interplanetary magnetic field. These data, although sporadic, can provide a remote tracer of the geometry of the field.

- Ground-based magnetometer observations every hour at a high-latitude magnetic observatory. (The Svalgaard-Mansurov effect in earth-based magnetometer records provides a continuous, reliable determination of the polarity of the IMF sector structure. To resolve multiple crossings of the heliospheric current sheet for long-term studies, the polarity should be provided every hour.)

7. *Ene _Jetic-Particle Spectrum, Composition, and Anisotropies*

- Direct spacecraft measurements of the energy spectrum, composition, and anisotropies of energetic particles (cosmic rays) beyond the influence of the earth. Current detectors are generally limited to energies below about 300 MeV. Lower-energy data should be made available on an hourly basis. At higher energies, where counting rates may be a limitation, the time resolution should be at least once per solar rotation.

- Neutron monitor measurements of cosmic rays up to 60 GeV. The technique uses the earth as a spinning spacecraft for which the earth's magnetic field acts as a built-in magnetic analyzer. This use of neutron monitors adds to the reasons for maintaining them. Underground neutron detectors can extend the energy range beyond that of neutron monitors and should be maintained.

- Riometers, an inexpensive, ground-based system, measuring the intensity of low-energy particles emitted by the sun.

THE MAGNETOSPHERE: QUANTITIES TO BE MEASURED

Scientific Rationale

Observations pertaining to the magnetosphere have been made for many decades through the use of global ground-based magnetometer networks. In some cases, these ground-based data have been used to construct families of global indices represented by aa, Kp, Ap, and Dst. More recently, the AE family of indices has been developed as a measure of auroral zone electrojet current systems. These ground-based indices represent proxy information indicating the configuration and state of the magnetosphere. Ground magnetometers also provide the long-term record used to monitor the secular variation of the earth's internally generated magnetic field.

For the purposes of long-term solar-terrestrial research, it is important to continue to provide the magnetic indices and to track the secular variation. This entails keeping in operation a sufficiently dense and properly distributed network of ground magnetic observatories. High priority should be given to maintaining the magnetic indices for the following reasons.

Magnetic indices are the barometers of solar-terrestrial weather. Their records document the unique history of the storms and calms in the earth's solar-terrestrial environment in the same way that Weather Bureau records document the history of blizzards, floods, and droughts that affect the United States.

The records permit knowing the state of the solar-terrestrial environment at any given time, for example, knowing if a magnetic storm or substorm is in progress, and if so, the stage of its life cycle. Such information is indispensable for relating individual magnetospheric measurements, which are necessarily local, to the global magnetospheric state.

The records enable comparing states of the solar-terrestrial environment at different times. This capability is widely used to bin data taken at different times and places in the magnetosphere into groups belonging to a particular magnetospheric state, thereby letting researchers accumulate enough data to assemble a global montage for that state. Thus, monitoring the state of the magnetosphere by means of the magnetic indices permits a statistical approach to comprehensive synoptic studies. This is apt to be the only practical way to obtain such information for the foreseeable future.

The magnetic records from which the indices are compiled are themselves immensely valuable. The spatial and temporal details

that are lost in the indices are needed for studies of many important phenomena, among them, sudden commencements, impulses, and micropulsations. These magnetic records should be stored along with other ground magnetometer data to give sufficient areal coverage to permit long-term studies of the secular variation of the geomagnetic field. The geomagnetic secular variation is important to solar-terrestrial research because the internal field has already changed enough during the space era to have caused a measured alteration in the population of energetic particles that is in effect attached to the field. Further, monitoring the secular variation gives insights into the global nature of the much larger excursions that are known from proxy data to have occurred in the past. To discuss the solar-terrestrial environment that prevailed when the geomagnetic field was much different than now requires good global models of the field for such times.

Over the last three decades, earth-orbiting spacecraft have made direct in situ measurements of the magnetic field, electric currents, plasma composition and distribution functions, and energetic particle fluxes in the magnetosphere. It is important to monitor and archive in situ magnetospheric measurements for the following reasons.

Whereas, in principle, the sun and the solar wind can be monitored continuously from a single space platform, to monitor the magnetosphere continuously would require a network of satellites. This is impractical. Instead researchers have adopted a statistical approach to determine how the magnetosphere changes in time. One assumes that a particular magnetospheric state corresponds to a particular value of magnetospheric activity index, such as Kp. Then a time line of Kp can be read as a time line of magnetospheric states. The states are found by accumulating in situ magnetospheric data from as many spacecraft as possible for as long a time as possible, until a magnetospheric montage can be constructed for each index value. Under this heading, we include also the polar-orbiting satellites whose measurements, when combined statistically, map polar cap and auroral zone phenomena. The most recent magnetospheric and high-latitude montages (e.g., the Tsyganenko-Usmanov magnetic field model, polar cap convection models, and high-latitude field-aligned current models) are proving to be powerful tools for investigating magnetospheric dynamics and magnetosphere-ionosphere coupling. There is still enormous room for improvement in spatial coverage and accuracy, especially for the infrequent index values, and there is still a need to build montages based on other activity indices

and other magnetospheric parameters. These yet-to-be-constructed, more accurate, and more comprehensive montages depend on continued monitoring and archiving of magnetospheric parameters. Constructing these montages and extracting the information they contain are certain to lead to important advances in magnetospheric science.

While it is true that a fixed activity level determines a fixed magnetospheric state, this concept does not adequately account for the magnetosphere's inherent time-dependent phenomena. To study these requires another strategy, which also relies on long-term monitoring and archiving of in situ magnetospheric data. The basic ways in which the magnetosphere manifests time-dependent behavior—storms, substorms, convection bays, transpolar arcs—involve major refiguring of its shape and restructuring of its features. Understanding these events entails mapping the changes in the magnetosphere's shape and structure as the events pass through their life cycles. Events of any one type differ widely in duration, intensity, extent, location, structure, and shape. Thus a statistical approach to a synoptic study of the life cycle of any of the classes of magnetospheric events cannot yield a sharp image of the phenomenon and, perhaps, cannot even resolve one class of event from another. Further, while a magnetospheric event runs its course, it engages a much larger portion of the magnetosphere than a single spacecraft can survey. It follows that synoptic studies of time-dependent magnetospheric phenomena require simultaneous multispacecraft observations. Such studies are now being carried out in the CDAW and PROMIS coordinated data analysis approach to global synoptic studies of magnetospheric events. This is possible only if magnetospheric data are monitored and archived to build an adequate data base for event selection. The more comprehensively and continuously the responsible agencies carry out magnetospheric monitoring and archiving, the likelier it will be that these programs will succeed.

To record long-term changes in magnetospheric size, shape, structure, composition, and time-dependent processes requires continuous in situ monitoring and archiving. Chapter 5 of this report documents a significant multiyear trend in the abundance of ions in the magnetosphere of atmospheric origin. Such changes may result from long-term alterations of the magnetosphere's boundary conditions, that is, in the prevailing state or in the dynamical character of the solar wind or of the atmosphere and ionosphere. Long-term alterations in the magnetosphere's boundary conditions may, in turn, result from the changes in the prevailing levels or in the dynamical

character of the sun's electromagnetic and particle outputs as it undergoes its activity and magnetic cycles with slowly increasing and then decreasing amplitudes. The recently discovered variable magnetospheric energetic electrons should be continuously monitored, because their peak fluxes can importantly modify upper atmospheric chemistry. It is also important to carry out long-term in situ magnetospheric monitoring and archiving to learn how magnetospheric structure, particle populations, and behavior respond to the secular variation of the geomagnetic field.

For the foreseeable future, our understanding of magnetospheric structure and dynamics must be pieced together by combining in situ satellite data and ground-based data. As noted above, because ground-based geomagnetic activity indices extend continuously from before the space age through the early space age to the present, they have great importance to long-term solar-terrestrial research. The existence of these records also increases the importance of continuous in situ magnetospheric monitoring and archiving, because comparing and correlating space-based data can lead to a more thorough and proper physical interpretation of spatial conditions that correspond to the level and changes in geomagnetic indices on the ground. Such improved understanding greatly increases the value of global indices and offers the possibility of inferring a continuous record of magnetospheric configurations and dynamics extending backward in time, in some cases for many decades.

It is important to monitor and archive in situ magnetospheric data to document in the magnetospheric parameters the history of solar-terrestrial events. As a discipline responsible for this subject matter, solar-terrestrial science should be able to answer questions like: "What did the magnetosphere do during the great solar-terrestrial events of August 1972?" and "How did the magnetosphere respond to the monster solar wind streams of 1974?" Such questions arise in investigations in magnetospheric physics itself and in interdisciplinary work. To optimize data coverage of unpredictable occurrences of historical significance, among which are the extreme event, the classical event, the unusual event, the bizarre event, the perfect event, and the rare event, magnetospheric monitoring should be carried out as comprehensively and continuously as possible.

In addition to monitoring and archiving the basic particle, field, and remote sensing data, some specific magnetospheric parameters should be extracted from these data and archived and disseminated. In a loose sense, extracted magnetospheric parameters relate to basic

magnetospheric data the way geomagnetic indices relate to basic geomagnetic field measurements.

As the buffer between the solar wind and the ionosphere-atmosphere system, the magnetosphere processes and then transmits or redeposits the fluxes of mass, momentum, and energy that it receives from both sides. The mere size of this processing and distributing unit is an important and variable parameter that should be monitored by noting where and when any spacecraft crosses the bow shock, the magnetopause, or the plasmapause. Using standard models, data product agencies can present the information in the form of equivalent subsolar distances. The locations of these major magnetospheric boundaries normally change gradually under the influence of solar wind dynamic pressure changes. The magnetosphere can also compress abruptly when an interplanetary shock wave passes, and inflate in a few hours when the ring current builds to a magnetic storm. Relying on crossings of opportunity for information on boundary positions, which is the only practical method, limits sample frequency to the order of one per day or less.

The size of the polar cap, i.e., the region defined by "open," nonconjugate magnetic field lines, is an important global magnetospheric parameter. With image processing algorithms, its radius can be determined from satellite imagery such as provided by the Defense Meteorological Satellite Program (DMSP). The DMSP satellites, with orbital periods of 100 min, are to be continuously in place into the indefinite future. Thus every 50 min a given DMSP spacecraft will pass over one pole or the other and give data on polar cap size, shape, and position.

A major concern of magnetospheric physics is the energy input rate from the solar wind. The total magnetospheric energy input rate can be determined in the form of 5-min averages from an upstream solar wind monitor. Although there is controversy about the "best" composite solar wind parameter to characterize solar wind-magnetosphere coupling, there is general agreement that the main parameters involved are the solar wind speed and the IMF strength and direction. The solar wind ram pressure (ρV^2) also affects the energy input rate. A standard energy input index should be published in the same way as the geomagnetic indices, such as AE and Dst. Since energy dissipation processes can be related to AE and Dst, an energy input index would enable researchers to perform a variety of energy budget studies of interest to long-term solar-terrestrial science.

The plasma and energetic particle distribution functions throughout the magnetospheric system must be determined in order to know and understand the system and its interactions with the solar wind and ionosphere. This is another instance in which continuous long-term monitoring and archiving of in situ data are needed to build global montages and to monitor changes in time. Data from synchronous-orbit satellites and low-altitude polar-orbiting satellites would be especially useful. In addition to bulk energetic particle and plasma measurements, information on composition is crucial. Recent experience has demonstrated important long-term changes in ion composition. To determine where magnetospheric ions originate and to understand the nature of the magnetospheric acceleration processes that produce energetic particles, the ion mass and charge state compositions need to be determined. As a minimum, plasma instruments should separate H^+, He^+, He^{++}, O^+, O^{++}, and O^{+n} ($n \geq 3$). Energetic particle sensors should at least separate masses H, He, CNO, and heavies; if possible, energetic particle sensors should also determine charge as well as mass.

Long-Term Observations Needed

State-of-the-art measurement needs are presented below.

8. *Global Magnetospheric Scale and Structure*
    • Solar wind dynamic pressure and composition (H/He) at 5-min resolution.
    • IMF strength and direction at 5-min resolution.
    • Continuous particle and field data from polar-orbiting satellites and magnetospheric monitoring satellites to build magnetospheric and high-latitude statistical montages.
    • Dst index derived from optimal mid-latitude ground magnetometer stations (individual records also important).
    • Auroral images showing polar cap size and shape, as opportunity provides, but with an expectation of 50-min resolution.
    • Direct bow shock, magnetopause, and plasmapause detection by spacecraft in elliptical orbits, as opportunity provides.

9. *Main Magnetospheric Current Systems*
    • Magnetopause (Chapman-Ferraro) current strength and position.
    • Ring current strength from Dst.
    • Ring current asymmetry parameter obtained by spatial Fourier analysis of input data for Dst ($Dst = D_0$, asymmetry $= D_1$).

We propose this as a new standard index to monitor the strength of the high-latitude field-aligned currents.

- Birkeland Region I and II current systems from auroral magnetometer and polar-orbiting spacecraft.
- Cross-tail current and tail-field strength, B_t, using geostationary and near-tail elliptical orbit spacecraft, as opportunity provides.

10. *Electric Fields Associated with Main Current Systems*

- Solar wind flow speed, density, and vector magnetic field from a near-earth monitor (e.g., SOHO and WIND).
- The high-latitude electric field measured by low-altitude polar-orbiting satellites.
- The AE family of geomagnetic indices as a rough measure of the high-latitude electrical potential.
- High-latitude geomagnetic data from a network of magnetometers sufficiently dense to permit inferring the high-latitude potential distribution from the pattern and amplitude of magnetic perturbations (5-min resolution).
- Distribution functions of precipitating particles measured from low-altitude polar-orbiting satellites to acquire statistical information on the parallel electric field.

11. *Magnetospheric Energy and Mass Transport*

12. *Magnetospheric Particle Populations*

- Solar wind parameters as specified in item 8 above from a near-earth monitor (e.g., SOHO and WIND).
- A standardized solar wind energy input index.
- Solar, planetary, and galactic energetic particle fluxes as part of the data returned from planned interplanetary monitoring spacecraft.
- Ionospheric mass influx rate from low-altitude, polar-orbiting spacecraft to the extent practical.
- Ionospheric Joule heating rate as inferred from AE and where possible from spaceborne magnetic records.
- Auroral particle precipitation energy flux as inferred from AE.
- Auroral particle precipitation energy flux measured by auroral x-ray imagers and polar-orbiting plasma sensors, as opportunity provides.
- Ring current plasma energy injection rate as inferred from the rate of change of Dst

- Particle measurements by geostationary satellites, as available.

- Tail energy storage as inferred from polar cap size as measured by imaging from polar-orbiting satellites.

- Magnetospheric particle composition as determined by magnetospheric monitoring satellites, especially from synchronous orbit, as available.

THE THERMOSPHERE-IONOSPHERE: QUANTITIES TO BE MEASURED

Scientific Rationale

The thermosphere is that rarefied portion of our atmosphere lying between 80 and 500 km above the earth's surface, where the temperature increases dramatically with altitude. Solar electromagnetic energy in the ultraviolet at wavelengths shorter than 200 nm strongly interacts with the gases in the thermosphere to establish its basic chemical, thermal, and dynamic structure. Variations in the solar UV radiation introduce variations in the structure of the thermosphere on time scales that are less than a day, causing the atmosphere to expand and contract with changing solar UV output.

Large amounts of solar wind energy also are deposited in the high-latitude regions of the thermosphere through auroral processes. This energy sometimes locally exceeds the absorbed solar electromagnetic energy.

As a result, the thermosphere is a dynamically active region, with large variations about its global mean state caused by variations in both solar ultraviolet radiation and solar wind plasma. The thermosphere is also subject to forcings from below in the form of upward propagating tides, gravity waves, and other disturbances from the middle atmosphere.

Embedded within the thermosphere, the ionosphere is maintained primarily by the absorption of solar EUV radiation. The charged particles that make up the ionosphere are strongly influenced by electric and magnetic fields. These fields, in turn, are affected by the distributions and motions of the charged particles. Mutual neutral gas/plasma interactions affect the overall structure of both the ionosphere and the thermosphere, and there is an important need to consider them as a mutually interacting system.

There is no individual index that can characterize the state of the thermosphere and ionosphere. Instead global measurements of

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the coupled fluid system are needed to describe the circulation, temperature, and compositional structure of the regions. Additional measurements are needed to describe the energetics, such as infrared emissions that act to cool the thermosphere and airglow emissions that characterize the atomic and molecular processes that occur locally. The thermosphere and ionosphere together change in response to changes in the solar x-ray, EUV and UV spectral irradiance, and geomagnetic storms and substorms. Since there are long-term changes in solar x-ray, and EUV and UV radiation, the properties of the thermosphere and ionosphere are also expected to differ. It is a goal of long-term solar-terrestrial research to characterize and understand these thermospheric changes and to relate these to various solar-terrestrial linkages.

Long-Term Observations Needed

State-of-the-art measurement needs are listed below.

13. *Solar and Auroral Energy, Momentum, Mass, and Charge Transfer into the Thermosphere and Ionosphere*

- Full-disk solar x-ray, EUV, and UV spectral irradiance measurements, between $1 < \lambda < 250$ nm, are needed.
- Solar wind measurements of density, velocity, and magnetic field vector are needed for determining energy and momentum inputs into the earth's magnetosphere, ionosphere, and thermosphere.
- Distributions of solar energetic particles bombarding the earth's ionosphere, thermosphere, middle and lower atmosphere (e.g., solar protons and galactic cosmic rays), and their time variations, are needed.
- Auroral particle energy spectra are needed to determine ion and chemical production rates, energy inputs (including the energy distribution function of auroral electrons and protons), and their spatial and temporal evolution. Global and regional auroral spectral images are important for obtaining the global energy input and the spatial and temporal variations. Estimates of global auroral power inputs, determined from particle measurements onboard NOAA satellites, provide an important global index.
- Measurements of auroral type, frequency, location, and temporal and spectral variations are important for determining the characteristics of the columnar energy input processes.
- Measurements of electric and magnetic fields are necessary to determine energy and momentum inputs into the ionosphere and

thermosphere and the global ionospheric current and electric field distributions.

14. *Global Circulation, Temperature, and Compositional Structure of the Thermosphere and Its Response to Solar and Auroral Variability*

15. *Ionospheric Plasma: Global Circulation, Temperature, Composition, Distribution of Currents and Fields, Response to Solar and Auroral Variability*

• Satellite and ground-based measurements of temperature, composition, and winds are required to derive the global structure of the thermosphere and its response to solar and auroral variability. An important thermospheric index is the global mean exospheric temperature obtained by averaging measurements of the global distribution of exospheric temperature.

Global measurements of temperature and composition have been used to construct global empirical models. These models describe the thermospheric response to variations in various solar and auroral indices (e.g., solar 10.7-cm radiation, Ap). There is no corresponding empirical model to describe winds at the present time. The empirical models have wide use for prediction of satellite drag and in providing background properties for other geophysical studies. It is important to obtain new measurements to better define the thermospheric response during different solar activity and magnetic activity cycles and to define long-term trends and variability.

• Satellite and ground-based measurements of ionospheric plasma parameters, such as electron and ion number density, electron and ion temperature, electric fields and currents, and magnetic field variations, are needed to determine the global structure of the ionosphere and its response to solar and auroral variability.

• Ionospheric indices, such as total electron content, TEC; critical radiowave frequency of the ionospheric F_2 layer, F_0F_2; and height of the F_2 layer, h_m, have been useful in describing ionospheric variability over a solar cycle, the response to solar flares, sector boundary crossings, and other solar forcings.

• Incoherent scatter radar and ionosondes provide important information on the dynamics properties of the ionosphere, thermosphere, and magnetosphere interactions. Ionospheric data have been used to construct empirical models, such as the International Ionosphere Reference model, that are useful in prescribing global ionospheric properties for communication transmissions and geophysical

studies. There is an important need to provide new data for these models to describe better the long-term changes (e.g., intercycle differences) in ionospheric properties.

- Optical photometry, spectroscopy, and interferometry in emission and absorption are important techniques for determining atomic, chemical, radiative, and energetic processes that are operating in the thermosphere, ionosphere, middle atmosphere, and exosphere.

- Measurements of Doppler broadening and line positions of certain airglow features have also provided important dynamic information such as temperature and winds.

- Individual station measurements and global campaign studies, such as CEDAR (Coupling, Energetics, and Dynamics of Atmospheric Regions), provide important information on determining the basic state of the thermosphere and ionosphere and its response to solar and auroral activity. Long-term measurements are needed to define intercycle differences of solar activity and secular changes. These airglow measurements also provide important information on the chemistry of the upper atmosphere.

16. *Interfaces (Energy, Momentum, Mass, Charge Transfer) Between Magnetosphere, Thermosphere, Ionosphere, and Middle Atmosphere*

- Measurements of the global circulation, temperature, and composition of the middle atmosphere are needed to determine the response of this region to solar variability. They are also needed to define the characteristics of disturbances, such as tides and gravity waves, that originate in the middle atmosphere but propagate upward and affect the thermosphere and ionosphere directly, and through dynamo action the magnetosphere.

- Galactic cosmic ray measurements–neutron and other more energetic monitors–provide information on atmospheric ionization rates that have an important effect on electrical conductivity variations in the troposphere and middle atmosphere. This information is also important for studies on global atmospheric electricity.

- Measurements of the vertical earth-ionosphere potential difference are needed to determine the extent of the coupling of solar-terrestrial electrical disturbances into the global electric circuit.

7
Coordinated Planning for Long-Term Solar-Terrestrial Observations

Over the past two decades, the introduction of satellite-based observing systems, providing in situ measurements with high precision and resolution, has brought about a quantum increase in understanding of the solar-terrestrial processes. Building on new knowledge, new ground-based observations have also been implemented to move the field toward the goal of optimum data gathering networks. There is a consensus that when the same quantities are being measured, solar-terrestrial observations from space platforms are superior to proxy data in terms of accuracy, resolution, and representativeness. Many observations can only be made from space platforms, for example, x-ray solar images and most solar wind parameters. However, because it is unlikely that sufficient satellite observing systems can be supported for continuous global characterization of the variability of the solar-terrestrial system, certain ground-based observations will be needed indefinitely, for example, geomagnetic indices and magnetic records from observatory networks that map global ionospheric currents. Furthermore, it is not yet possible to determine the optimum mix of space and ground-based observations. Nor has the optimum configuration of observing networks been systematically studied.

The panel concludes that satellite and ground-based observing systems will continue to be added to the data gathering networks and in some cases will supersede older systems. This is essential

to the continued vitality and quality of solar-terrestrial research. We anticipate that the process of phasing in and out and replacing ground-based observations, which has already begun, will continue during the next two to three decades. To struggle under decreased budgets to maintain reliable but technologically inferior proxy data records is to go against this trend. Instead, exercising judgment and step-by-step decision making on replacing existing data records with technically superior data would facilitate the transition process and use limited resources wisely. Coordinated long-term planning, taking into account observational needs, plans for new space and ground-based observations, and the comparative value of existing systems, is needed, rather than a single static listing of current data records.

Under these circumstances and anticipated trends, an appropriate policy could be one that provides a means to plan, in a timely fashion, for establishing the vital new satellite and ground-based observations that should be supported over the long term, thereby in some cases permitting a planned phase-out of older direct or proxy observations.

Such a policy would require a standing committee of scientists from the solar-terrestrial and related fields—possibly the Committee on Solar-Terrestrial Research—with ad hoc panels as necessary, together with agency representatives, to develop timely long-range transition plans to establish viable new solar-terrestrial observing systems, such as the solar x-ray imager, for long-term operations. The committee would have equal responsibility for designing data gathering strategies, network optimization, and data acquisition, processing, archiving, and accessibility planning. Based on these plans, decisions could be made on a reasonable phasing in and out of technologically superior and inferior or proxy observations, or on plans to improve or consolidate observations where new understanding or technology makes this desirable.

The panel has recommended that such an interagency committee be established and institutionalized within the international scientific organizations as soon as possible.

The panel recognizes that individual agency budgets may face cuts so severe that there is no alternative within the agency but to terminate a long-term solar-terrestrial observing program. Solar-terrestrial science has no claim for preferential funding over other equally important scientific fields. To obtain funding for long-term

solar-terrestrial observation programs, the community must demonstrate consensus on goals and scientific rationale, and develop interagency and international plans for the highest priority programs.

In the face of possible unplanned terminations, a policy could be adopted now, calling for procedures to fund, concurrently with the operation of measurement systems, for the processing, archiving, and accessibility of all data records on a current basis. This would prevent loss of unprocessed data in the event of an unplanned or surprise closing. In addition, such a policy would immediately strengthen current long-term observational programs and facilitate solar-terrestrial research by improving the accessibility of important data records. Under interagency planning, a national solar-terrestrial data center could be designated and jointly funded to maximize the usefulness of current observations.

In the future, any observation producing solar-terrestrial direct or proxy information can, in principle, be eliminated when two conditions are met. The first is that reliable, long-term, superior data have become available. The second is that the algorithm must have been determined that converts between the new data and the discontinued proxy data. The second is necessary to be able to compare past and future records.

New satellite vehicles dedicated to solar-terrestrial observations, such as WIND, may be the only means to obtain some solar-terrestrial data records. This is the most costly approach. A policy of adding solar-terrestrial observing systems to multimission satellites, such as the solar x-ray imager on GOES, presents a sound fiscal and operational approach to long-term observations. Close coordination among NASA, NOAA, and DOD under a joint planning approach, such as the solar x-ray imager epitomizes, is more cost-effective.

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Appendix:
List of Acronyms

aa AE Ap Dst Kp	Geomagnetic indices
ACRIM	Active Cavity Radiometer Irradiance Monitor
AE-E	Atmospheric Explorer-E
AFGL	Air Force Geophysics Laboratory
AU	Astronomical unit
BBSO	Big Bear Solar Observatory
CDAW	Coordinated Data Analysis Workshop
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
DE-1	Dynamics Explorer-1
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
ERB	Earth radiation budget
EUV	Extreme ultraviolet
GISMOS	Global Incoherent Scatter Measurements of Substorms
GOES	Geostationary Operational Environmental Satellite
GTMS	Global Thermospheric Mapping Study
HAO	High Altitude Observatory
HEOS	Highly Eccentric Orbiting Satellite

ICCSTR	Interagency Coordinating Committee for Solar-Terrestrial Research
ICSU	International Council of Scientific Unions
IGY	International Geophysical Year
IMF	Interplanetary Magnetic Field
IMP	Interplanetary Monitoring Platform
IMS	International Magnetospheric Study
ISEE	International Sun-Earth Explorer
ISTP	International Solar-Terrestrial Program
KPNO	Kitt Peak National Observatory
MHD	Magnetohydrodynamic
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NOAO	National Optical Astronomy Observatories
NRC	National Research Council
NSF	National Science Foundation
NSO	National Solar Observatories
PROMIS	Polar Region and Outer Magnetosphere International Study
RSTN	Radio Solar-Terrestrial Observing Network
SBIR	Small Business Innovation Research
SBUV	Solar Backscatter Ultraviolet Satellite System
SMM	Solar Maximum Mission
SOHO	Solar and Heliospheric Observatory
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor
UARS	Upper Atmosphere Research Satellite
UV	Ultraviolet
WDC	World Data Centers
WMO	World Meteorological Organization