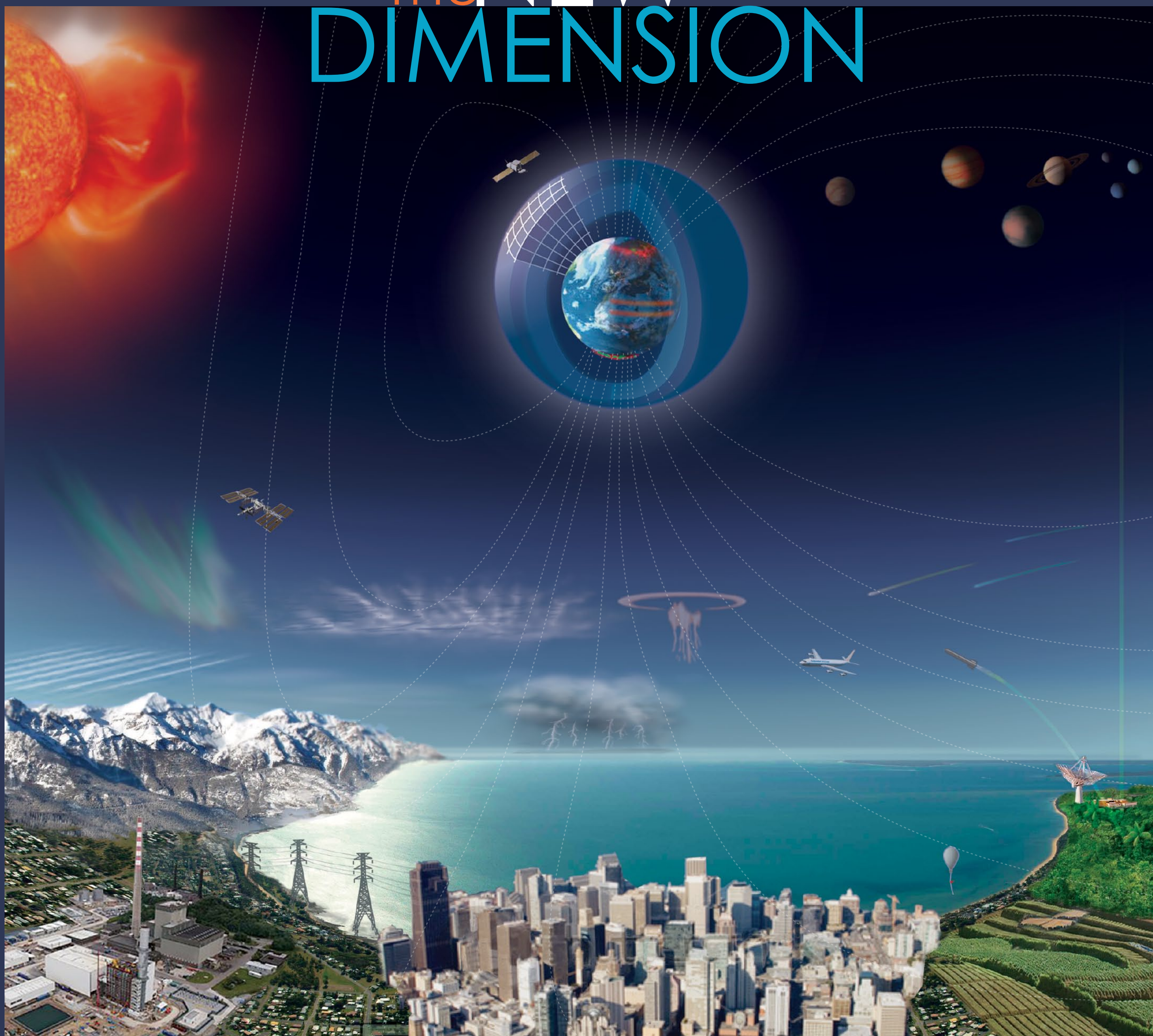
CEDAR
The NEW DIMENSION



STRATEGIC VISION

for the National Science Foundation Program on

COUPLING, ENERGETICS AND DYNAMICS OF ATMOSPHERIC REGIONS


Man must rise above the Earth – to the top of the atmosphere and beyond — for only thus will he fully understand the world in which he lives.
– Socrates

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Noctilucent clouds
in the summer arctic.
Photo by Jan Erik
Paulsen.

Foreword

Broader initiatives within the geoscience community are burgeoning, and it is appropriate that the CEDAR community become an integral part of those larger activities. The CEDAR program has maintained its prominence and vitality for over 25 years by reviewing, evaluating, and implementing strategic priorities that respond to pressing scientific and technical issues. In this scientific progression, there are certain moments where a major program shift is warranted. This document serves to acknowledge a need for a program shift and describes a bold transformation in the mission of the CEDAR program that anticipates the next generation of scientific breakthroughs and fosters cross-disciplinary activities by exploring connections across CEDAR science and other disciplines.

At the time of this writing, new discoveries in CEDAR research are being made that require knowledge of linkages and processes outside the traditional focus of CEDAR. This reflects the twenty-first century approach to understanding the Sun-Earth system by exploring new avenues of progress, building on past decades of accomplishments. While technological advances have always been instrumental in scientific discovery, the extraordinary pace of recent ground-based and satellite observing methods, data processing and assimilation, and computer simulation capabilities have propelled virtually all aspects of CEDAR research beyond classic discovery mode science in a remarkably short time.

Since its inception, the charter of CEDAR has been to study the coupling processes within the upper atmosphere and its neighboring regions above and below. Past scientific planning by the CEDAR community is captured in the Phase I, II, and III documents, which express detailed questions pertaining to issues in the upper atmosphere. What has emerged from CEDAR research is the recognition that many of these natural coupling processes are linked through system processes that demonstrate *complexity* (i.e., comprising many interacting elements that exchange energy, momentum, and mass through nonlinear, dynamical pathways and, as a whole, producing properties not obvious from the properties of the individual parts).

In this document, no specific questions are posed; that is left to the research community to formulate and propose. Instead, a new paradigm in CEDAR research is presented, one that complements CEDAR's focus on the upper atmosphere with a broader, more encompassing view that recognizes the linkages and processes among different aspects of the Sun-Earth system and acknowledges the vital role the upper atmosphere plays in maintaining a habitable and sustainable planetary system for a technology-reliant society. This more comprehensive focus is the basis for the next step of the program: adding a "new dimension" to CEDAR.

CEDAR: The New Dimension calls for the proactive development of a systems perspective to study the upper atmosphere. Systems theory has the goal of understanding the behavior of a large number of mutually interacting and interrelated components. The systems approach is an explicit focus on how interdependent and variable processes within the upper atmosphere, and with other regions, combine to produce observed conditions and responses. This approach enables transferable concepts across individual systems, scales, and disciplines to facilitate progress in understanding many diverse aspects and distant linkages within the Sun-Earth system. The adoption and implementation of a systems science approach to CEDAR research is more realizable today with the rapid expansion of multi-dimensional databases, increasing computational capabilities and sophistication of numerical tools, and emergence of new sensor technologies.

This document provides the impetus to guide the next decades of CEDAR research activities. However, it will require the same grass-roots effort that founded CEDAR to make this bold transformation where new initiatives, new researchers, and new discoveries will be born at all levels of scientific inquiry.

Jeff Thayer, University of Colorado, May 2011
CEDAR Chair 2007–2010

Executive Summary

The Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) Program, funded by the National Science Foundation's Atmospheric and Geospace Sciences Division, studies the interaction region of the Earth's tenuous upper atmosphere. This region, which separates interplanetary space from the lower atmosphere and biosphere, plays a vital role — not only in maintaining the habitability of the planet, but also as the location for the majority of human investment in operational space assets. Since CEDAR's inception more than 25 years ago, a growing appreciation of the interdependencies between different aspects of the whole Earth environment, together with the rapid evolution of supporting technologies and infrastructure, enable and warrant a new perspective on CEDAR science in order to accelerate progress in high-priority research areas such as geocomplexity, global change, Earth dynamics, and space weather.

To understand the processes that govern the coupling, energetics, and dynamics of the upper atmosphere, and its linkages with the lower atmosphere, space, and the Universe beyond, it is useful to envision the upper atmosphere as an *interaction region*. The concept of an interaction region can be generalized to unify the study of Earth's environment with that of other planetary and solar system bodies occupying the tenuous plasma environment of space. As one of the most complex examples of a space-atmosphere interaction region (SAIR), the Earth — which is readily accessible to all modern research tools of ground-based and space-based investigation — offers an extraordinary opportunity to not only advance our understanding of our home planet, but to elucidate the very nature of interaction regions everywhere. By operating state-of-the-art observational and modeling facilities in new, comprehensive campaigns, CEDAR researchers can begin to resolve the major sources of, and processes responsible for, the levels of variability observed in the SAIR.

The mission of CEDAR is continuously evolving to anticipate the next generation of scientific breakthroughs and foster cross-disciplinary activities by exploring connections between CEDAR science and other disciplines. The *New Dimension* of CEDAR provides a transformative step to advance prediction of upper atmosphere conditions and to understand this region's interconnections to other parts of the Sun-Earth system. The CEDAR mission is to understand the fundamental properties of the space-atmosphere interaction region (SAIR); identify the interconnected processes that define the SAIR's global behavior, evolution, and influence on the Sun-Earth system; and to explore the SAIR's predictability.

CEDAR research creates the breakthrough science and intellectual framework that elucidates the linkages to both the lower atmosphere and near-space regions, and provides awareness of our increasing vulnerabilities. The evolution and maintenance of life on Earth is intimately linked to the development of Earth's atmosphere. As society continues to evolve and develop more sophisticated infrastructure, its dependence on the properties and behavior of the upper atmosphere becomes more acute and varied. Our reliance on space-based technologies for communication, navigation, and resource management is growing rapidly, and with it, our vulnerability to disruptions caused by sporadic space weather events, as well as secular atmospheric evolution. A key focus of the CEDAR program is to contribute to the understanding, prediction, and potential mitigation of space weather impacts on our technologically reliant society through the development of observational networks and whole atmosphere models.

The Earth's upper atmosphere is not a closed system. Across its open boundaries, fluxes of mass, momentum, and energy take the form of solar photons, electromagnetic energy, energetic charged particles from the sun and magnetosphere, neutrals and ions escaping the upper atmosphere, waves, and minor species transport from the lower atmosphere. Waves in particular are fundamental in boundary exchange processes as they can transport fluxes of energy, momentum, and composition across great distances. Another example of exchange processes across boundaries is related to electrical properties of the Earth system. The geomagnetic field serves as an energy pathway between the SAIR and distant regions of the magnetosphere — and the dynamic and continuous redistribution of charge between these regions leads to significant electrical energy dissipation in the ionosphere and thermosphere. Sufficiently detailed observations of each of these various exchanges are not always possible; strategies to target measurements of salient parameters must be developed in order to most usefully constrain theoretical and model developments.

Space-atmosphere coupling accounts for hydrodynamic and magnetohydrodynamic processes that influence, with mutual efficiency, the behavior of the upper atmosphere and its plasma. CEDAR has been successful in identifying neutral-plasma coupling processes within the SAIR, but a major challenge remains in quantifying, with sufficient accuracy and precision, the transformation of energy, mass, and momentum throughout the system and the influence of these transformations on the system's properties. Comprehensive observational campaigns that provide much needed multi-scale and multi-parameter data will challenge the CEDAR modeling community to focus on the SAIR's system processes, which at this time are far from being integrated.

In addition to the SAIR's response to sporadic and periodic changes in external fluxes, boundary conditions, and internal coupling processes, the region also exhibits secular evolution of its mean state. Such long-term evolutionary change in the SAIR "climate" may in turn alter its short-term variability or multi-scale response. Understanding the full scope of global change throughout the lower and upper atmosphere, and the interplay with space climate, is important to obtain a complete physical description of aeronomic processes, as well as to support satellite operations and to mitigate space debris hazards. Efforts to resolve long-term evolution from short-term variability will require continued investment in the acquisition and analysis of long-term data sets, further development of physics-based models, continued refinements in statistical modeling, better knowledge of connections with solar and Earth processes, and the application of these resources for effective prediction and forecasting.

A major challenge for the future of CEDAR science is to develop an integrated, multi-scale picture of geospace processes and how these contribute to the broader Sun-Earth system. Another challenge is to understand the dynamic (highly time varying) and potentially unstable response of the Sun-Earth system to its drivers. A systems science approach can facilitate interaction and collaboration between various members of the geosciences community and provide fertile ground for innovative ideas. The systems approach is not a radical departure from historic CEDAR methodology. Rather, it is an explicit focus on how interdependent and variable processes within the SAIR, and between the SAIR and other regions, combine to produce global conditions. By its nature, this focus moves us away from correlations and snapshots, and towards patterns of change, interrelationships, and complexity.

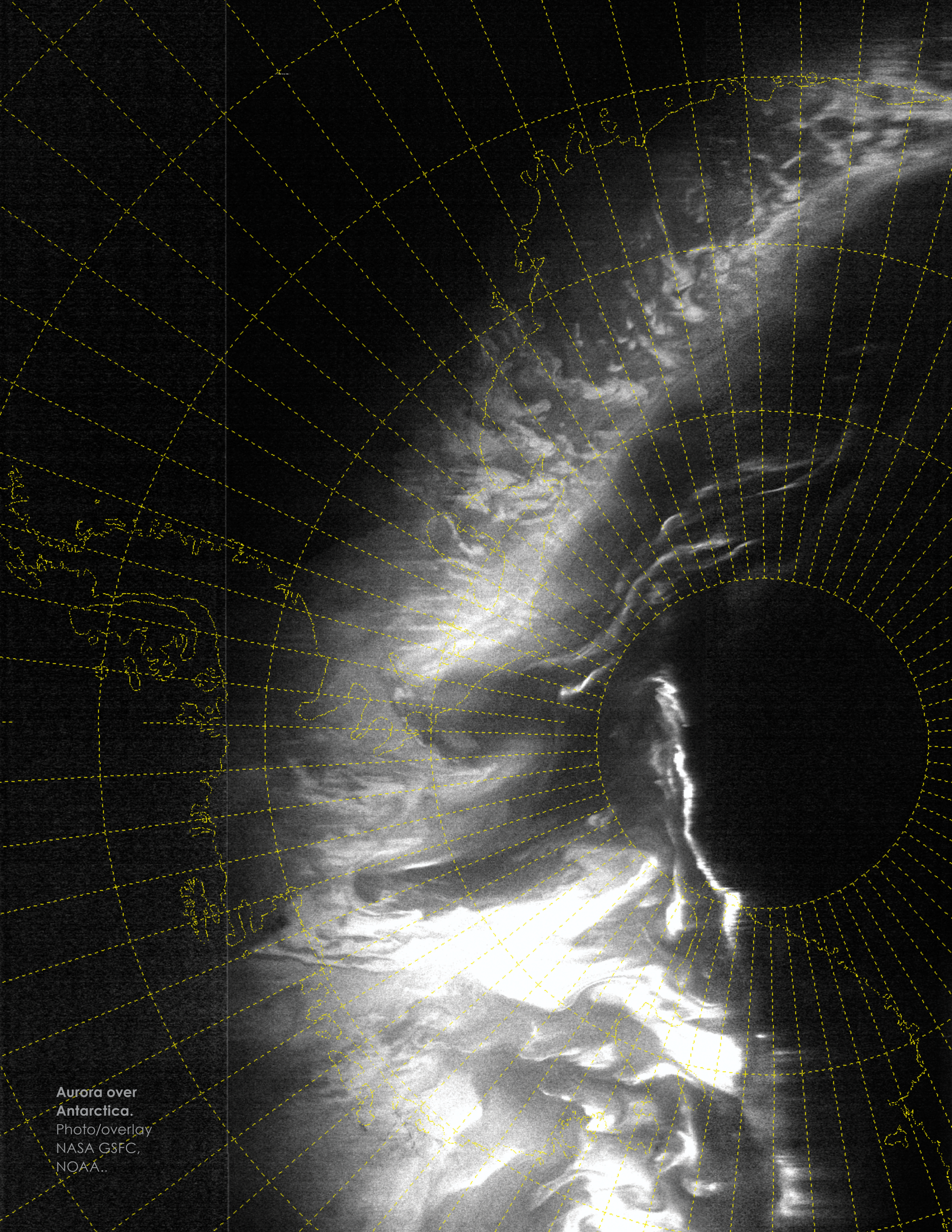
Current understanding of the SAIR as a system that exhibits *complexity* – characterized by having multiple drivers, by featuring adaptive feedback and memory, by its nonlinear response and instabilities, and by exhibiting sensitivity to initial conditions – emerges from a solid background of CEDAR research. In general, system complexity is comprised of many interacting elements that influence one another through nonlinear, dynamical pathways. Focusing on the interaction among physical coupling processes builds upon CEDAR's past and continuing research on individual components and processes. But it also pushes us toward global questions and new ways of viewing problems, providing fertile ground for innovation and exposing gaps in our knowledge. The New Dimension focuses on complexity within the SAIR as a transformative step to advance prediction of the geospace state and to understand the interconnections of geospace with other parts of the Sun-Earth system. Aspects of this complexity include the importance of initial conditions, precondition, and memory; instability; nonlinearity; feedback; and emergent behavior.

The SAIR inherently is a multi-scale system, with energy, mass, and momentum inputs occurring over a wide range of scales. CEDAR observations, models, and analysis techniques are being used to unravel the upper atmosphere's influences on the three-dimensional dynamics of the geospace system, from the smallest scales (e.g., decameter-scale structure in the aurora) to the largest scales (ion and neutral outflow to space), using the concepts inherent in cross-scale coupling. Experience in CEDAR has taught us that the breakthroughs needed to transform our understanding of the global geospace system will require studies focused on coupling, complexity, and the integrative role of the geospace system in the extensive Sun-Earth system.

CEDAR: The New Dimension promotes this expanded focus by developing a systems perspective to study the SAIR. A number of strategic thrusts are identified as guidance and impetus for the community in the coming decade.

1. Encourage and undertake a systems perspective of geospace.
2. Explore exchange processes at boundaries and transitions in geospace.
3. Explore processes related to geospace evolution
4. Develop observational and instrumentation strategies for geospace system studies
5. Fuse the knowledge base across disciplines in the geosciences.
6. Manage, mine, and manipulate geosciences/geospace data and models.

This directive does not abandon time-tested CEDAR approaches involving observation, theory, and modeling to acquire detailed understanding of the components of the larger system. Instead, the new directions to be pursued should occur in parallel with traditional CEDAR approaches. The enabling technologies discussed in this document will not only make it possible to undertake such a two-pronged approach; they will also make the journey scientifically rewarding and fruitful.



Aurora over Antarctica.
Photo/overlay NASA GSFC, NOAA..

1 Introduction

Focusing on complexity within the upper atmosphere provides a transformative step toward accurately and reliably predicting upper atmosphere conditions, and toward understanding this region's interconnections to other parts of the Sun-Earth system.

The Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program, funded by the National Science Foundation's (NSF's) Atmospheric and Geospace Sciences Division, studies the interaction region of the Earth's tenuous upper atmosphere, which separates interplanetary space from the lower atmosphere and biosphere. Not only does this region play a vital role in maintaining the habitability of the planet, but it is also home to the majority of human investment in operational space assets.

The upper atmosphere environment is impacted by energetic particles, solar radiation, and interplanetary magnetic fields that drive "space weather" disturbances in the region, leading to strong electric currents, order-of-magnitude changes in neutral density and temperature, and major redistributions of plasma. At the same time, the circulation and variability of the upper atmosphere are dramatically impacted by waves carrying energy and momentum upward from hurricanes, thermal tides, and surface features. This region is where space and

"The most fruitful areas for growth of the sciences are those between established fields. Science has been increasingly the task of specialists, in fields which show a tendency to grow progressively narrower. Important work is delayed by the unavailability in one field of results that may have already become classical in the next field. It is these boundary regions of science that offer the richest opportunities to the qualified investigator."

– Norbert Wiener

Earth's atmosphere interact, forming a critical boundary that must be studied to advance our understanding of the whole Earth system. The need to understand and predict this dynamic environment is made more urgent by our growing dependence on technological infrastructure such as electric power grids or communication satellites, which are vulnerable to serious collateral damage by space weather effects [Severe Space Weather Events—Understanding Societal and Economic Impacts, National Academy of Science, 2008].

The NSF CEDAR Program was formed more than 25 years ago through a grass-roots scientific effort that remains vibrant today. Community science plans, known as the CEDAR Phase documents, have been developed periodically to assess and prioritize upper atmosphere research topics. The most recent Phase III document, completed in 1996, focused CEDAR science efforts and consolidated resources to attack detailed science questions in four specific areas. Since then, growing appreciation of the interdependencies between different aspects of the whole Earth environment, together with the rapid evolution of supporting technologies and infrastructure, enable and warrant a new perspective on CEDAR science in order to accelerate progress in high priority research areas such as geocomplexity, global change, Earth dynamics, and space weather.

The purpose of this community document, *CEDAR: The New Dimension*, is to describe a transformation in the mission of the CEDAR program that anticipates the next generation of scientific breakthroughs and fosters cross-disciplinary activities by exploring connections between CEDAR science and other disciplines.

1.1 A new mission

As a complement to the detailed and specific science questions posed by CEDAR in the past, this new mission emphasizes a broader, more encompassing view of the upper atmosphere and recognizes that this region must be studied as an integrated system to fully understand its response to external and internal stresses and the subsequent impact on other regions.

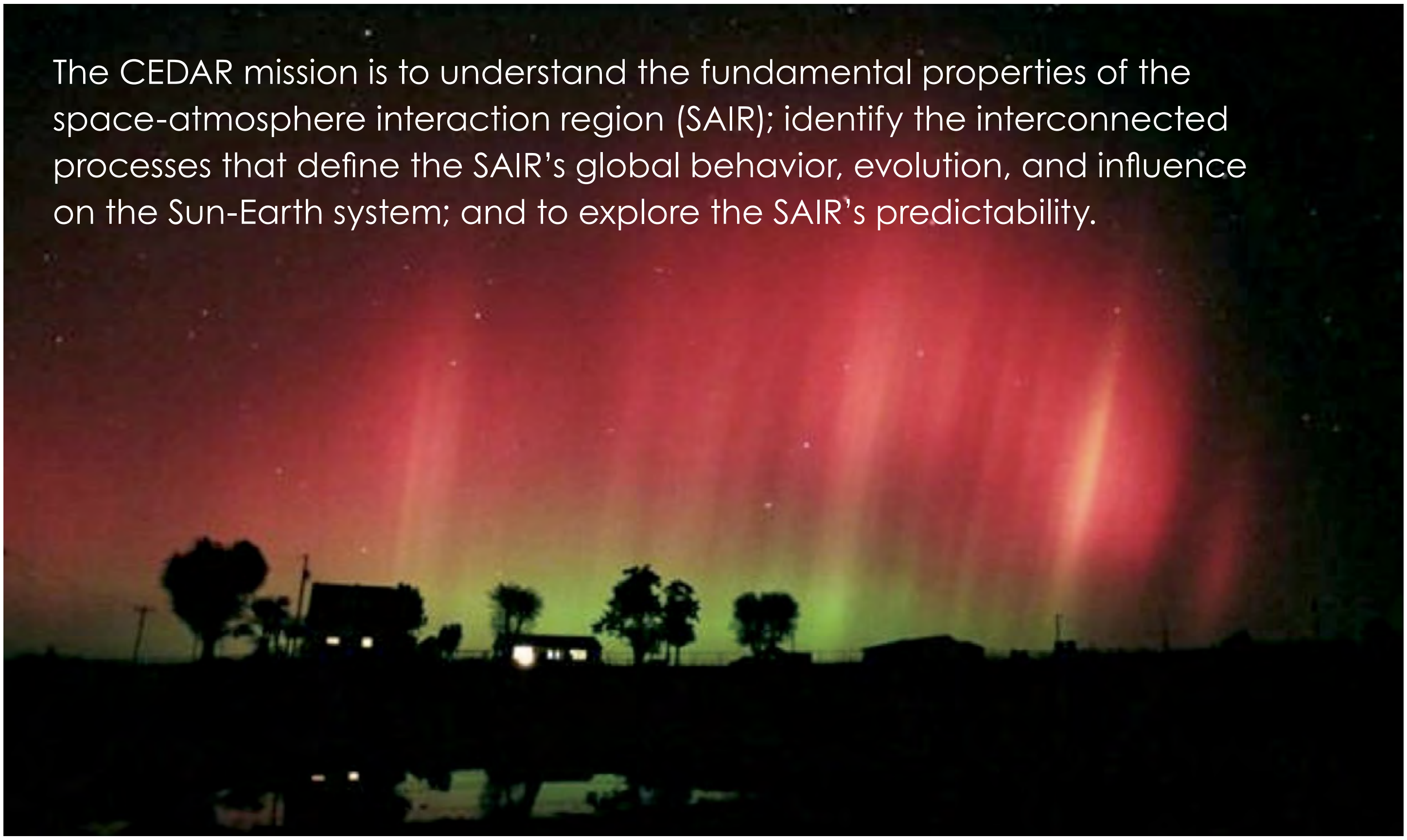
The nonlinear, coupled, and dynamical aspects of the upper atmosphere have long presented a challenge for its comprehension and prediction. The Earth's atmosphere is not simply a linear superposition of its constituent atmospheric regions, but rather a system with *complexity*. The term complexity is used to describe a system comprised of many interacting elements that, as a whole, exhibit properties not obvious from the properties of the individual parts. This description is characteristic of Earth's upper atmosphere and represents a necessary added dimension to CEDAR science.

CEDAR: The New Dimension focuses on complexity within the upper atmosphere as a transformative step toward predicting upper atmosphere conditions accurately and reliably, and toward understanding this region's interconnections to other parts of the Sun-Earth system.

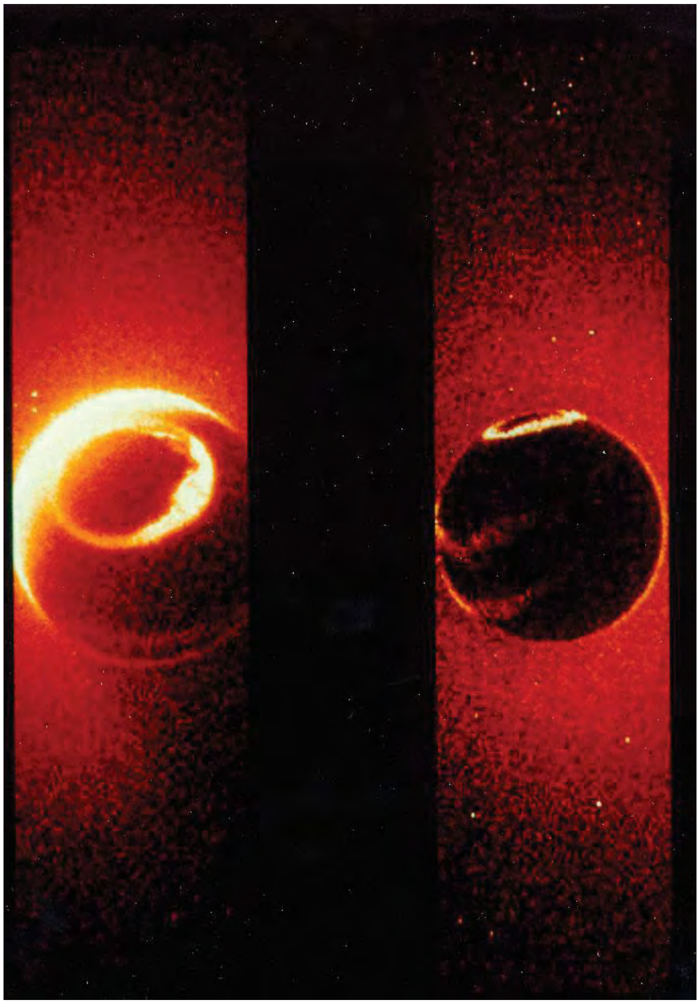
This holistic, systems science view is increasingly shared by other areas of geoscience. Such synergy allows CEDAR to exchange ideas and understanding with disciplines that study other aspects of the solar-terrestrial system such as solid earth, ocean, lower atmosphere, magnetosphere, solar, and interplanetary space. The formulation of new research goals for CEDAR, along with the development and deployment of supporting technologies and infrastructure, must be leveraged from and coordinated with other programs' plans for more extensive observing networks, modeling efforts, and broader visionary goals. These collaborations will allow CEDAR to address broader and more encompassing research topics that will generate exciting, new insights into the workings of the coupled Earth system, with far-reaching impact.

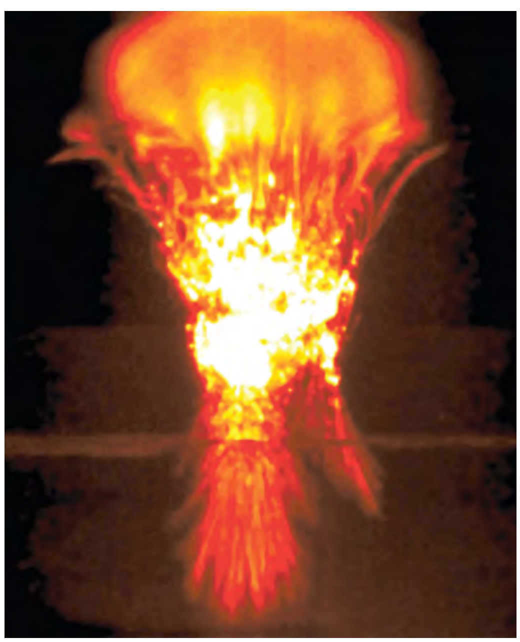
To complement this new dimension of CEDAR, a CEDAR mission statement was crafted to provide the community with a broad, motivational statement that defines CEDAR:

The CEDAR mission is to understand the fundamental properties of the space-atmosphere interaction region (SAIR); identify the interconnected processes that define the SAIR's global behavior, evolution, and influence on the Sun-Earth system; and to explore the SAIR's predictability.



Escaping Atmosphere: Earth's geocorona of hydrogen and other natural atmospheric emissions.





Electrical Connections: Middle atmosphere sprites connecting tropospheric lightning discharge with ionosphere charges.

1.2 Societal relevance

The Earth's upper atmosphere is a key component of the Sun-Earth system, owing to this region's vital role in shielding the surface of the planet from harmful solar radiation and thus sustaining life on earth. Beyond ensuring habitability, however, this region also directly impacts the sustainability of modern society and human well-being, which are increasingly reliant on space-based technologies for daily activities. CEDAR research creates the breakthrough science and intellectual framework that improves our understanding of processes significant to the upper boundary of Earth's atmosphere, elucidates the linkages to both the lower atmosphere and geospace regions, and provides awareness of our increasing vulnerabilities.

Habitability: Our Whole Earth System

The evolution and maintenance of life on Earth is intimately linked to the development of its atmosphere. As we seek to explore other planets within our solar system and discover exoplanetary systems, it is essential that we understand the many influences that initiate and sustain life. Our own early atmosphere was created through geologic outgassing and extraterrestrial bombardment, which added heavier volatile elements to the hydrogen and helium atoms present since planetary formation. However, it was the advent of aerobic life 3.5 billion years ago that began a process leading to an oxygen rich atmosphere, differentiating Earth from its nearest terrestrial neighbor. That oxygen, along with nitrogen, forms an absorbing shield that screens the surface from harmful solar UV radiation and energetic particles, permitting the vigorous evolution of life.

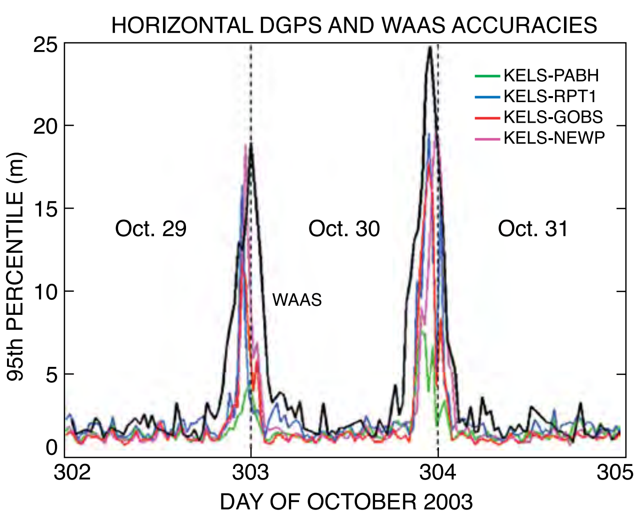
This shielding is not maintained without consequence. Energy from the sun continuously bombards the upper atmosphere, intensifying atmospheric gaseous escape, ripping electrons from the bodies of neutral molecules and atoms to form the ionosphere, energizing gas emissions in the form of airglow and auroras, and raising temperatures to more than one thousand degrees Kelvin.

The ionosphere, a conductive shell of plasma surrounding Earth that arises as a consequence of solar-atmosphere interactions, is essential to the balance of planetary electric charges. This shell of free electrons continuously works to balance charge distributions created in the magnetosphere (visually demonstrated by the continuous presence of aurora). This conductive shell also balances charge distributions induced by ground and cloud electric potentials, as demonstrated by the recent discovery of upper atmosphere sprites and jets. The electrical connections from space to the Earth's surface are poorly understood, but may play a critical role in understanding tantalizing correlations between the sun and Earth's climate.

Electron-Atmosphere Impact: Auroral rays produced by neutral oxygen impacted by energetic electrons. Photo by Craig Heinselman.

As much as water and sunlight are needed for initiating life, properties of the upper atmosphere are important for maintaining it. The Earth's solar system neighbors, Mars and Venus, illustrate opposite extremes of atmospheric evolution, but are proof of the frailty of a planetary atmosphere with liquid water oceans.

The evident potential for a terrestrial planet to rapidly evolve into a state unable to support life demands a thorough understanding of the evolution and stability of atmospheric constituents — a key focus of the CEDAR Program.

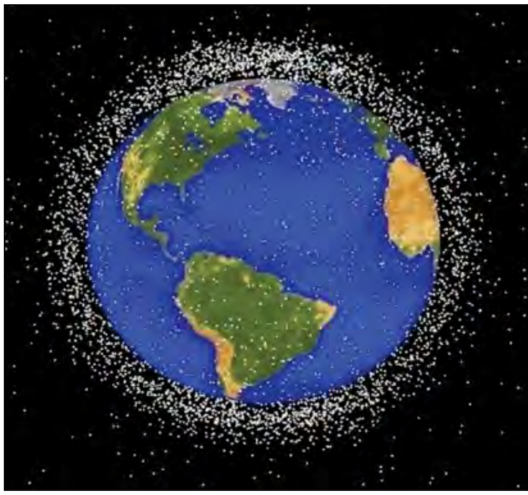


Geomagnetic Storm Effects: Typical GPS positioning errors are a few meters but during storm enhanced density events errors can be 15–25 meters.

Sustainability of Our Technologically Reliant Society

As society continues to evolve and develop more sophisticated infrastructure, its dependence on the properties and behavior of the upper atmosphere becomes more acute and varied. Our reliance on space-based technologies for communication, navigation, and resource management is growing rapidly — and with it, our vulnerabilities to disruptions caused by sporadic space weather events as well as secular atmospheric evolution. Variations in upper atmospheric density and temperature can affect the orbital trajectories and lifetimes of the increasing number of operational satellites and space debris. In addition, ionospheric density perturbations associated with space weather events frequently disrupt GPS positioning systems and block high frequency radio communications. Such detrimental effects are not limited to space-based assets, because strong electric currents generated by solar storms are also able to disrupt electric power grids.

As severe as some of the space weather impacts on societal infrastructure have been over the past few solar cycles, much more devastating "superstorms" are possible, and even likely, in the future. The last occurrence of such a storm in 1859, known as the Carrington event, completely disabled the telegraph system, with operators receiving burns and electric shocks



Orbital Debris (left): The number of satellites in low earth orbit is increasing, along with our vulnerability to disruptions of these space-based assets.

Commercialization of Space (right) will be a societal issue in the future, requiring in depth knowledge of our geospace environment. Many of the commercial enterprises will lie in low earth orbit, centrally located in the thermosphere and ionosphere.

from the geomagnetically induced currents flowing through the telegraph lines.

Recently, the Administrator of the Federal Emergency Management Agency (FEMA) acknowledged the potentially catastrophic effect of another Carrington-scale event on modern communication, power, air traffic, and water infrastructure by incorporating space weather events into its natural disaster preparedness plan.

Another aspect of CEDAR's relevance to sustainability and human well-being relates to our ability to adapt to changing conditions. Interest in geoengineering, with the goal of modifying and potentially controlling atmospheric parameters — such as temperature — for societal benefit, has grown with increasing awareness of climate change. While geoengineering proposals, such as reflecting more sunlight by introducing reflective elements in the upper atmosphere, may offer solutions to the problem of global warming, such efforts may have unintended and potentially catastrophic consequences owing to incomplete understanding of feedback and coupling processes within the Earth system. It is important that researchers in all aspects of solar-terrestrial science be prepared to provide authoritative information pertaining to the changing conditions of our planet, whether natural or engineered, that are likely to occur in the twenty-first century. New societal issues such as geoengineering, space debris, and the commercialization of space are presenting new problems that will require a much improved understanding of the upper atmosphere to be properly addressed.

A key focus of the CEDAR Program is to contribute to the understanding, prediction, and potential mitigation of space weather impacts on our technologically reliant society through the development of observational networks and whole atmosphere models.

Sunset over western South America. International Space Station Imagery, NASA.

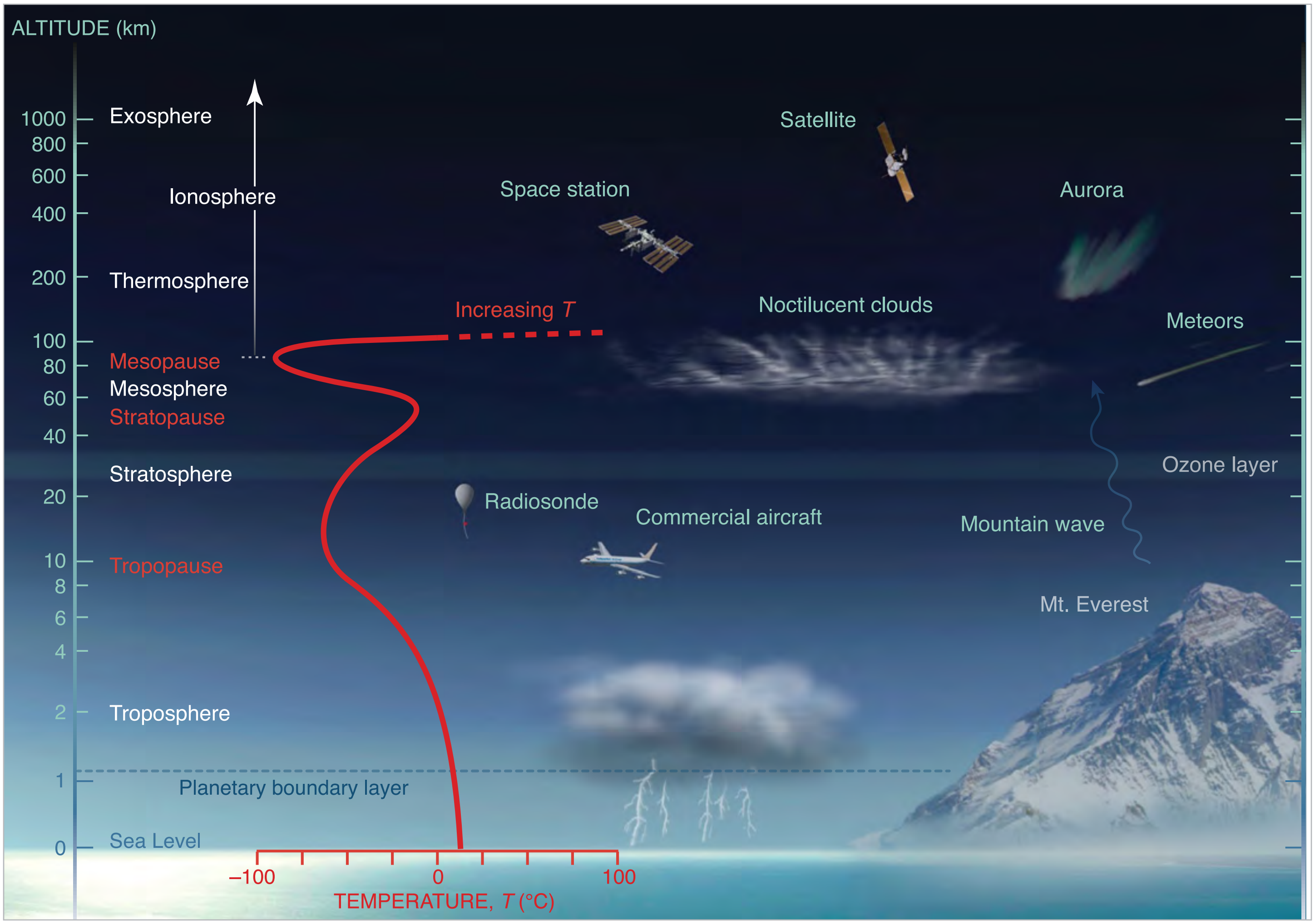
2 The Space-Atmosphere Interaction Region

To understand the processes that govern the coupling, energetics, and dynamics of the upper atmosphere, it is useful to envision this as an *interaction region*, coupling the lower atmosphere with space and the universe beyond.

The upper atmosphere includes the ionosphere, thermosphere, and mesosphere (ITM). The exosphere and plasmasphere are the spaceward extensions of the ITM's neutral and plasma constituents, respectively, leading into the Earth's magnetosphere. Collectively the ITM, exosphere, plasmasphere, and magnetosphere comprise the geospace environment. The troposphere is referred to as the lower atmosphere, and the stratosphere, mesosphere, and lower thermosphere comprise the middle atmosphere.

The upper atmosphere is a dynamic, complex region that communicates with its neighbors—the neutral gas-dominated lower atmosphere and the plasma-dominated space environment—through the transfer and transformation of energy, mass, and momentum.

The concept of an interaction region can be generalized to unify the study of Earth's environment with other planetary and solar system bodies that lie in the tenuous plasma environment of space. The



Atmosphere Regions: Earth's atmosphere and geospace environment making up the space-atmosphere interaction region.

physical and chemical processes occurring between a body's solid or gaseous surface and the fully ionized gases in regions well beyond involve fundamentally important aspects of science. For objects with dense gases at their visible surface (Sun, stars, the giant planets of our solar system, and exoplanets), investigation of their interaction regions include direct ion-neutral coupling, photochemistry of both neutrals and ions, and plasma transport. A further complex setting for interaction region science occurs for worlds where surface topology also modulates upward coupling from neutrals to plasmas. Earth, Venus, Mars, and Titan are specific examples of such environments. Further complexities occur in the presence of a strong intrinsic geomagnetic field that couples the plasma to the neutral gas; Earth, Saturn, and Jupiter are examples of planets whose atmospheres are magnetically influenced in this way.

That one of the most complex examples of a space-atmosphere interaction region — Earth — is readily accessible to all modern research tools of ground-based and space-based investigation offers an extraordinary opportunity not only to advance our understanding of our home planet, but to expand our knowledge of the very nature of interaction regions everywhere.

2.1 Space-Atmosphere Variability

An outstanding challenge in terrestrial upper atmosphere research is specifying the state of the space-atmosphere interaction region (SAIR) at a particular time and location; a limitation manifest by significant levels of variability that often rival the value of the mean state. This variability is driven by the nonlinear, dynamical response of the SAIR to temporally and spatially changing fluxes of energy, mass, and momentum that cross its boundaries from space and the lower atmosphere. Not only does this response depend strongly on the initial state of the SAIR and the conditions at its boundaries, it depends on the nature of the fluxes themselves.

The periodic and sporadic variability of the SAIR, along with its secular evolution, must be characterized in order to identify vulnerabilities, including potential tipping points and emergent behavior, which may influence the habitability of the planet and the maintenance of modern society.

CEDAR scientists have made significant progress in developing observational tools to probe the variable nature of the SAIR , but often in isolated, highly focused campaigns. Meanwhile, contemporary physics-based models of the upper atmosphere lack a complete set of inputs, boundary conditions, and validation procedures to adequately account for all relevant processes. A more complete understanding of the SAIR calls for more extensive spatial and temporal observations of multiple parameters simultaneously and more complete modeling development.

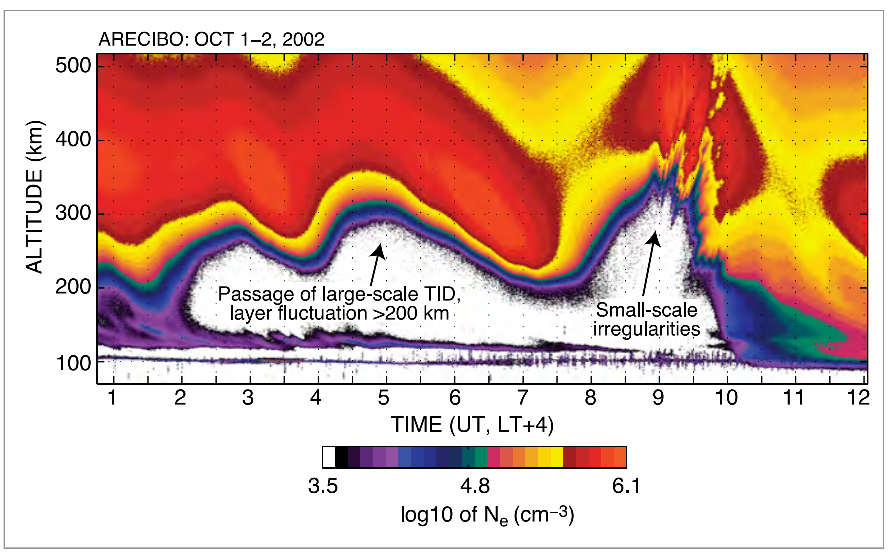
By operating state-of-the-art observational and modeling facilities in new, comprehensive campaigns, CEDAR researchers can begin to resolve the major sources of, and processes responsible for, the levels of variability observed in the SAIR.

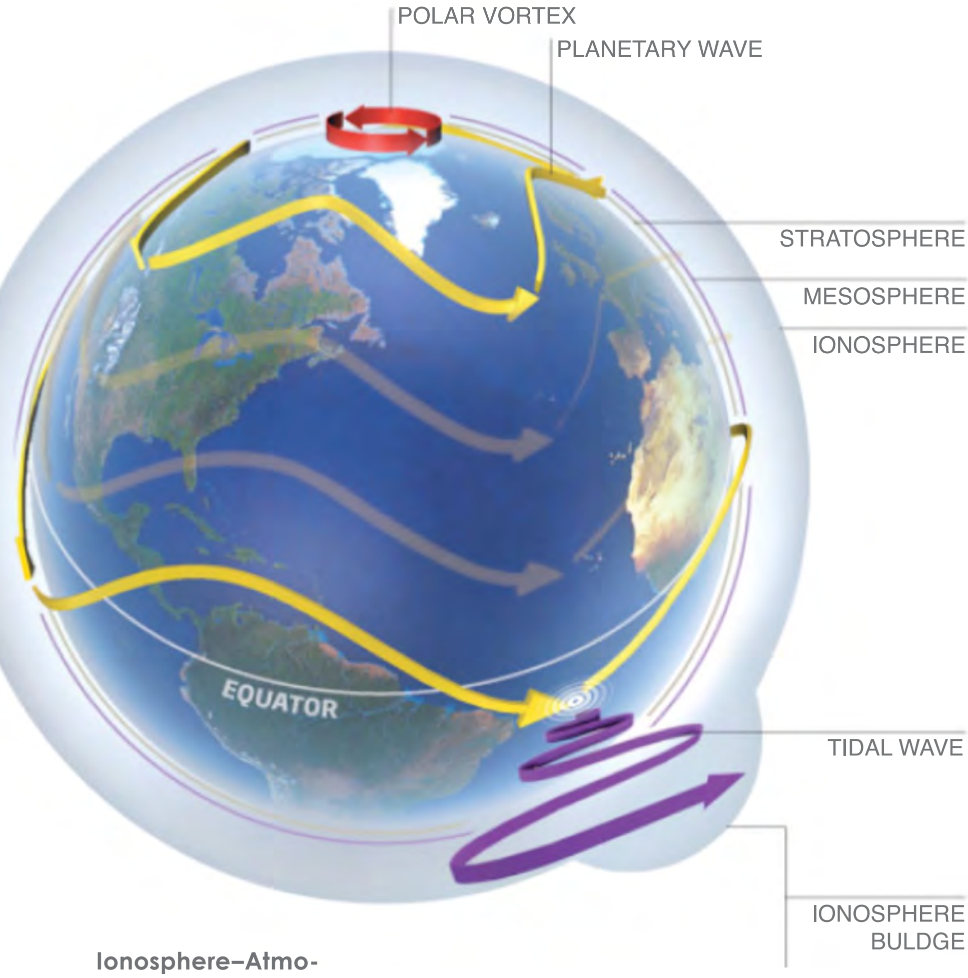
2.2 Space-Atmosphere Fluxes

The Earth's upper atmosphere is not a closed system. Across its open boundaries, fluxes of mass, momentum, and energy take the form of solar photons, electromagnetic energy, energetic charged particles from the sun and magnetosphere, neutrals and ions exiting the ITM, and atmospheric wave momentum and minor species transported from the lower atmosphere.

Waves in particular are fundamental in boundary exchange processes, as they can transport fluxes of energy, momentum,

Ionospheric Waves: Traveling ionospheric disturbances and small-scale irregularities impressed on the ionospheric electron density.





Ionosphere–Atmosphere Coupling: A depiction of terrestrial weather effects, identified by planetary wave action in the polar stratosphere, impacting the equatorial ionosphere.

and composition across great distances. Magnetohydrodynamic Alfvén waves establish communication between the magnetosphere and the SAIR. Meanwhile, hydrodynamic atmospheric waves can be internally generated, making latitudinal connections, or externally generated in the lower atmosphere, propagating upward into the SAIR. Such waves span a wide range of spatial and temporal scales and thus, historically, have been challenging to observe. Indeed, CEDAR scientists have long struggled with understanding traveling atmospheric disturbances (TADs) as well as traveling ionospheric disturbances (TIDs), planetary waves, gravity waves, and tides —which even today are broad categories of many unresolved wave types. As theory and modeling focus on the properties of specific waves, it is important that innovative observational networks, in the form of distributed arrays of instrumentation covering many different spatial and temporal scales, are exploited in order to provide needed insight and validation.

Another type of exchange processes across boundaries is related to electrical properties of the Earth system. The geomagnetic field serves as an energy pathway between the SAIR and the distant regions of the magnetosphere, and the dynamic and continuous redistribution of charge between them leads to significant electrical energy dissipation in the ionosphere and thermosphere. Meanwhile, the electric potential difference between the ionosphere and the lower atmosphere requires a balance of electrical charge that, at times, results in abrupt discharges that link the ionosphere with the lower atmosphere through electrical channels such as sprites and jets.

Sufficiently detailed observations of each of these various exchanges are not always possible, such that strategies to target measurements of salient parameters must be developed in order to most usefully constrain theoretical and model developments.

Future CEDAR initiatives to resolve outstanding issues regarding the nature of such fluxes require strong collaboration with scientists in other areas with complementary observational and modeling programs, such as the NSF's Geospace Environment Modeling community and the Lower Atmospheric Observing Facilities program.

2.3 Space-Atmosphere Coupling

Space-atmosphere coupling accounts for hydrodynamic and magnetohydrodynamic processes that influence, with mutual efficiency, the behavior of the upper atmosphere and its plasma. CEDAR has been successful in identifying neutral-plasma coupling process within the SAIR, but it is a major challenge to quantify with sufficient accuracy and precision the transformation of energy, mass, and momentum through the system or to specify the influence of these forces on the system's properties.

A recent discovery that demonstrates the global extent of coupling in the SAIR is based on observations indicating a connection between sudden stratospheric warming events and significant perturbations in low-latitude ionosphere vertical drifts and total electron content (TEC). Very strong ionospheric plasma modifications at the equator have been linked to planetary wave activity identified by stratospheric temperature enhancements at the poles. The variability in these ionospheric parameters is significant, comparable to that which occurs during major geomagnetic storms. The linkage between these phenomena — which occur at different altitudes, latitudes, and times — is believed to arise from an interaction between planetary waves in the lower atmosphere and atmospheric tides.

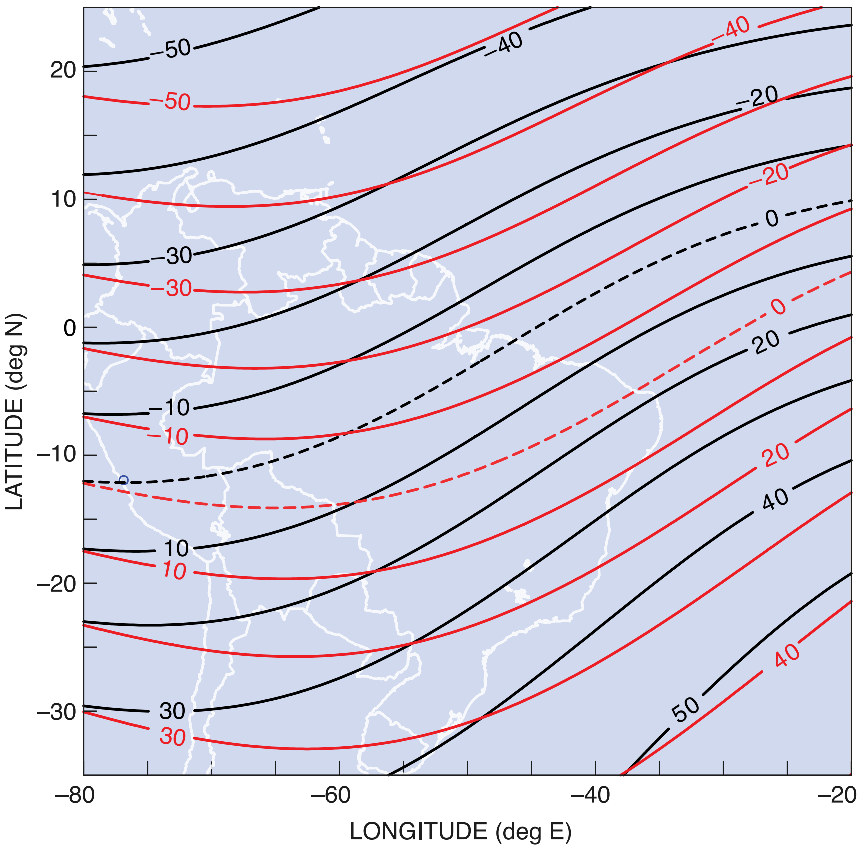
This example of large-scale and long-distance upper atmospheric coupling was, until recently, very difficult to detect and demonstrates the need for new observational methodologies that would enable similar relations to be identified and investigated. CEDAR infrastructure, in conjunction with those of other disciplines studying the Sun-Earth system, will form the observational network needed to resolve the coupling processes at work throughout the SAIR. Indeed it is very probable that initial findings already indicate how observational networks should be configured.

Comprehensive observational campaigns, providing much needed multi-scale and multi-parameter data, will be a challenge for the CEDAR modeling community to simulate/predict and to account for all of the coupling processes in the SAIR, which at this time are far from being integrated.

2.4 Space-Atmosphere Evolution

In addition to the space-atmosphere interaction region's response to sporadic and periodic changes in external fluxes, boundary conditions, or internal coupling processes, the SAIR also exhibits secular evolution of its mean state. Such long-term evolutionary change in the SAIR "climate" may in turn alter its short-term variability or multi-scale response. Furthermore, space-atmosphere evolution must be fully understood in order to assess and address society's needs in areas such as climate disruption, climate change, and geoengineering.

Long-term changes in the SAIR are influenced by trends in geophysical parameters, not only at meteorological altitudes



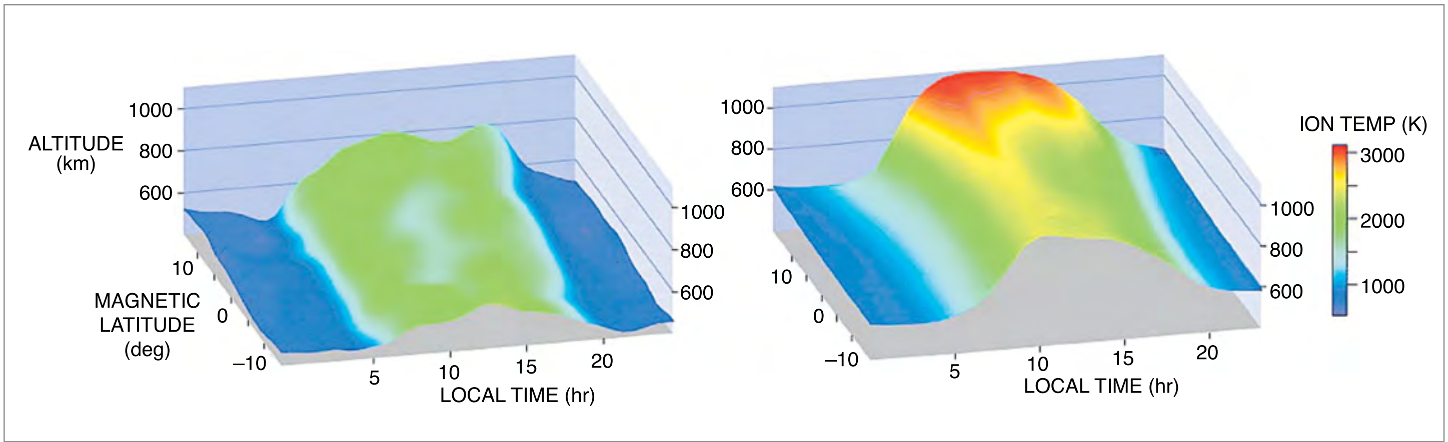
Magnetic Field Evolution: Contrasting 2010 and 1960 epochs of magnetic field dip angle at low latitudes. Dashed lines represent the magnetic equator. Contours drawn in black (red) represent the Earth's magnetic field in 2010 (1960).

(climate change), but at all levels from the space environment to the deep core of the Earth. For example, the Earth's magnetic poles are known to reverse on geological timescales, involving a slow variation in the relative strength of the field and its direction. Such long-term changes are ongoing even now, as demonstrated by the many-degree change in magnetic field dip angle over the equator during the past 40 years (see figure above).

Long-term variability of the sun manifests as gradual changes in solar activity, solar wind pressure, and extreme ultraviolet (EUV) radiation production. The latest solar minimum from late 2007 to mid-2009 marks the lowest EUV production and longest duration in the past four solar cycles, producing unprecedented cold temperatures in the ionosphere and a significantly compressed thermosphere. Such extreme values of SAIR state parameters are not captured by contemporary models such as the International Reference Ionosphere (IRI), which is based on the accumulated knowledge of ionospheric conditions spanning multiple solar cycles and thus embodies our knowledge of typical ionospheric behavior (see figure at right).

Observations of the distribution of ions indicate that the dynamics of the ionosphere have also changed, in poorly understood ways, in response to such low solar activity. Furthermore, the compression of the neutral thermosphere has led to a more sensitive response of thermospheric density to geomagnetic activity, as well as to planetary and tidal wave propagation from the lower atmosphere. This period of extreme solar minimum was accompanied by a weaker than normal interplanetary magnetic field, cosmic rays at record high levels, high tilt angle of the solar dipole magnetic field, and low solar wind pressure. All of these solar surface, solar wind, and interplanetary parameters comprise a change in the space climate and play an integral role in secular evolution of the SAIR.

The natural laboratory represented by the SAIR allows us to extract quantitative measures of the effects of anthropogenic influences on Earth's climate. In 1989, Roble and Dickinson predicted that one consequence of increasing CO_2 levels would be a decrease in the temperature of the upper atmosphere, which in turn causes a decrease in density at constant altitude. Studies of density changes, via observations of the effect of atmospheric drag on satellite orbits, have revealed that thermospheric density is, in



Solar Minimum Ionosphere: C/NOFS satellite-observed ion temperature (left)compared to expected conditions based on the International Reference Ionosphere (IRI) model (right).

fact, systematically decreasing by several percent per decade in this region.

Anthropogenic global change due to increases in CH_4 emissions can increase atomic hydrogen and thus H_2O concentration near the mesopause, potentially altering polar mesospheric cloud production and associated radiative energy balance. Planetary and gravity wave activity is also expected to increase, churning up the SAIR and leading to increased variability and uncertainty regarding how the SAIR will behave in the presence of more vigorous wave activity.

Understanding the full scope of global change throughout the upper atmosphere — and the interplay with space climate — is important to obtain a complete physical description of aeronomic processes, as well as to support satellite operations and to mitigate space debris hazards. With improved understanding, the CEDAR community will be able to quantify the susceptibility of the system to new, or changed, influences, including those related to anthropogenic activities.

The unraveling of long-term trends presents challenges because of the interplay with shorter time scale phenomena, which themselves are poorly understood. Present-day data analysis techniques to detrend the shorter-term processes are crude, and much work is needed to improve upon them.

Efforts to resolve long-term evolution from short-term variability will require continued investment in the acquisition and analysis of long-term data sets, the further development of physics-based models, continued refinements in statistical modeling, better knowledge of connections with solar and Earth processes, and the application of these resources for effective prediction and forecasting.

These are long term goals, and CEDAR must adjust its priorities and funding mechanisms in order to appropriately invest in such fundamentally important projects.

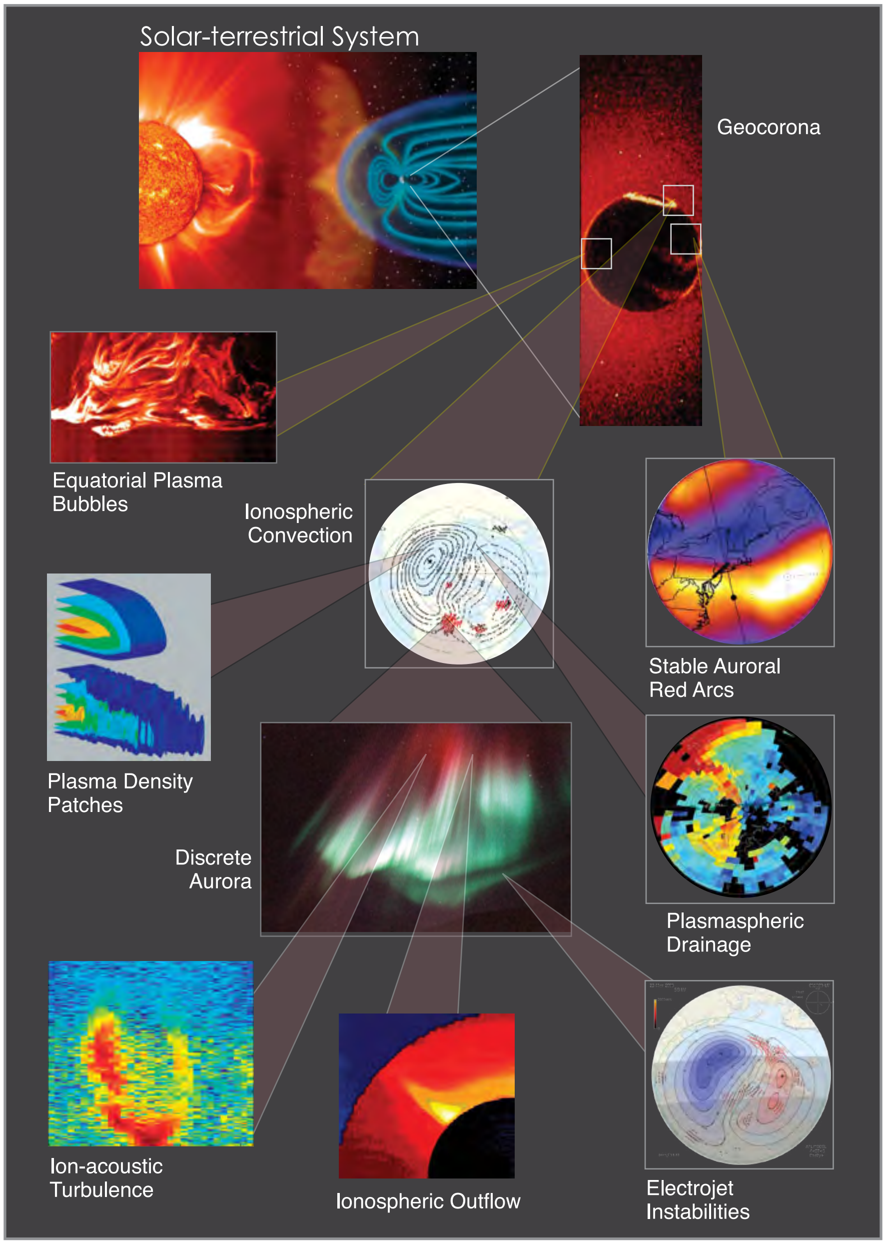

Neutral wind
E-fields
Particles
Thermosphere
energy
balance
Wave heating
Plasma
waves

3 The Systems Perspective

The systems approach transcends the concept of scale, enabling the characteristics of a complex system to be generally applied to many problems in the Sun-Earth system.

Enormous strides have been made in recent decades by the CEDAR community in understanding the coupling, energetic, and dynamical processes occurring within the upper atmosphere. These advances have been facilitated by major improvements in instrumentation and measurement techniques, experimental facilities, and observing networks — which are starting to provide unprecedented volumes of data on processes operating across the system. Together with concurrent progress in computational techniques, these advances have enabled the development of ever more sophisticated, multi-dimensional geospace models, which offer the promise of greater physical insights and improved ability to forecast disruptive events and their potential impacts.

A major challenge for the future of CEDAR science is to develop an integrated, multi-scale vision of how geospace works and how it contributes to the broader Sun-Earth system. Another challenge is to understand the dynamic (highly time varying) and potentially unstable response of the system to its drivers. Space weather is a prime example of this kind of phenomenology. A systems theoretical approach to



Systems within Systems: The Sun-Earth system and the embedded systems within the ITM.

understanding the SAIR can bridge these different challenges and provide a structure and focus to evolve our understanding.

Systems theory has the goal of understanding the behavior of a large number of mutually interacting and interrelated components. In general, a system is defined as a mapping between drivers (input) and resulting states (output); for example, the relationship between solar extreme ultraviolet flux and ionospheric density. The problem of system identification, CEDAR's traditional focus, is one of determining the physical processes responsible for the observed system response. If the initial state is known (controlled conditions) and the drivers are measured, characterizing the system (the physics) is tantamount to the scientific method.

Systems can be interconnected and embedded within larger systems, as the ITM is embedded within the Sun-Earth system. The intellectual framework of the systems view enables transferable concepts across individual systems, scales, and disciplines to advance and facilitate progress in understanding many distinct aspects of the whole system. In fact, one of the utilities of the system approach is that it transcends the concept of scale enabling the characteristics of a complex system to be generally applied to many problems in the Sun-Earth system.

For example, the study of the aurora may focus on the excitation mechanisms responsible for generating the emission, or on the closure of electric currents in the magnetosphere and ionosphere system. A systems science approach treats these distinct aspects of aurora in a common way, focusing on the identification of the system inputs (such as precipitating electron energy spectra or electric potential differences), the definition or measurement of the system (such as emission excitation rates or energy dissipation rates), and the observation or prediction of the system response (such as auroral brightness or field-aligned current strength).

A systems approach is not a radical departure from historic CEDAR methodology. Rather, this approach provides an explicit focus on the manner in which interdependent and variable processes within the SAIR, and between the SAIR and other regions, combine to produce global conditions. By its nature, this focus moves us away from correlations and snapshots, and towards patterns of change, interrelationships, and complexity.

Systems science and the large volume of data often required demand advanced observing capabilities and computer technologies. Meanwhile, systems science considerations can help establish optimal technological and infrastructure capabilities by identifying specific functionality required to fill existing gaps in understanding. The adoption and implementation of a systems science approach to CEDAR research is more realizable today with the rapid expansion of multi-dimensional databases, increasing computational capabilities and sophistication of numerical tools, and the emergence of new sensor technologies. By locating instruments strategically to measure key inputs and outputs throughout the entire geospace system, integration of multi-modal data with state-of-the-art theoretical understanding will enable predictions of the state of the complex Sun-Earth system with unprecedented spatiotemporal scales.

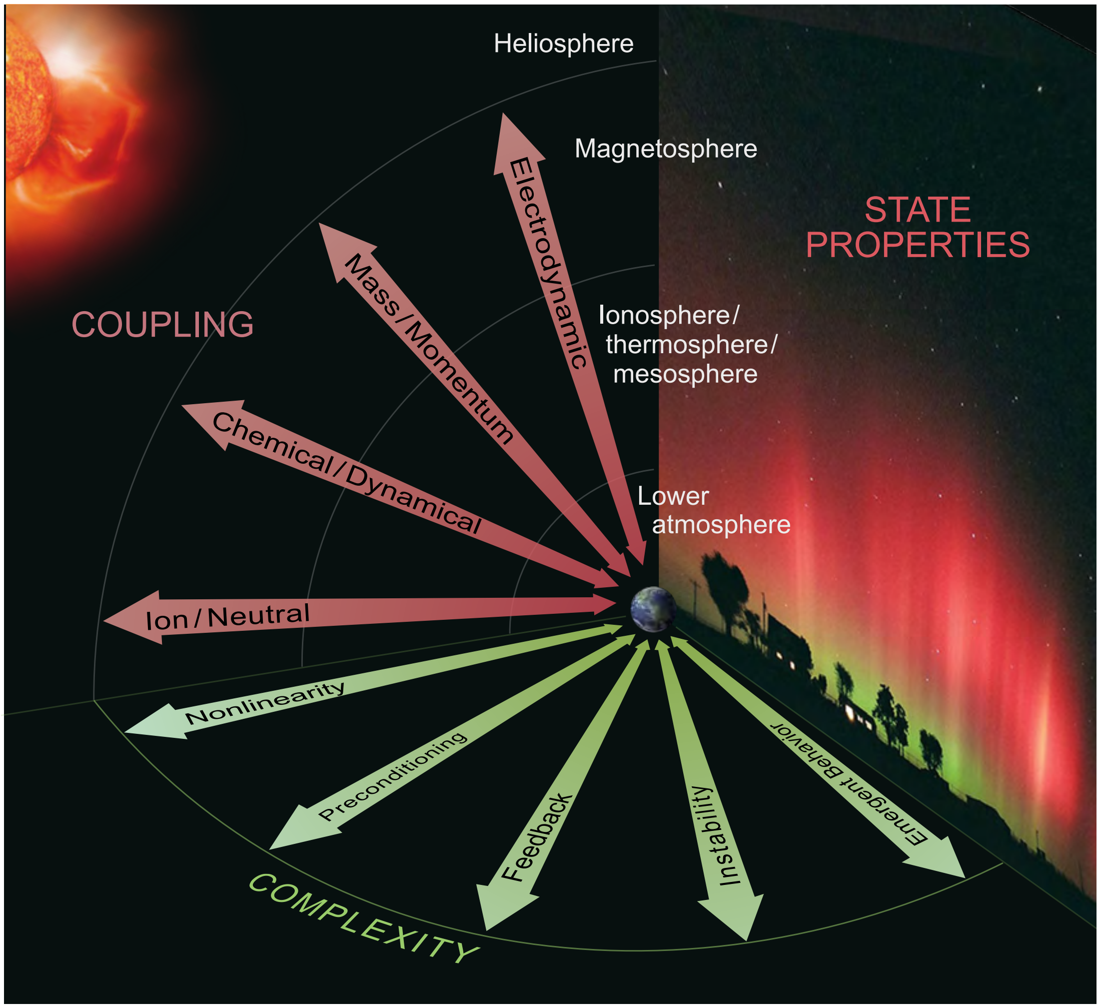
As an added benefit, a systems science approach can facilitate interaction and collaboration between various members of the geosciences community and provide fertile ground for innovative ideas. Thus, *CEDAR: The New Dimension* must be implemented in coordination with plans for more extensive observing networks, modeling efforts, and interdisciplinary collaborations that together will yield exciting new scientific results.

3.1 Complexity

As described in Section 2, the ionosphere, thermosphere, and mesosphere (ITM), along with the exosphere and plasmasphere, broadly define the regional components of the SAIR. These components are themselves systems, which are interconnected and embedded within the Sun-Earth system. Current understanding of the SAIR as a system that exhibits complexity —characterized by multiple drivers, adaptive feedback and memory, nonlinear response and instabilities, and sensitivity to initial conditions — emerges from a solid background of CEDAR research.

In general, system complexity is comprised of many interacting elements, which influence one another through nonlinear, dynamical pathways. Observations and modeling of the SAIR have revealed the presence of electrodynamic, mass/momentum, plasma-neutral, and chemical-dynamical coupling on multiple temporal and spatial scales between atmospheric layers, latitude zones, constituents, and flow regimes. What has emerged from this research is the recognition that many of these coupling processes exhibit complexity.

Complexity as a new dimension in the CEDAR domain: The state properties represent observables and are the manifestation of coupling and complexity by the entire interconnected system, with complexity adding a new dimension to CEDAR research through nonlinearity, preconditioning, feedback, instability, and emergent behavior.



For example, a particular disturbance or instability can trigger multiple nonlinear feedbacks among system components, which can amplify, attenuate, or even change the nature of the expected response. The resulting behavior depends on the initial state of the SAIR and its dynamical history (which includes preconditioning of system components and system memory). As such a system responds to forcing, unexpected behavior can emerge as a consequence of complexity of the interconnected system itself rather than from the individual system components or a single coupling process. As a result, analyzing a system that exhibits complexity in terms of a linear superposition of its individual components, without regard to initial conditions or dynamical history, is insufficient to advance an understanding of how the system behaves and responds. Instead, clear cause and effect can be understood only when these effects are accounted for in an integrated way.

Focusing on the interaction among physical coupling processes builds upon past and continuing research on individual components and processes initiated by CEDAR. But such focus also pushes us toward global questions and new ways of viewing problems, which provides fertile ground for innovation and clarifies gaps in our current knowledge.

COMPLEXITY EXAMPLES

CEDAR: The New Dimension focuses on complexity within the SAIR as a transformative step toward predicting the geospace state accurately and reliably, and toward understanding the SAIR's interconnections to other parts of the Sun-Earth system. Exciting results from the CEDAR program are described below, and provide tantalizing glimpses of five phenomena that illustrate complexity within the SAIR. These, and other examples not described here, provide a rich resource for illustrating and guiding the New Dimension phase of CEDAR.

COMPLEXITY EXAMPLE

Initial Conditions, Preconditioning, and Memory

The initial conditions (inputs) of a system must be specified in order to predict its state at future times. If certain states can only be reached with the correct choice of initial conditions, then the set of initial conditions that permit that state define the system's precondition. Systems for which the present input is derived from previous outputs are said to have memory. A particularly complicated situation arises when preconditioning can only be satisfied by systems with a particular history.

Preconditioning and memory appear to be necessary for a number of important phenomena in upper atmospheric physics. For example, the neutral atmosphere and ionosphere respond strongly to both magnetospheric energy sources and solar EUV enhancements, with responses ranging over wide temporal and spatial scales. Moreover, the neutral gas preserves the recent history of energy inputs and stores that energy in neural inertia to be released at a later time and place. Periodic or impulsive energy inputs embedded within longer active time periods may cause different dynamics within the system to emerge, such that the thermospheric and ionospheric response to the second or third substorm in a series of substorms may be quite different than the response to the first. If a system has memory and requires preconditioning, the definition of the initial time becomes very important. As a result, observations, theories, and models of the system must include time scales that span the complete memory of the system.

COMPLEXITY EXAMPLE

Nonlinearity

Many of the component regions of the SAIR exhibit nonlinear behavior, which is to say that their response to multiple inputs is not, in general, the superposition of the responses to the inputs taken separately. Crucially, the outcomes of nonlinear systems are not independent but are instead coupled. In the SAIR, nonlinearity provides a mechanism for transporting energy, mass, and momentum across spatial scales.

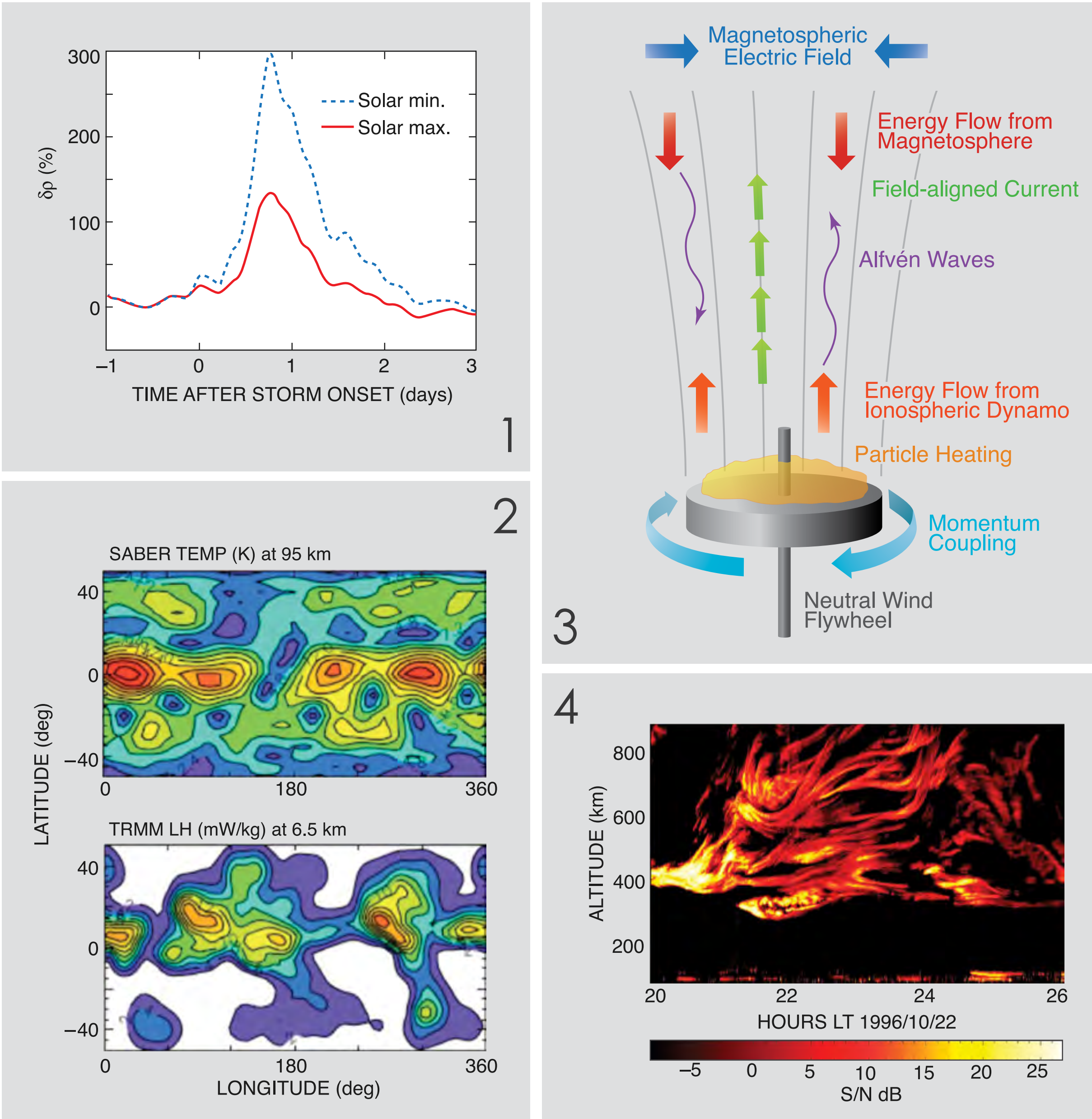
Atmospheric waves — such as tides, planetary, and gravity waves — are an example of nonlinear dynamical phenomena in the SAIR. The frontier in our understanding of waves and tides in the upper atmosphere lies not in the linear theory of these waves, but in the quantification of wave amplitudes and variability produced by nonlinear interactions between individual wave modes or between waves and the mean state of the ITM. In turbulent regions, energy can be cascaded from larger to smaller scales, where it is readily dissipated, or sometimes from smaller to larger scales, where it can accumulate in reservoirs. Wave mode coupling can also behave like scattering phenomena, transporting energy and other quantities between widely separated regions via circuitous pathways.

COMPLEXITY EXAMPLE

Feedback

If an output from an event in the past influences the occurrence of an event in the present or future, there is feedback in the system. Systems with feedback often exhibit complex behaviors that would be difficult to diagnose and understand outside of a systems science approach.

The upper atmosphere inherently is a multi-variable system, with properties experiencing a wide range of



1 **Preconditioning:** Thermosphere density change differs by 200% at 400 km altitude for the same geomagnetic energy input but preconditioned with solar maximum and solar minimum EUV fluxes.

2 **Nonlinearity:** Latitude-longitude distributions of the diurnal component of (top) latent heating rate at 6.5 km altitude derived from TRMM satellite data and (bottom) the corresponding measured diurnal temperature amplitudes at 95 km derived from TIMED/SABER temperature measurements. Differences between these two latitude-longitude structures are due to vertical evolution of the tidal wave spectrum as a result of wave-mean flow and wave-wave non-linear interactions, and differential dissipation within the wave spectrum.

3 **Feedback:** Neutral motions driven by past forcing feedback electrodynamically on present electrical connections by driving dynamo fields.

4 **Instability:** Equatorial plasma instability forms spontaneously and regularly at low magnetic latitudes. The underlying free energy is gravitational. A broad spectrum of plasma irregularities is produced spanning scale sizes from tens of cm to hundreds of km. Energy is coupled from the large-scale irregularities, which serve as a persistent reservoir, to small-scales, where dissipation is most efficient.

temporal and spatial responses. Consequently the role of feedback in the system can occur via many physical processes. One example is the behavior of currents in the ionosphere. The net current depends on the electron density, electric field, neutral density, and neutral wind. Each of these state properties can have a different response to a past input leading to an alteration of the current configuration.

The neutral wind is particular challenging because of its long memory of past forcing due to its inertia. Thermospheric winds can be modified by interactions with electric currents. However, if the neutral wind is also responding to past forcing from other sources, it can modify the electric current configuration and strength with consequences felt throughout the geospace system. The modified currents then feed back on the neutral winds to create a complicated feedback loop. Feedback is also very common in chemical and dynamical interactions that occur throughout the ITM.

COMPLEXITY EXAMPLE

Instability

One characteristic property of a complex system like the SAIR is nonlinearity that leads to instability, a condition where one or more of the system parameters exhibit growth without bound. Most interesting is what happens when free energy accumulates and is then abruptly released in various upper-atmospheric and ionospheric instabilities.

Neutral and plasma instabilities are common in geospace, where they complicate data analysis, interpretation, and modeling considerably. Instability effects are often parameterized where they cannot be treated using first principles theory or modeling. Reducing reliance on parameterization is a goal of CEDAR science if complete system identification is to be achieved.

COMPLEXITY EXAMPLE

Emergent Behavior

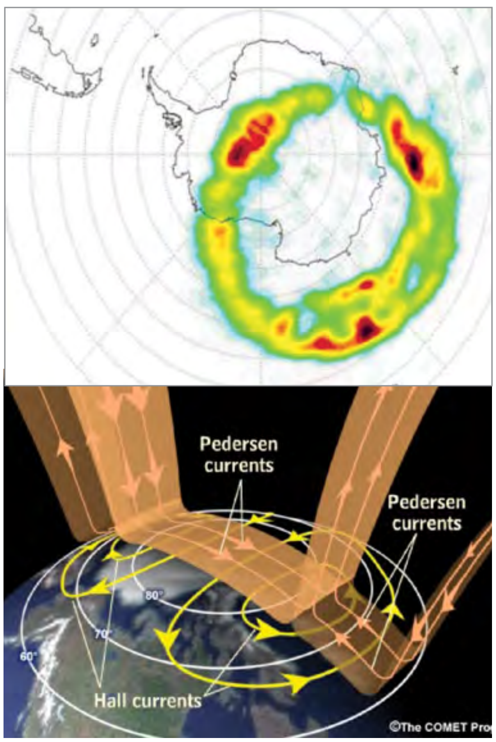
Perhaps the most interesting characteristic of complex systems is the emergence of new features resulting from the interaction of a large number of system components — where such emergence could not have been anticipated based on properties of components acting individually. Although it is yet unclear which features in geospace represent emergence, there are some strong candidates. These include ionospheric super-fountains, great red auroras, storm enhanced densities, and increased NOx transport into the stratosphere during sudden temperature enhancements. Each of these phenomena is a signature of strong coupling between the upper atmosphere and other regions in geospace or the lower atmosphere.

For example, super-fountain and storm enhanced densities have their source in high-latitude penetrating electric fields, and thus are tied to the physical processes that produce electric shielding in the inner magnetosphere. The shielding, in turn, is modified by ionospheric conductivity gradients. Only during extreme events do these penetrating electric fields achieve magnitudes necessary to lift the ionosphere to high altitudes before shielding can be reestablished, resulting in deep, spatially extended depletions of the equatorial ionosphere seen at no other time.

Progress in understanding each of these phenomena and, more importantly, in understanding what their appearance implies about coupling and complexity in geospace requires an integrative approach that takes into account the dynamically evolving interaction between regions.

3.2 Cross-Scale Coupling

The SAIR inherently is a multi-scale system, with energy, mass, and momentum inputs occurring over a wide range of scales. For example, while auroral arcs occur over size scales of less than 10 km, the size of the auroral oval is typically about 5,000 km (almost three orders of magnitude larger) and dayside heating by solar EUV photons spans 40,000 km. These different scales of energy generate highly structured ionospheric conductivity and electric fields that create a tremendous challenge in CEDAR research to observe, estimate, and predict.



Scale (top): The auroral oval depicts a large range of spatial as well as temporal scales.

Energy (bottom): Currents closing in the ionosphere can exhibit significant variability in time and space, altering the amount of energy deposited in the ITM.

One consequence of such multi-scale structuring at high latitudes is the notorious problem of “missing energy” in numerical models, whereby global circulation models required increases in Joule heating (a form of friction) by factors of 2 to 3 in order to adequately reproduce observations of the global wind field and neutral temperature structure. Using the accepted statistical patterns of particle precipitation and plasma convection as model inputs, it was possible to reproduce either the temperatures or the winds, but not both at the same time. It became apparent that there was a need to increase the temperature (through Joule heating) without increasing the winds (through momentum transfer between ions and neutrals) — a puzzling requirement, since increasing either the average electric field or particle precipitation (input) increased both temperature and winds (output).

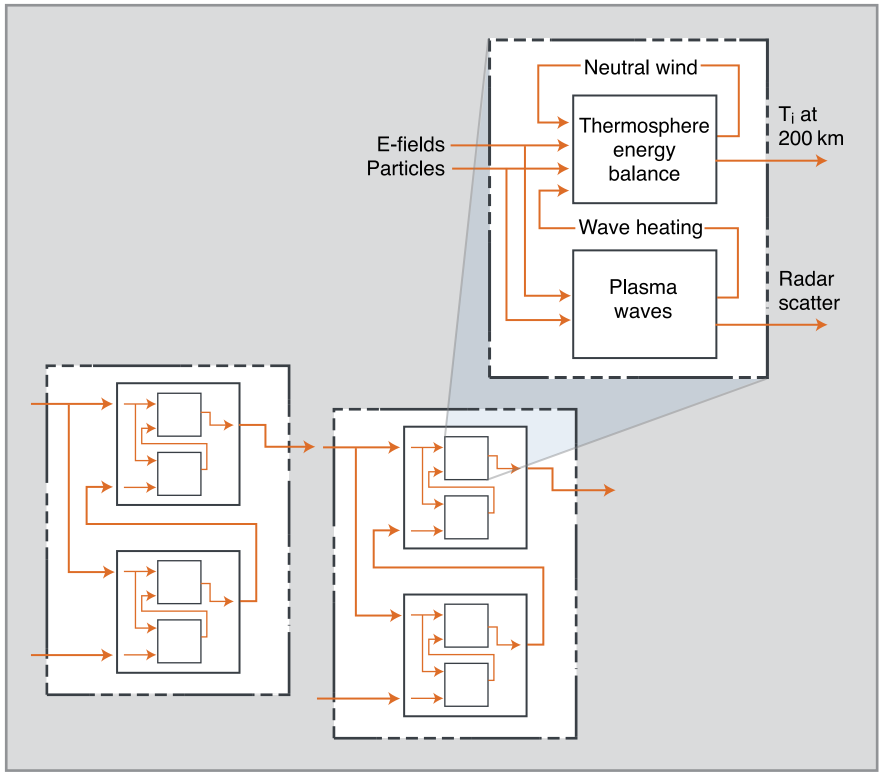
Small-scale variability in the high-latitude ion convection has been proposed as a way to solve the missing energy puzzle. Electric field variability can increase the Joule heating without increasing the neutral winds. Numerous studies have investigated and supported the importance of small-scale electric field variability in the calculation of the global energy budget of the thermosphere. It turns out that small-scale electric field variability can contribute up to 50% of the total Joule heating. Thus, sub-grid structure in energy input can lead to global-scale response of the ITM through cross-scale coupling.

Conversely, CEDAR observations, models, and analysis techniques are being used to unravel the ITM influences on the three-dimensional dynamics of the geospace system, from the smallest scales (e.g., decameter-scale structure in the aurora), to the largest scales (ion and neutral outflow to space) using the concepts inherent in cross-scale coupling.

A “Cybernetic” Example

Cybernetics is the interdisciplinary study of the structure of a system that is regulated by the system characteristics. Cybernetics provides a useful framework for investigating complexity in the SAIR.

As an example, magnetospheric electric field mapping and energetic particles precipitating into the polar thermosphere strongly drive the state of the ITM system. The output of interest is the thermosphere neutral temperature. There is a known direct connection of thermosphere heating by particles and electric fields through collisions with the neutral gas. However, the state of the ITM as it responds to these



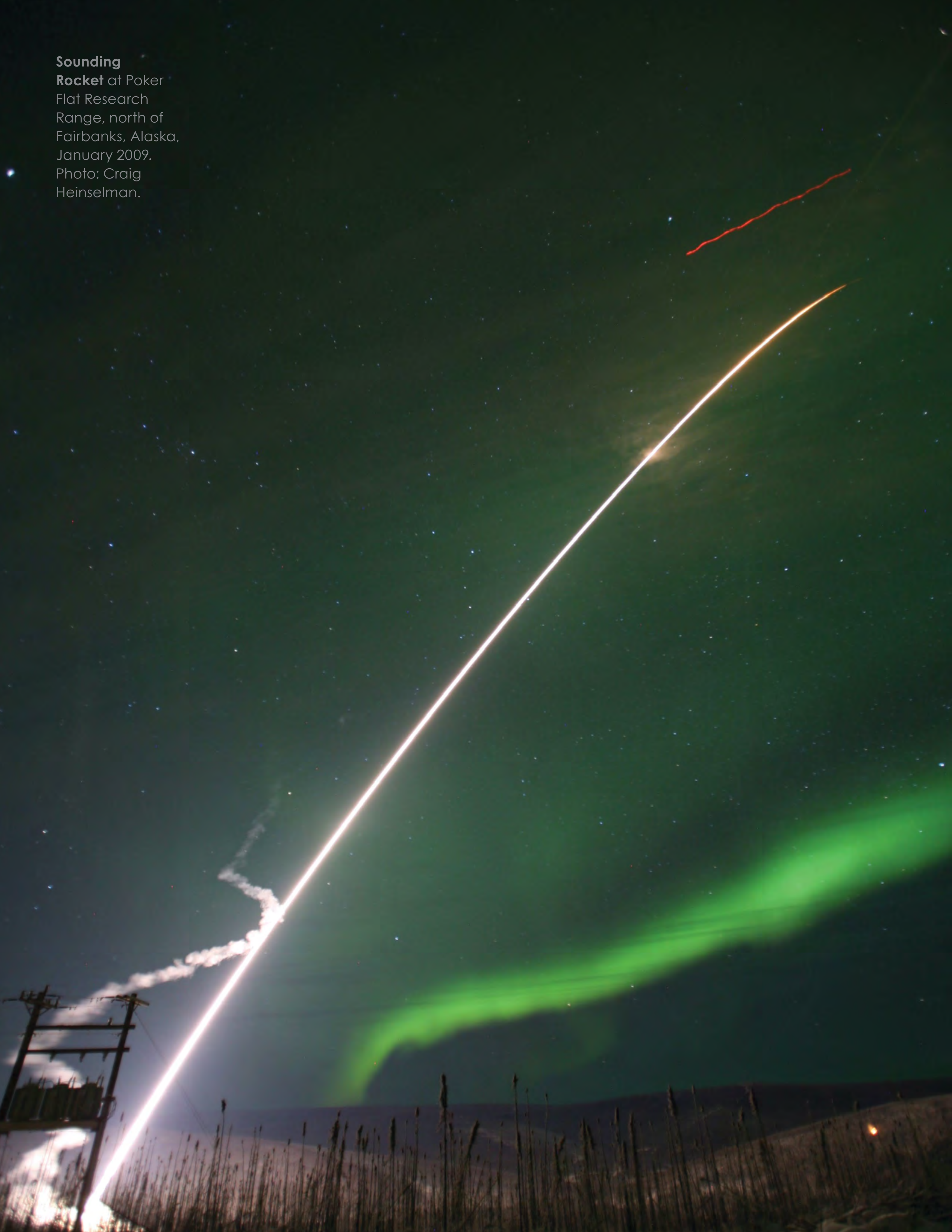
inputs depends on properties and behavior of the larger geospace system. The precipitating particles not only heat but also ionize the thermosphere, altering the conductivity of the ionosphere and the electrical coupling with the magnetosphere leading to a modification of the source electric fields and energetic particles. This feedback changes the inputs and consequently the thermosphere temperature observed as an output of the system. Furthermore, nonlinearity is introduced through chemical processes in the thermosphere/ionosphere. Particle precipitation leads to the production of NO, which acts as a radiator and a dominant cooling mechanism for the thermosphere.

As noted earlier, a system's prior state may also have an influence on its present state, which is to say that the system exhibits hysteresis or memory. Thermosphere gas motion can alter the Joule heating of the gas. The massive inertia of the neutral gas retains memory of past forcing and can alter the present response of the system. As mentioned above, the highly structured and temporally varying nature of Joule heating in the polar regions challenges the resolution of the most sophisticated models and observations, and leads to a global-scale change in thermosphere temperature, demonstrating cross-scale coupling. Moreover, the input electric fields can drive instabilities in the lower ionosphere that produce plasma wave heating of the electrons. This temperature change in the electron gas can further alter the chemical interactions occurring between the plasma and neutral gas and impact the thermosphere gas energy budget. Finally the thermospheric temperature change can enhance heavy ion outflow to the magnetosphere, which can lead to the saturation of solar wind driving in the ionosphere through the magnetospheric response to the mass loading by these heavy ions ejected from the ionosphere.

This subsystem example is considered complex, not because it is difficult, but because it represents a highly dynamic, nonlinear, and potentially unstable system. Traditionally this complexity has been treated as something to be overcome by looking at the problem in different ways or by breaking system into its constituent processes.

However, experience in CEDAR has taught us that the breakthroughs needed to transform our understanding of the global geospace system will require studies focused on complexity itself. And this complex system is but one part of a larger complex system that includes the sun, interplanetary space, magnetosphere, ionosphere, thermosphere, mesosphere, and the lower atmosphere and the processes that couple them.

Cybernetic Example: Systems within systems prevail in the SAIR. Each system's complexity is coupled to others over various scales and results in a response that can only be determined through an integrated system analysis.



Sounding Rocket at Poker Flat Research Range, north of Fairbanks, Alaska, January 2009. Photo: Craig Heinselman.

4 The Way Forward

The 21st century approach to understanding the Sun-Earth system is to explore new avenues of progress, building on past decades of accomplishments.

While technological advances have always been instrumental in scientific discovery, the extraordinary pace of recent ground-based and satellite observing methods, data processing and assimilation, and computer simulation capabilities have propelled virtually all aspects of space physics beyond classic discovery mode science in a remarkably short time. Discovery itself has taken on a new meaning in the field, one that includes the identification of hidden linkages necessary for understanding complex systems driven by internally and externally coupled components. It is this aspect of CEDAR science that needs development and direction to open new avenues for discovery.

CEDAR: The New Dimension promotes this activity by being proactive in developing a systems perspective to study the SAIR. To motivate action for this plan, a number of strategic thrusts are identified as guidance and impetus for the community in the coming decade. This directive does not abandon time-tested CEDAR approaches involving observations, theory, and modeling to acquire detailed understanding of the components of the larger system. The strategic thrusts described here must be pursued in parallel with traditional scientific approaches. The enabling technologies discussed in this document have not only made it possible to undertake such a two-pronged approach; they have also made it scientifically rewarding and fruitful.

Twenty-fifth anniversary CEDAR meeting, 2010. Photo: Douglas Geiger.

1 STRATEGIC THRUST Encourage and Undertake a Systems Perspective of Geospace

Mission: To understand global connectivities and causal relationships involving the SAIR and to determine their influences on the interaction region and the whole Earth system. The ultimate goal is to contribute to a holistic model of the Earth system that includes all interacting components — from the Earth's core to geospace. This effort is aimed at predicting future conditions with the accuracy and reliability needed to explore methodologies for continued human wellbeing and sustainable technological development of our planet.

Focus: As described in earlier sections, the SAIR exhibits the characteristic behavior of a coupled and complex system. A wide variety of coupling and complexity mechanisms are present that determine the state of the ITM and significantly influence other geospace regions. The majority of these mechanisms have their basis in neutral-ion interactions, wave-mean interactions, and electrodynamic, chemical and dynamical processes. It is impossible, for example, to understand the detailed development of a geomagnetic storm without understanding mass and momentum flows between the ionosphere and the magnetosphere, as well as changes in magnetospheric electric fields and currents that result from dynamic variations in ionospheric conductivity. All of these processes (and even their component parts) have different relationships to solar driving, occur across a wide range of spatial and temporal scales, and combine in ways that we do not yet understand to produce a global geospace system response. CEDAR has taught us that major uncertainties hinder progress in this area. For example, the global pattern of neutral winds, central to understanding processes involving ion-neutral coupling, is known only in an average sense. This climatological characterization is insufficient to address the dynamically evolving linkages that produce ionospheric storm fronts, create ionospheric depletions, structure neutral and ion outflows, and produce a range of ionospheric instabilities that interrupt communication systems. It is also insufficient to investigate vertical transport processes, such as the draw of aurorally produced nitric oxide down into the stratosphere through the polar vortex to destroy ozone. Despite the major role electrodynamic interactions play in linking the SAIR to the magnetosphere and lower atmosphere, the self-consistent patterns of field-aligned currents, precipitation, ionospheric conductivity, polarization electric fields, jets and sprites have never been adequately integrated to describe the electrical system of Earth.

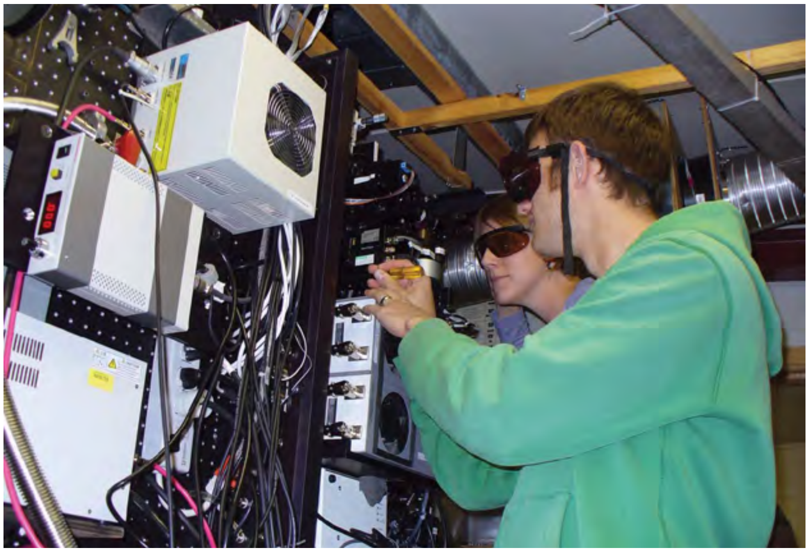
CEDAR's New Dimension Program will set priorities and design a strategy aimed at transforming our understanding of the SAIR and its influence on the whole Earth system using the intellectual framework of system science. This represents a paradigm shift in how the Sun-Earth science community must advance in order to solve future problems.

Such a program requires innovative new instrumentation focused on long-standing unknowns, and the development of next-generation global models aimed at representing the major coupling and complexity processes that determine the state of the SAIR — exploring its predictability and investigating mechanisms for self-consistently including sub-grid scale phenomena that influence the global system response.

Implementation:

- Investigate the applicability of formal systems-theoretical methodologies to better understand complexity in the SAIR
- Explore system characteristics of the space-atmosphere interaction region in terms of nonlinearities, preconditioning and memory, feedback, instabilities, emergent behavior, and cross-scale coupling
- Augment the review criteria for the annual CEDAR proposal competition to include consideration of systems science formulation, and encourage organizers of the Annual CEDAR Workshop to highlight research that emphasizes a system science approach or view

Training and education of students along with researchers is an integral part of CEDAR success.



2 STRATEGIC THRUST
Explore Exchange Processes at Boundaries and Transitions in Geospace

Mission: To understand the transformation and exchange of mass, momentum, and energy at transitions within the ITM and through boundaries that connect with the lower atmosphere and the magnetosphere. Studying these transitions and boundaries in terms of physical processes enables new knowledge about the nature of space-atmosphere interaction regions applicable to Earth and other planetary bodies.

Focus: This scientific thrust focuses on how components of a complex system communicate through mass, momentum, and energy exchange across intervening boundaries and transform within the ITM. The components may be spatially distinct (such as the thermosphere and mesosphere) or overlapping in space but dominated by different processes (such as the ionosphere and thermosphere). Interactions among components is a common feature of complex systems; thus new knowledge in this area is applicable to a wide range of planetary, solar system, exoplanetary, and cosmic environments where neutral gases interact with plasmas.

The SAIR contains a variety of unique interactions between neutrals and plasmas. These interactions mediate the flux of harmful energetic solar photons, solar wind plasmas, and high energy solar particles and dissipate the energy by electromagnetic interactions with the neutral gas. Equally, SAIR interactions can amplify influences from the lower atmosphere. The boundaries between the SAIR and the rest of the Sun-Earth system regulate energy, mass, and momentum exchange. Identification and quantification of flux transport across boundaries is an essential element to this thrust.

Implementation:

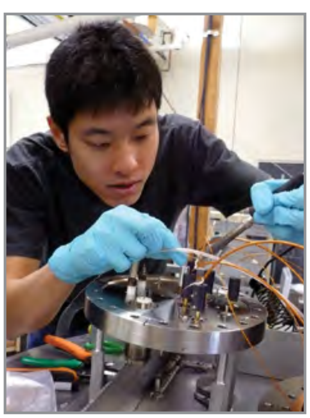
- Characterize sources and sinks, internally and externally to the SAIR and their possible variations due to the coupling and complexity of the Sun-Earth system
- Advance theories and coupled models that account for processes at transitions and across boundaries
- Develop computational resources, techniques, and analyses enabling predictive capabilities that incorporate boundary and transitional effects

3 STRATEGIC THRUST
Explore Processes Related to Geospace Evolution

Mission: To understand and predict evolutionary change in the geospace system and the implications for Earth and other planetary systems.

Focus: Earth's climate is changing, not only at meteorological altitudes, but at all levels from the magnetospheric boundary to the deep core of the Earth. The overall behavior and future evolution of the geospace system results from the integration of changes across all regions, and from the interactions among those regions. Historically, the various geospace regions have

Students' energy and enthusiasm trail blaze the future for small satellites.



been studied by different communities, using different techniques, and often driven by different motivations. There has been little perceived need, or apparent relevance, in accounting for variations occurring in adjacent regions. The CEDAR community has been, and remains, spectacularly successful in addressing issues within its own region of study, but has made only minor inroads in addressing cross-region coupling and energy flows with neighboring systems of the lower, denser atmosphere and the plasma-dominated magnetosphere.

The understanding of SAIR evolution will be important in applying this knowledge to other planetary systems. Thus, this strategic thrust also embodies planetary aeronomy and the evolutionary processes that can be important in a planet's habitable development. CEDAR science is closely related to the broad field of planetary aeronomy. Comparative planetary aeronomy remains a fertile research path to the development and validation of dynamic and chemical models, through applications to similar systems with characteristically different forcing and composition. Our understanding of atmospheric evolution is couched in the knowledge of the evolutionary paths taken by our nearest terrestrial neighbors.

Implementation:

- Conduct studies to identify and isolate observables that most significantly reflect and influence long-term changes in geospace conditions
- Ensure calibration and validation of relevant observations for reliable identification of long-term trends
- Develop funding and observing models to maintain and improve long-term databases that have become the hallmark of CEDAR science for many years
- Conduct studies of comparative planetary aeronomy to advance physical understanding of atmospheric evolution

4 STRATEGIC THRUST Develop Observational and Instrumentation Strategies for Geospace System Studies

Mission: To develop instruments capable of measuring system properties necessary to examine the coupling mechanisms and complexity within the SAIR. To exploit existing and planned observational assets in order to optimize scientific return.

Focus: Strategic developments and deployments of future scientific instrumentation are critical for advancing CEDAR research and understanding in the field. The multivariate-system nature of our research requires that simultaneous observations spanning the varied aspects and regions of the system are needed to address adequately its complexities and couplings. Carefully coordinated sets of observations from ground-based sensor networks and satellites could drive major breakthroughs in our understanding of the connections and feedbacks between geospace regions. A broad spectrum of radio, optical, in-situ, and remote-sensing techniques is needed to provide the continuous, simultaneous observations dictated by the characteristics and processes of the ITM system.

In the same way that *CEDAR: The New Dimension* incorporates the resources of the diverse CEDAR research community to address system-level issues, the approach requires the proper incorporation of the growing number of separate instrument arrays (ISRs, SuperDARN, HF/MF radars, lidars, magnetometers, imagers, FPIs, GPS and other sensors). The existing and developing infrastructure must also provide observations of our complex, coupled system with the resolution and cadence needed to unravel its complexity. A distributed array of sensors for observing the SAIR is envisioned as an evolutionary initiative, with a larger and more capable future, particularly when combined with advanced data processing and mining techniques, such as innovative search algorithms, image and pattern recognition software, and automated data correlation tools.

Implementation:

- Coordinate multi-platform observational campaigns that take advantage of existing and new instrumentation and facilities
- Conduct studies to determine the optimum type and placement of large observatories or instruments and plan for strategic deployment of future instruments that best serve the needs of the CEDAR community
- Develop smart sensors (e.g., autonomous, reconfigurable, robust, low-power) that optimize measurements in response to changing geophysical conditions
- Pursue the advancement of innovative, space-based sensing platforms including small satellites, suborbital rockets, and large space missions for CEDAR research

5 STRATEGIC THRUST
Fuse the Knowledge Base across Disciplines

Mission: To promote collaborations in related but distinct disciplines of geosciences, mathematics, engineering, and physics to attract a greater variety of researchers and students, thus spawning new ideas and methodologies that will more rapidly advance geospace studies.

Focus: Investigations of SAIR frontiers require collaborations of researchers in multiple CEDAR disciplines contributing a wide variety of data sets, intellect, research techniques, and models all focused on a common science objective. This does not happen by chance but requires organizational structure and carefully selected science topics around which to focus interactions. The phased adoption and evolution of structures that support and enable these interactions will help to revolutionize the way in which collaborative SAIR research is done now and in the future. The systems perspective demands this level of collaboration and embraces national and international activities that can mutually advance understanding of geospace.

The multidisciplinary makeup of CEDAR researchers enables this approach. CEDAR research lies firmly in mathematics, physics, engineering, geosciences, cyberinfrastructure, astronomy, and other distinct disciplines. CEDAR must formulate approaches to be better connected with broader activities and initiate new ones. Training and education of students along with researchers is an integral part of our success.

Implementation:

- Promote broader, interdisciplinary participation at the Annual CEDAR Workshop
- Coordinate with other geospace communities as well as engineering mathematical, and computational science communities to enhance CEDAR research and encourage collaborative pursuit of cross-disciplinary funding opportunities
- Work with the international community and organizations, such as CAWSES, ICESTAR, EISCAT, EGS, AOGS, etc., to formulate strategic approaches that address global issues
- Provide an interdisciplinary educational, research, and technology framework, including curriculum development, that excites, trains, and supports future generations of researchers in the field

6 STRATEGIC THRUST Manage, Mine, and Manipulate Geoscience Data and Models

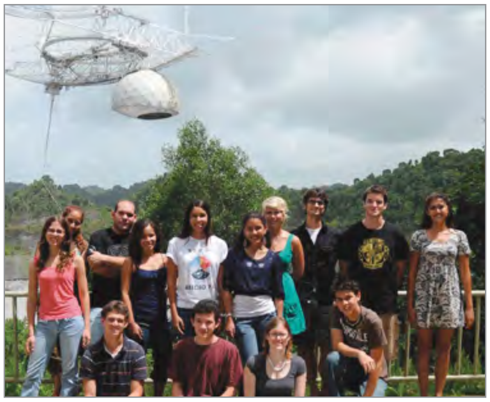
Mission: To tap the vast resources of burgeoning geoscience data to provide a new view of geospace: optimize information for proper deployment locations of key instruments and measurements to further scientific productivity: discover and explain patterns of change, interrelationships, and complexity; and contribute to determining the evolution of geospace by manipulation and evaluation of multiple observables over extended observing periods.

Focus: New data technologies have changed the research landscape of the upper atmosphere. The GPS revolution has opened an entirely new way to investigate ionosphere and middle atmosphere properties. New satellite missions provide data products of Earth science processes that serve as input to models for assimilation and prediction. New whole atmosphere models are under development, trailblazing a path towards predicting the system-level response of the atmosphere including geospace. Data parameterizations in numerical simulation will remain a necessity until models are extended to self-consistently describe their behavior. Data comparisons with models are also inefficient in determining what unknowns may be driving the system. Lastly, data need to be manipulated to provide the necessary observations of complex system behavior.

Implementation:

- Implement standardized data formats and calibration procedures that will facilitate data acquisition and the establishment of accessible and user-friendly databases
- Continue to evolve data assimilation schemes to integrate data with physics-based models for improved predictive capability
- Develop advanced analysis techniques needed for effective fusion of observations into sophisticated inference models
- Develop automated pattern analysis, detection, recognition, tracking, and reconstruction techniques for application to CEDAR data

Unique field experiences help develop the workforce of the future.



Acknowledgements

The development of this CEDAR planning document began during the fall 2007 CEDAR Science Steering Committee (CSSC) meeting. Subsequent CSSC meetings, plenary presentations and workshops at the annual CEDAR meeting, community input sessions and feedback, and a dedicated planning document workshop at the Woods Hole Oceanographic Institute (WHOI) in March, 2010, led to the assemblage of this document. It is important that such a community-wide and grass-roots process take place to insure the document captures the community's view of CEDAR's future. It is also important to acknowledge and thank direct contributors to the document: CSSC committee members from 2007–2011; NSF program managers: Drs. Robert Robinson, Robert Kerr, and Farzad Kamalabadi; The Woods Hole Oceanographic Institute and its director Dr. Susan Avery; and members of the CEDAR WHOI writing committee: Drs. Susan Avery, Anthony van Eyken, John Foster, Dave Hysell, Robert Kerr, Janet Kozyra, Larry Paxton, Aaron Ridley, Joshua Semeter, Jan Sojka, and Jeff Thayer. A special recognition goes to the National Science Foundation's Geospace Section Head, Dr. Richard Behnke, who has provided tireless support and encouragement to the CEDAR program since its inception. Further acknowledgements are to recognize Dr. Lara Waldrop for her extensive help in finalizing the document, and to SRI International who provided the talented Ms. Vicki Moore for illustrations and graphic design.

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Geomagnetic Storm Effects: Anthea Coster, MIT Haystack Observatory

Ionospheric Waves: Michael Nicolls, SRI International

Ionosphere–Atmosphere Coupling: Larisa Goncharenko, MIT Haystack Observatory and New Scientist illustration from Jon Cartwright, Phantom storms: How our weather leaks into space, *New Scientist*, 06 October 2009, p. 44-47.

Magnetic Field Evolution: Dave Hysell, Cornell University

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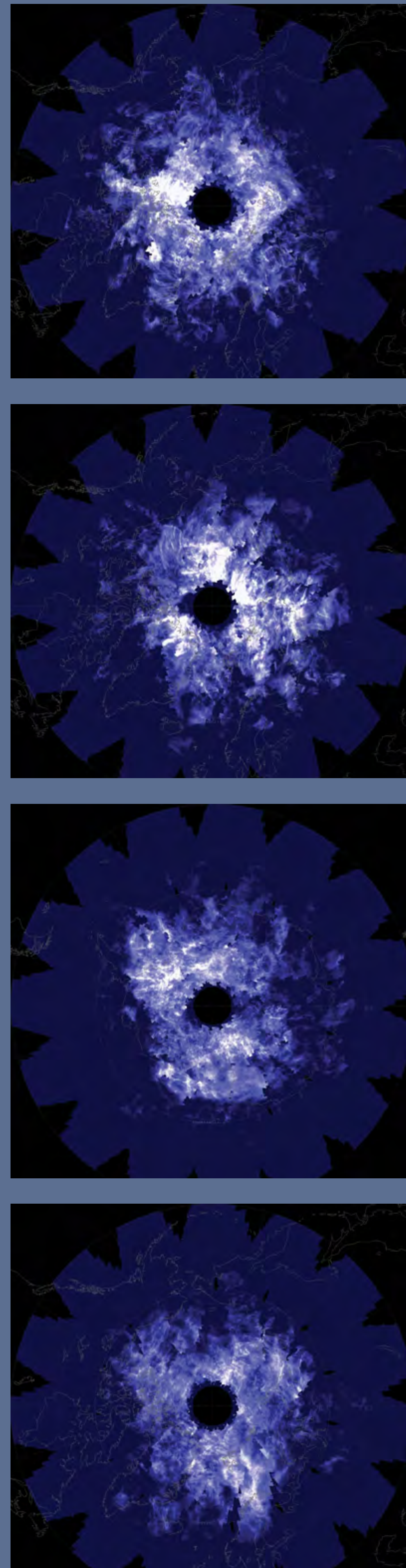
Systems within Systems: Joshua Semeter, Boston University

Complexity Examples: Preconditioning – Jiuhou Lei, University of Colorado; Nonlinearity – Jeff Forbes, University of Colorado; Feedback – Jan Sojka, Utah State University; Instability – Dave Hysell, Cornell University

Scale: Anthony van Eyken, SRI International

Energy: Stan Solomon (NCAR) and UCAR's The Comet Program

Edge of Space: Gary Thomas, University of Colorado



Edge of Space: "Daily Daisy" maps of polar mesospheric clouds.

CEDAR: THE NEW DIMENSION