CEDAR: *The New Dimension*

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1 Introduction

The Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) program, funded by NSF's Atmospheric and Geospace Sciences division, studies the interaction region of the Earth's upper atmosphere with interplanetary space and with the lower atmosphere. The space environment is filled with energetic particles, solar radiation and magnetic fields that drive "space weather" disturbances in our tenuous upper atmosphere. Mega-ampere electric currents, order-of-magnitude changes in neutral density and temperature, and major redistribution of charged particles in the ionosphere can occur rapidly in the upper atmosphere. At the same time, waves carrying energy and momentum upward from hurricanes, thermal tides and surface features dramatically impact its circulation and variability. Satellites orbiting in this complicated environment support infrastructures essential to the functioning of our modern society. The need to understand and predict this environment is made more urgent by our growing awareness of the interdependencies between societal infrastructures that can result in serious collateral damage when sensitive infrastructures (for example, electric power grids) are disrupted by space weather effects [*Severe Space Weather Events—Understanding Societal and Economic Impacts, National Academy of Science, 2008*].

The CEDAR program has maintained its vitality for over 25 years by planning, assessment, and prioritization of research goals that reflect pressing scientific and technical issues. Presently the questions posed by CEDAR are detailed and specific; however, the CEDAR community must complement these questions with a broader, more encompassing vision that recognizes the linkages between different aspects of the whole Earth system and the vital role the upper atmosphere plays in maintaining the habitability of our planet and in sustaining a society that is increasingly reliant on satellite technologies for vital services .

The purpose of this community document is to describe 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 between CEDAR science and other disciplines.

In its formative years, the CEDAR program evolved through a grass-roots scientific effort. This continues today and is essential for the program to remain vibrant and current. Community science plans for upper atmosphere research are described in the CEDAR Phase documents. The most recent Phase III document, completed in 1996, focused CEDAR science efforts and consolidated resources to attack specific science questions pertaining to four areas of research: Coupling with Lower Altitudes, Solar-Terrestrial Interactions, Polar Aeronomy and Long-term Variations.

Since the publication of the CEDAR Phase III document, new supporting technologies, not envisioned as contributing to CEDAR research in past years, have begun to reshape the research landscape. These include cyberinfrastructure, advanced communications, improved sensors, networking technology, computing power, precision navigation systems, small satellites, major research instrumentation and facilities, and distributed instrumentation and computing. Along with advances in understanding the coupling that links the upper atmosphere with other regions, these exciting developments have the potential to position CEDAR to make major contributions to high priority research areas, such as geocomplexity, global change, Earth dynamism, and space weather.

The rapid evolution of resources and discoveries, together with the increase in relevance and impact of CEDAR science, both enables and requires a new view of geospace to accelerate progress. This view is one of global perspective where the geospace environment must be analyzed as an integrated system to fully understand its response to external and internal stresses and their subsequent impact on other parts of the system. This holistic, systems science view is increasingly shared by other areas of geoscience and this document provides a plan to advance CEDAR in this new and evolving dimension.

The nonlinear, coupled and dynamical aspects of the Earth system challenge progress.The Earth's atmosphere is not simply a linear superposition of its constituent atmospheric regions but rather a complex system. 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 atmosphere and represents a necessary added dimension of CEDAR science.

CEDAR: *The New Dimension* focuses on complexity within the ITM as the next transformative step to properly and reliably predict geospace conditions and understand their interconnections to other regions in the Sun-Earth system.

This new appreciation of systems science requires a collaborative exchange of ideas and understanding with the other disciplines that study sub-regions in the solar-terrestrial system, i.e. solid earth, ocean, lower atmosphere, magnetosphere, solar and interplanetary space. This effort will allow CEDAR to address broader and more encompassing research questions the answers for which will have far-reaching impact. Integrative activities ongoing within CEDAR for many years will become mainstreamed, with a more explicit statement and unified direction toward broader CEDAR goals.

CEDAR: The New Dimension focuses on complex processes within the ITM system as the next transformative step to properly and reliably predict state behavior of geospace and understand its connectedness to other parts of the Sun-Earth system.

The development and deployment of technologies and infrastructure can then be assessed and prioritized in terms of their capabilities and strategic attributes that satisfy the emerging scientific needs. This advancement of science and resources must proceed with a sense of fiscal acuity. Thus, the formulation of the new goals for CEDAR must be leveraged from, and coordinated with, other programs' plans for more extensive observing networks, modeling efforts, and broader visionary goals that will generate new collaborations and exciting, new insights into the workings of the coupled Earth system.

The CEDAR Vision

To understand fundamental properties of the space-atmosphere interaction region, identify the interconnected processes that define its global behavior, evolution, and influence on the Sun-Earth system, and to explore its predictability.

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.

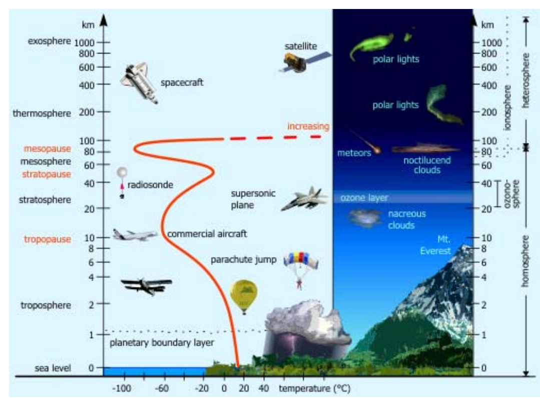
–Socrates

2. The Space-Atmosphere Interaction Region

To focus on the processes that structure the upper atmosphere, it is useful to envision it as an *Interaction Region* coupling the lower atmosphere with space and the universe beyond. Aeronomy is the study of the physics and chemistry related to the tenuous, partially ionized, space-atmosphere interaction region (SAIR) of Earth and is the research domain of the CEDAR community. This domain encompasses the ionosphere, thermosphere and mesosphere (ITM). The exosphere and plasmasphere are the spaceward extensions of the ITM's neutral and plasma constituents, respectively. Collectively the ITM, exosphere, plasmasphere and magnetosphere form the geospace environment. The troposphere is referred to as the lower atmosphere, and the stratosphere, mesosphere and lower thermosphere as the middle atmosphere.

That the space-atmosphere interaction region represents a form of boundary layer implies an exchange between the neighboring regions it separates, a change in their physical makeup, and a redistribution of mass, momentum and energy. The SAIR is a dynamic, complex boundary layer that communicates with its neighbors: the neutral gas-dominated lower atmosphere and the plasma-dominated space environment. Internal processes within this *Interaction Region* mediate the exchange between these distant and distinct regions. Energy, mass and momentum crossing its boundaries from above and below participate in a large number of transitions and transformations ultimately structuring the ITM in space and time.

The concept of an *Interaction Region* can be generalized to unify the study of Earth's environment with other planetary and solar system bodies. At Earth, and for virtually every object in the Universe, there is an *Interaction Region* coupling the visible surface of the object (star, planet, moon, comet, asteroid or planetoid) to the tenuous plasmas that surround it in space. The *Interaction Region* of a planetary body, which includes the ionosphere, thermosphere, and mesosphere, itself exhibits complex behavior. It is strongly coupled chemically, dynamically, and electromagnetically to the lower atmosphere and to the magnetosphere. The physical and chemical processes that occur between a body's solid or gaseous surface and the fully ionized gases in regions well beyond it involve fundamentally important aspects of science.



Earth's atmosphere and geospace environment making up the space-atmosphere interaction región.

For objects with dense gases at their visible surface (Sun, stars, the giant planets of our solar system, and exoplanets), the *Interaction Region* includes the classic studies of meteorological processes, photochemical layers of both neutrals and ionization, and plasma transport to regions beyond. A 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. Further complexities occur in the presence of a strong intrinsic geomagnetic field that couple the plasma to the neutral gas with Earth, Saturn and Jupiter examples of magnetically influenced atmospheres.

That one of the most complex examples (Earth) is readily accessible to all modern research tools of ground-based and space-based investigation offers an extraordinary opportunity to advance our understanding of our home planet, as well as the very nature of interaction regions everywhere. Within only a ~1000 km of the Earth's surface, it is possible to study a set of fundamental processes that appear throughout the Universe. Focusing on the SAIR of Earth draws together past and continuing research on individual components and processes initiated in CEDAR. Exploring Earth's SAIR in its entirety is an important next step in CEDAR's quest to understand the interconnected dynamical processes that determine the structure of the ITM, and ultimately will contribute to our understanding of how the Sun-Earth system works and what role the SAIR has on other worlds.

> 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

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3 Relevance

Over the last few solar cycles, observations and models have demonstrated the disruptive effects of space weather on electric power grids, satellites, aircraft HF communications, and GPS-positioning systems. As severe as some of these impacts have been, history tells us that stronger solar storms, than any yet experienced since the dawn of the space age, are possible and even likely in the future. An example of one such "superstorm" is the Carrington event of 1859. This particular solar storm occurred before the development of most of today's ground and space infrastructure. None-the-less, the crude telegraph system, in place at the time, provides a glimpse into the storms societal impact. Telegraph systems failed, operators received burns and electrical shocks as geomagnetically induced currents flowed through the telegraph lines.

Such an event like this today would likely have a devastating impact on society. The Administrator of the Federal Emergency Management Agency (FEMA) has now incorporated space weather events into its natural disaster preparedness plans. FEMA acknowledges that another Carrington event would not be localized to a particular region but would cause national and worldwide disruptions of basic infrastructure such as communications, power, air traffic, and water while costing billions of dollars in damage. Society's satellite fleets would most certainly not come through a Carrington event unscathed!

However, a Carrington-size event is not required to impact societal infrastructure. Solar storms regularly produce space weather disturbances at Earth. In the upper atmosphere (the domain of CEDAR), space weather events are responsible for the strong electric currents that disrupt electric power grids, the dramatic changes in ionospheric density that black-out HF radio communications, the steep gradients in ionospheric density that disable GPS positioning systems, and the auroral heating that increases neutral densities and thus enhances satellite drag. CEDAR science is crucial for understanding and eventually predicting these and a whole range of other space weather phenomena, which in turn carries direct benefit to modern society. Our reliance on space-based technologies for communication, navigation, and resource management is growing and evolving so rapidly that soon the entire world will be dependent on operational space assets for basic daily activities. CEDAR research creates the breakthrough science and intellectual framework needed for the next generation of space weather prediction models that will be used to mitigate the impacts of severe space weather on sensitive technologies and to protect society from catastrophic disruptions in critical services..

At a more fundamental level, but of equal importance, is understanding the role of the space-atmosphere interaction region in sustaining basic life and human wellness. As we seek to explore other planets within our solar system and discover new exoplanetary systems, it is essential that we understand the

How has the space-atmosphere interaction region contributed to making our planet habitable?

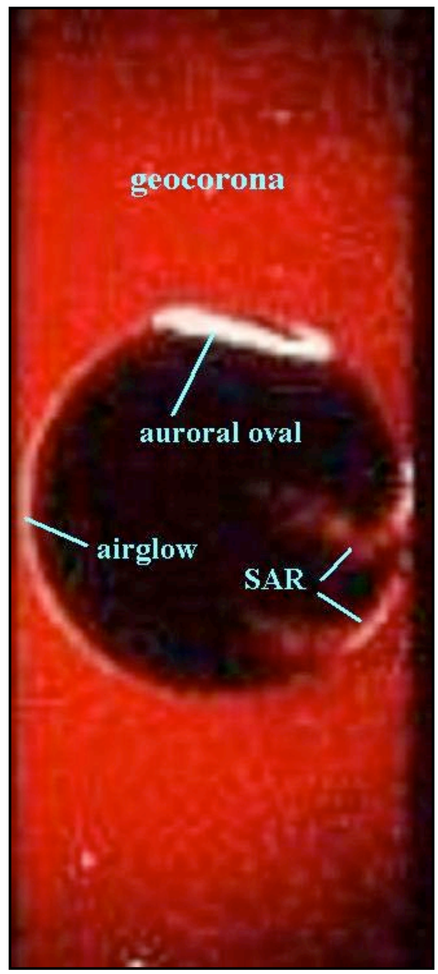
many influences that ultimately lead to initiating and maintaining life. The Earth's atmosphere plays a critical role in sustaining life, and the space-atmosphere interaction region is a fundamental part of the integrated atmospheric system and its connection to space. The ability of planets like Earth to support life is partly dependent on the chemical, dynamical, and energetic processes that occur within the SAIR. The broad rationale for an expanded view of CEDAR is to contribute to understanding the habitability and sustainability of our planet by taking a holistic approach to Earth's system.

Study of the SAIR improves our understanding of processes significant to the upper boundary of Earth's atmosphere, elucidates the linkages to both the lower atmosphere and near-space regions, and provides awareness of our vulnerabilities. As much as water and sunlight are imperative for initiating life, properties of the SAIR are important for maintaining it.

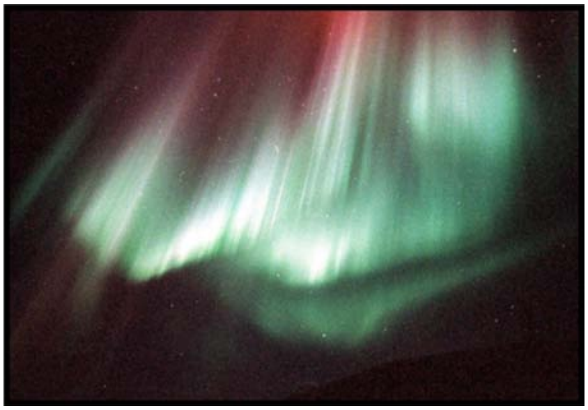
3a Habitability: Our Whole Earth System

Understanding the many influences that initiate and maintain life on planets like Earth is essential for human wellbeing over the long term. The evolution of life is intimately linked to the development of our atmosphere. During planetary formation, the Earth's atmosphere consisted primarily of hydrogen and helium. Over time, geologic outgassing and extraterrestrial bombardment added heavier volatiles that were entrained within the early atmosphere. Hydrogen, and, to a lesser extent, helium can attain sufficient thermal energy from the sun to overcome Earth's gravitational bounds and escape the planet, a process that continues today. Following its formation 3.5 billion years ago, aerobic life began a process that led to an oxygen rich atmosphere, differentiating Earth from its nearest terrestrial neighbor. That oxygen, along with nitrogen, formed an absorbing shield in the upper portions of the atmosphere, screening the surface from harmful solar UV radiation and energetic particles and permitting the vigorous evolution of life.

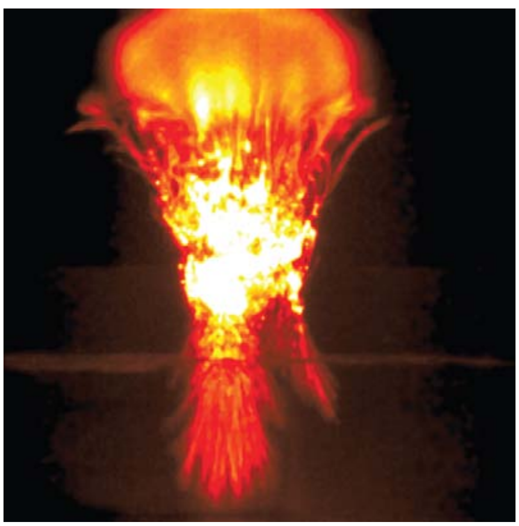
This shielding is not maintained without consequence. Energy from the sun



Earth's geocorona of hydrogen and other natural emissions. NOT SAR, CHANGE LABEL 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. This energy transport across the geospace system must be accounted for and treated consistently with energy processes in other parts of the whole Earth system in order to fully represent the evolution of the atmosphere and its influence on life and human wellbeing.



Auroral rays produced by neutral oxygen impacted by energetic electrons.



Middle atmosphere sprites connecting tropospheric lightning discharge with ionosphere charges.

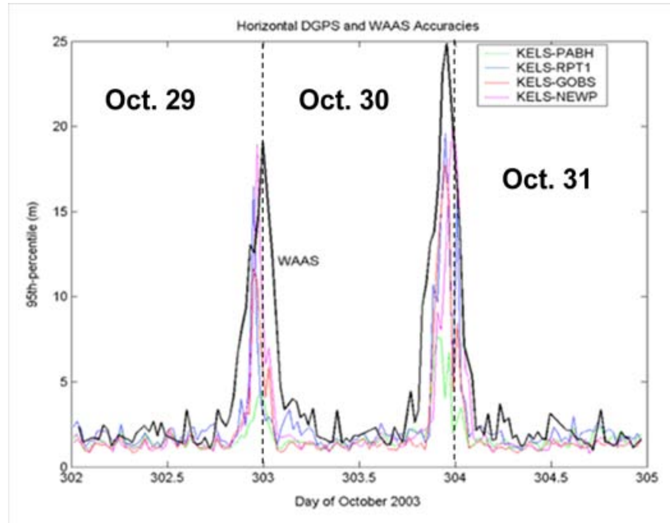
For instance, the current composition of the atmosphere, and the evolution of all terrestrial planetary atmospheres, depends upon the rate of escape of light gases from the top of the atmosphere. The Earth's solar system neighbors, Mars and Venus, illustrate opposite extremes of atmospheric evolution in CO_2 dominated atmospheres, and both are proof of the frailty of liquid water oceans on geologic time scales. It is evident that a terrestrial atmosphere can rapidly evolve to a state that is unable to support life. Understanding, for example, the evolution and stability of all hydrogenous species in the atmosphere demands a systems approach that couples processes from the Earth's crust and biosphere to the outermost atmospheric region, the exosphere, and geospace.

The ionosphere, a conductive shell around the 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 counter charge distributions created in the magnetosphere (visually demonstrated by the continuous presence of auroras), a process that leads to significant electrical energy dissipation in the ionosphere and thermosphere. 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 aspects of the whole Earth system are poorly explored, yet, by their very nature, connect widely separated regions of the Earth system, linking geospace to the ground in an electrical circuit which must be studied as an entire system to fully understand.

3b Sustainability of Our Technology-Reliant Society

As society continues to evolve and develop more sophisticated infrastructure, its dependence on the properties of the SAIR becomes more acute and varied. For example, prior to 1960, satellites were not part of the societal infrastructure and thus consequences of geospace dynamics were not part of the socio-economic equation. Today, with ever increasing reliance, satellite technology plays a major role in modern society. Thus, new ITM questions – such as how precisely do thermosphere density variations affect satellite drag, or how and when do ionospheric density variations cause GPS signal disruption? – become critical societal issues.

How does a society sustain its expansive technological enterprise under changing space-atmosphere conditions and how might societies best adapt in response to changes? The concept of geoengineering based on present and future technologies has re-emerged during the recent debate of global warming, whereby engineering methods are considered to modify and potentially control an important atmosphere parameter, specifically temperature. Geoengineering proposals, such as reflecting more sunlight by introducing reflective elements in the upper atmosphere, offer potential solutions but will most certainly introduce new issues. Without adequate knowledge of how the whole Earth system responds to anthropogenic alterations, the results of such efforts will be unpredictable and may have catastrophic consequences.



Typical GPS positioning errors are a few meters but during storm enhanced density events errors can be 15-25 meters.

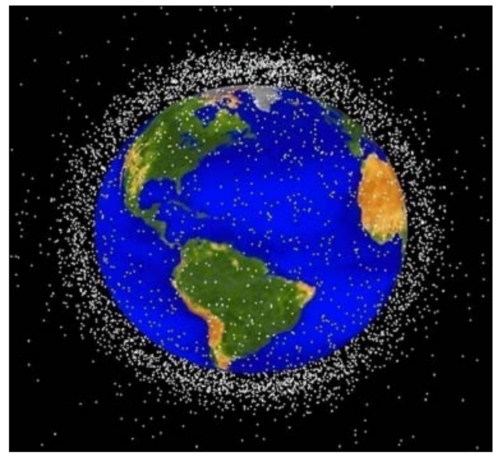
A present-day demonstration of geoengineering is the anthropogenic production of carbon dioxide. Carbon dioxide concentrations have increased in the upper atmosphere at a comparable rate to that in the lower atmosphere. Although considered a greenhouse gas in the troposphere by trapping heat and leading to higher temperature, carbon dioxide in the mesosphere is a very efficient infrared radiator that acts to cool the region. This enhances downward heat

How does a society sustain its expansive technological enterprise under changing space-atmosphere conditions and how might societies need to adapt in response to changes?

conduction in the thermosphere leading to an overall compression of the thermosphere gas, which alters circulation patterns in the upper atmosphere that are responsible for the transport of other important chemical species. In turn, these changes affect the spatial distribution and concentration of the Earth's ionosphere, which impacts societal dependencies on communication and navigation.

This is just one demonstration of a significant, evolutionary change that can occur in the upper atmosphere due to lower atmosphere transport of a "minor" anthropogenic species, the different roles species play in different atmospheric regimes, and the cascade of effects that can lead to alterations important to society. It is unclear at this time how these effects may communicate to other regions of the whole Earth system through feedback and coupling processes, and a full understanding of such phenomena demands a collaborative, systems science approach to the problem. It is important that researchers in all aspects of solar-terrestrial science be prepared to provide authoritative information pertaining to altering conditions of our planet – be it natural or geoengineered – that are likely to occur in the 21st century. New societal issues, such as space debris and the commercialization of space, are presenting new problems that will require a much better understanding of the ITM to properly address.

CEDAR will contribute to the advancement of whole atmosphere models, develop new observing technologies, expand observational networks, and educate and train future scientists to contribute to human wellbeing and the sustainability and adaptability of society. Owing to the growing dependence on technology, in particular space and space-sensitive technologies, the most immediate societal impact of CEDAR research will concern technology-reliant societies.



Space debris is a growing problem with the image above depicting space objects in low earth orbit.

The commercialization of space 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.

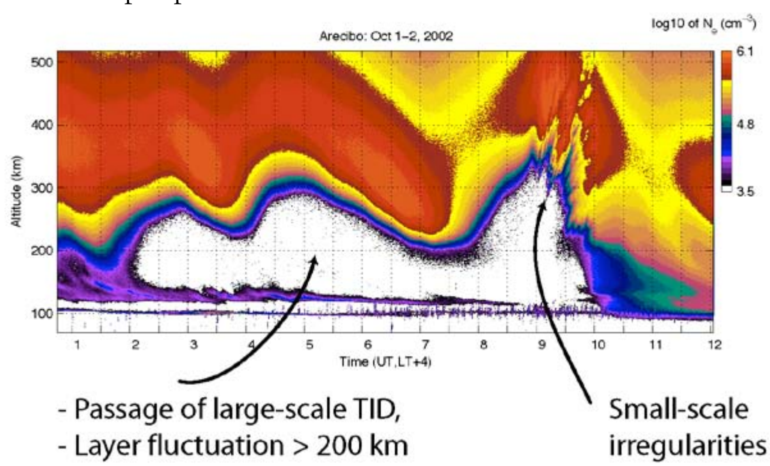
4. Variability in the Space-Atmosphere Interaction Region

An outstanding challenge in upper atmosphere research is accounting for the significant levels of variability in the space-atmosphere interaction region (SAIR), often rivaling the value of its mean state. This variability is driven by the nonlinear dynamical response of the ITM to changing temporal and spatial fluxes of energy, mass and momentum that cross its boundaries from space and the lower atmosphere. Furthermore, complex interactions between plasma and neutral gases lead to internal processes that can amplify these variations. This behavior raises the question: “Is the SAIR region ever in steady state or is it continuously changing by internal and external influences?” CEDAR scientists have made significant progress in developing observational tools to probe these changes, but often in isolated single focus campaigns. Today’s understanding is that all too often unraveling the various processes at work calls out for more extensive measurements and/or measurement of multiple parameters. Complex physics based models lack a complete set of inputs and boundary conditions and are missing important processes. Today’s state-of-the-art observational and modeling facilities, if operated in new comprehensive campaigns, can begin to resolve the major sources of, and processes responsible for, the levels of variability observed in the SAIR.

The evolution of the complexity within the SAIR depends strongly on the initial state of the system, its boundary conditions, and the fluxes crossing its boundary. The variability and its evolution must be understood in order to recognize changes in the ITM and its possible vulnerabilities, extending perhaps to questions of tipping points and emergent behavior that may influence the human wellbeing of the planet.

4a Space-Atmosphere Fluxes

The upper atmosphere is not a closed system. Across its open boundaries, fluxes of mass, momentum and energy are exchanged with space and with the lower atmosphere driving the SAIR far from equilibrium. These fluxes take the form of solar photons, electromagnetic energy, energetic particles , neutrals and ions from the ITM, and atmospheric wave momentum and minor species from the lower atmosphere. They respond in magnitude as well as temporal and spatial evolution to a wide variety of input and output processes. In most cases there is a



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

need to combine observations from more than one instrument and/or model to "determine" a flux. CEDAR will pave the way for these types of measurements by coordinating the necessary facilities, instruments and models for progress..

Waves are fundamental in boundary exchange processes as they can carry energy, momentum and mass across great distances. Alfven waves are a type of magnetohydrodynamic wave that establishes communication between the magnetosphere and the SAIR. Atmospheric waves are hydrodynamic waves that can be internally generated within the SAIR making latitudinal connections(for example, traveling atmospheric disturbances (TADs)) or externally generated propagating upward from the lower atmosphere into the SAIR. Waves span the spectrum of spatial and temporal scales and significantly influence the degree of variability within the ITM. They provide one of the most difficult challenges to observers. CEDAR infrastructure provides single-point observations from which wave trains can rarely be unambiguously deduced. As theory and modeling focus in on specific wave types it will be important that observational networks are developed to capture their actual properties. Indeed CEDAR scientists have long struggled with the general category of TADs and traveling ionospheric disturbances (TIDs) which even today are broad categories of many unresolved wave types. Innovative use of technology, the GPS TEC earthquake monitoring system, has revealed fine-scale coherence of TIDs in ways CEDAR scientists have struggled to unravel for decades. Further such innovation, in the form of distributed arrays of instrumentation, is needed over many different scale lengths.Study of wave processes and their exchange across boundaries is essential for understanding coupling and connections throughout the SAIR.

Another example of exchange processes across boundaries is related to electrical properties of the Earth system. The nature of the magnetic field serves as a pathway for mass, momentum, and energy exchange between the SAIR and the distant regions of the magnetosphere. These dynamic exchange processes often morph through more than one form before being dissipated. Observations of each of these different forms are not always possible hence strategies need to be developed to concentrate measurements of selected parameters with sufficient temporal and spatial resolution to capture these dynamic exchanges. In so doing, theoretical and model developments will be most usefully constrained. The CEDAR initiatives in resolving such larger systems require strong collaboration with scientists in other areas with complementary observational programs, such as Geospace Environment Modeling community.

Furthermore, the electric potential difference between the ionosphere and the lower atmosphere requires a continuous redistribution of charge that, at times, result in abrupt discharges connecting the ionosphere with the lower atmosphere through electrical channels called sprites and jets. The electrical system between Space and Earth is a vital area of research that constitutes a boundary exchange needing more in-depth investigation.

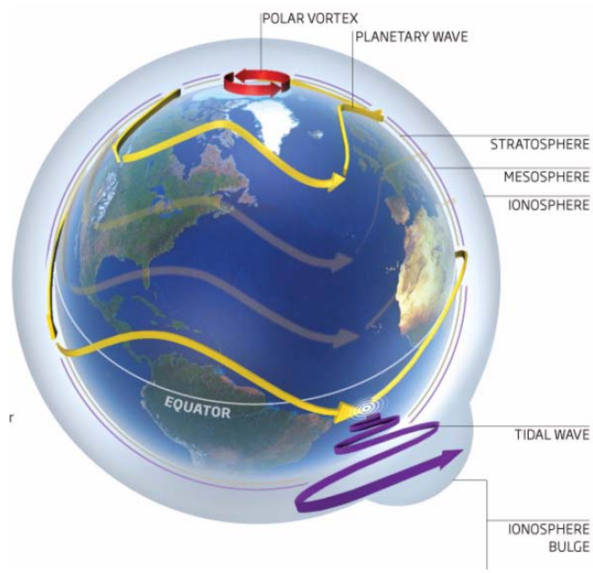
The CEDAR program must focus its future efforts on understanding and quantifying more completely space-atmosphere fluxes and the resulting exchange of energy, mass, and momentum that occur within the ITM.

4b Space-Atmosphere Coupling

Space-atmosphere coupling accounts for hydrodynamic and magnetohydrodynamic processes that influence, with mutual efficiency, the response of the neutral gas and plasma. This neutral-plasma coupling is fundamental to ITM processes. CEDAR has been successful in identifying coupling process within the ITM but it is a major challenge to track how energy, mass and momentum transform through the system and alter the system's properties.

A recent example is based on observations indicating a connection between sudden stratospheric warming events, vertical drifts, and TEC perturbations in the low-latitude ionosphere. The changes are remarkable and comparable to those that occur during major geomagnetic storms. The linkage between these different altitudes and separate latitude events most probably lies in the dynamics of the planetary and gravity wave system of the lower atmosphere, and their interaction with the atmospheric tidal system. Recent findings relate very strong F-region plasma modifications at the equator to polar stratospheric warmings after a transport delay of several days. Such a long delay, over pole to equator distances and ionosphere to stratosphere altitudes has, until recently, masked this long-distance coupling/driver phenomena from being discovered.

This SSW / SAIR example demonstrates the need for new observational methodologies that would enable such relations to be identified and studied. CEDAR infrastructure, in conjunction with those of other disciplines within the Sun-Earth system, will form the observational network needed to resolve the coupling processes at work. Indeed it is very probable that initial findings already indicate how observational networks need to be configured. With comprehensive observational campaigns, the challenge to the modeling community will readily focus their attention on the main coupling processes, which at this time are far from being integrated.



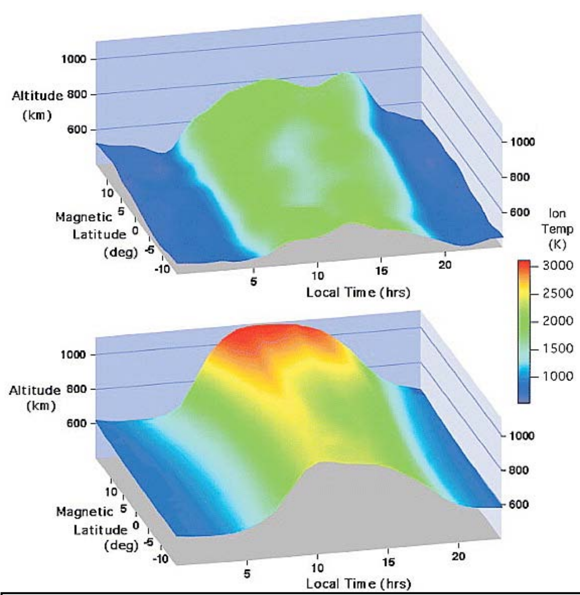
A depiction of terrestrial weather effects, identified by planetary wave action in the polar stratosphere, impacting the equatorial ionosphere. Adopted from New Scientist article.

4c Space-Atmosphere Evolution

The SAIR is a dynamical system that experiences change from wave cycles to solar cycles and beyond. From a systems perspective, evolution of the SAIR considers its dynamic response at multiple temporal scales as constituents, external sources, and internal processes change over time.

The Earth is changing and there are compelling and urgent needs for our CEDAR community to expand and develop basic science research to assess and answer society's concerns and needs in areas such as climate disruption, climate change, space climate, and geoengineering. Furthermore, long term evolutionary change in space climate or Earth climate may alter short-term system variability or multi-scale temporal response in the SAIR.

Long term changes in the SAIR are influenced by climate changes in the lower atmosphere as well as changes in the space climate. The space climate relates to gradual changes in solar activity, solar wind, 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 compressed thermosphere.



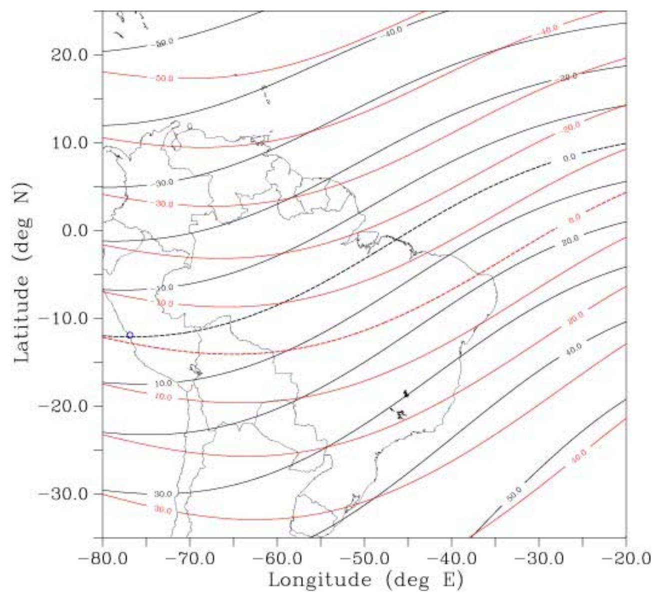
C/NOFS satellite observed ion temperature (upper panel) compared to expected conditions based on the International Reference Ionosphere (IRI) model (bottom panel). Adopted from Heelis et al. 2009.

The figure above contrasts ion temperature observations in the ionosphere with the IRI model during the solar minimum phase in 2008. The IRI model is based on the accumulated knowledge of ionospheric conditions spanning multiple solar cycles and thus embodies our knowledge of usual ionospheric behavior. However, the observations show a contracted ionosphere closer to the Earth's surface, which is cold and less dense than ever before seen. Furthermore, the distributions of ions indicates that the dynamics of the ionosphere have also changed in unknown ways. Equally diverse effects are being observed in thermosphere parameters with the thermosphere density contracted to levels never observed during the space era. This has also led to more impulsive responses of the thermosphere density to geomagnetic activity and a greater influence on the ITM from planetary and tidal wave propagation from the lower atmosphere.

This period of low solar minimum was also 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 how the ITM will evolve. Many other consequences of this change in space climate are presently being investigated, but these changes must also be accompanied by knowledge of how Earth's climate change is impacting the ITM.

The changing Earth's climate is not only occurring at meteorological altitudes, but also at all levels from the magnetospheric boundary to the deep core of Earth. Evolution of the Earth's magnetic field is evidence of this fact. Over time, the Earth's magnetic poles wander, the relative strength of the field varies, and the relative direction changes – as demonstrated by the many degree change in magnetic field dip angle over the equator over 40 years (see Figure).

The natural laboratory provided by the ITM system allows us to extract quantitative measures of the effects of anthropogenic influences. In 1989, Roble and Dickinson predicted that a 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 by observing the effect of atmospheric drag on satellite orbits have revealed that thermospheric density is, in fact, systematically decreasing by several percent per decade near 400 km altitude .



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).

Anthropogenic global change with increases in CH_4 emissions can increase hydrogen levels and thus H_2O near the mesopause that could alter polar mesospheric cloud production. Planetary and gravity wave activity are expected to increase churning up the ITM and leading to increased variability and uncertainty in how the system will evolve under this more vigorous wave climate. Understanding the full scope of global change throughout the atmosphere, and the interplay with space climate, is important in order to obtain a complete physical description of aeronomic processes, as well as for practical goals pertaining to satellite operations and space debris hazards. With this 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 that, themselves, are poorly understood. CEDAR scientists, on the one hand, confirm there are trends that are consistent with the cooling of the IT region, while also finding aspects of these data sets that show the reverse trend. Today's best interpretation of the ionosphere's long-term trends remains confused with qualitative appeals to other dependences that may lead to mixed long-term trends. Present-day techniques used to detrend the shorter-term processes are crude, and much work is needed to improve upon them.

This effort 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/forecasting. These are long term goals and CEDARmust adjust its priorities and funding mechanisms in order to appropriately invest in long-term, climatological projects.

5. The Systems Perspective

Enormous strides have been made in recent decades in understanding the individual parts of the SAIR system. These have been facilitated by major advances 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, multidimensional models of geospace. These models offer the promise of greater insights into the physical processes at work and improved ability to forecast disruptive events and their potential impacts.

A major challenge for the future is to develop an integrated, multi-scale picture of how geospace works and how it contributes to the broader Sun-Earth system. Another 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 approach to understanding the SAIR can bridge these different challenges and provide a structure and focus to evolve our understanding.

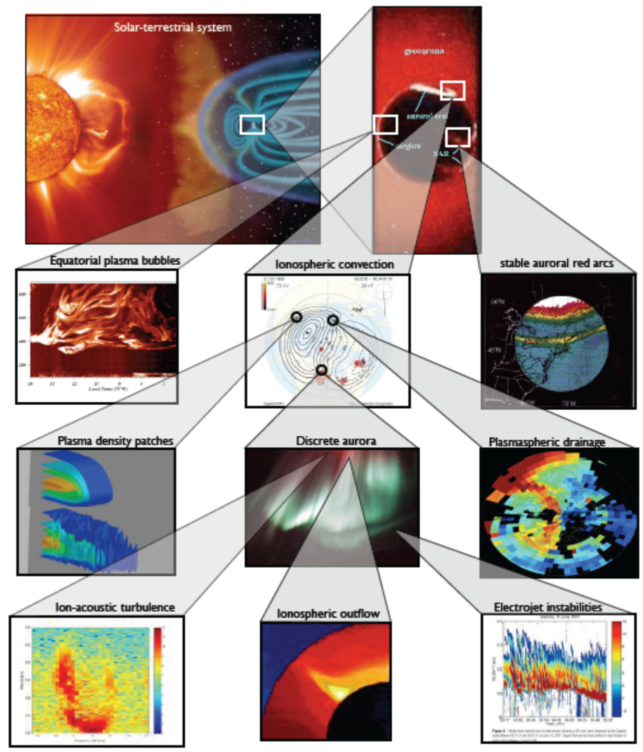
Systems studies have the goal of understanding the behavior of complex systems consisting of a large number of mutually interacting and interrelated parts. In general, a system is a mapping between observed drivers and resulting states, for example, between solar extreme ultraviolet flux and ionospheric density. The problem of system identification, which is where CEDAR puts most of its effort, is one of finding the physical processes that are responsible for the observed system response. If the underlying state is known (controlled conditions) and the drivers are measured (via experiment), determining the system (the physics) is tantamount to the scientific method.

The ionosphere, thermosphere, and mesosphere, which are themselves complex systems, along with the exosphere, plasmasphere, broadly define the parts of the SAIR system. The interactions in question involve coupling between atmospheric and ionospheric layers, latitude zones, constituents, flow regimes, and temporal and spatial scales. Many of the components of the system are characterized by having multiple drivers, adaptive feedback, memory, and sensitivity to initial conditions.

Systems can be interconnected and embedded within larger systems, as the ITM is embedded within the Sun-Earth system. The intellectual framework of the system view enables transferable concepts across systems and disciplines to advance and facilitate progress in understanding our whole Sun-Earth system. The study of the aurora may be directed towards the mechanisms responsible for the emission or towards understanding the closure of electric currents in the magnetosphere and ionosphere system. Although a different context, the concepts of the system view are the same with the need to identify the inputs, define or measure the characteristics of the system, and observe and predict the response. 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.

A 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 ITM, and between the ITM and other regions, combine to produce global SAIR conditions. By its nature, this focus moves us away from correlations and snapshots, to patterns of change, interrelationships and complexity.

System-level science and the large volume of data required demand advanced observing capabilities and computer technologies. The adoption and implementation of a systems approach is more realizable today with the rapid expansion of multidimensional databases, increasing computational capabilities and sophistication of numerical tools, and emergence of new sensor



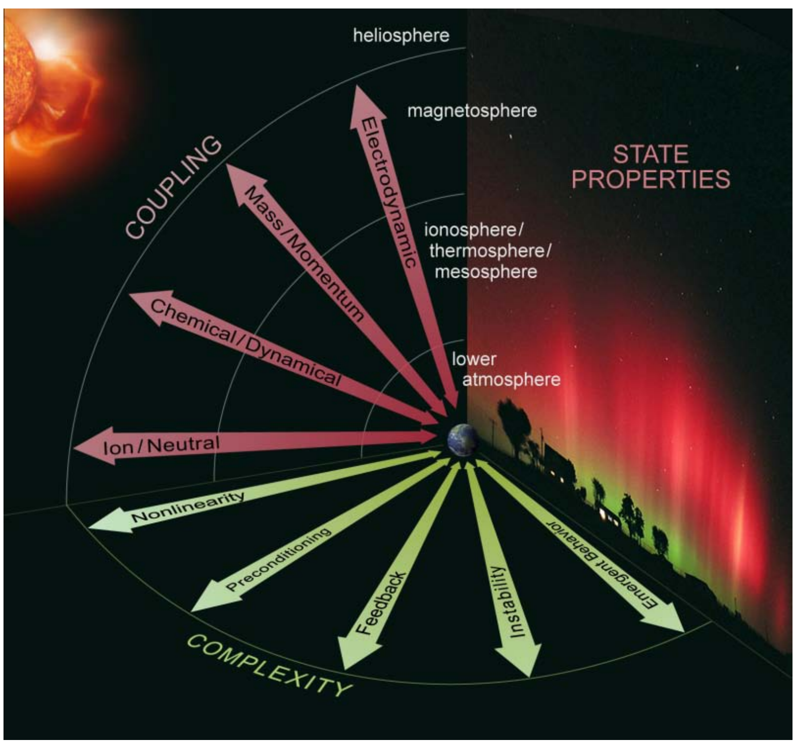
The Sun-Earth system and the embedded systems within the ITM.

technologies. The powerful and uniform formalism afforded by the systems approach will help synthesize results and provide more rapid evolution of the science. As an added benefit, the systems approach is expected to facilitate improved interaction and collaboration between members of the geosciences community focusing on different aspects of the system providing fertile ground for innovative new ideas.

Not only will the system view provide new insight into geospace and expose gaps in knowledge, it will help establish the technological and infrastructure needs and specific functionality required to fill those gaps. Thus, the formulation of CEDAR: *The New Dimension* must be developed in coordination with implementation plans for more extensive observing networks, modeling efforts, new collaborations that together will produce exciting new science. By locating instruments strategically so as to be able to measure key inputs and outputs throughout and across 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.

5a Complexity

The SAIR is a system that demonstrates complexity. Complex systems are environments comprised of many interacting elements exchanging energy, mass and momentum through nonlinear, dynamical pathways. Often, the individual elements themselves are complex systems. Current knowledge of the ionosphere, thermosphere, and mesosphere as a complex system emerges from a solid background of research in CEDAR. CEDAR's charter since its inception has been to study the coupling processes within the ITM and between the ITM and geospace. This research has led to advances in such areas as electrodynamic coupling, mass/momentum coupling, plasma-neutral coupling, and chemical-dynamical coupling. What has emerged from this research is the recognition that many of these natural coupling processes are linked through system processes that demonstrate complexity.



Complexity 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 can trigger multiple nonlinear feedbacks among system components, which can amplify, attenuate, or even change the nature of the expected response. The generation of instabilities and their interaction with the mean flow produces nonlinearities that can occur over a range of temporal and spatial scales. Initial conditions and history (which includes preconditioning of system components and system memory) matters in determining the final state of the system. As the system responds to forcing, unexpected behavior can emerge.

The origin of many of these features is contained in the complexity of the system and not in the individual components or a singular coupling process. What is observed is actually the integrated response of the entire interconnected system. As a result, it is not enough to break the system into smaller digestible pieces to advance an understanding of how the complex system behaves and responds. Clear cause and effect can be understood only when these effects are accounted for in an integrated way.

Thus, physical coupling processes must be linked with system complexity processes. Focusing on the interaction among these various processes draws together and completes past and continuing research on individual components and processes initiated in CEDAR. But it also pushes us toward global questions and new ways of viewing problems, which provides fertile ground for innovation. By casting these broader views, gaps in knowledge become clearer.

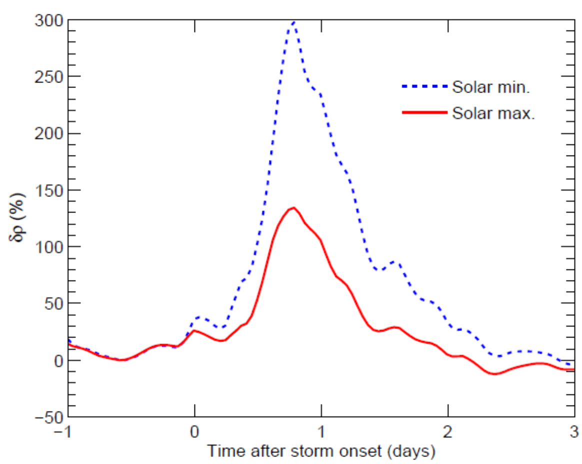
Experience from CEDAR indicates there are key areas, such as neutral winds, electrical conductivity and other basic properties, where breakthroughs are required in order to enable a first system-level understanding of the ITM. System science provides an intellectual framework which naturally focuses questions and integrates new knowledge in ways that will transform our understanding of the ITM system and its influences on geospace and the broader Sun-Earth system. CEDAR: *The New Dimension* focuses on complex processes within the ITM system as the next transformative step to properly and reliably predict state behavior of geospace and understand its connectedness with other parts of the Sun-Earth system.

Complexity considers the system characteristics and their response to the exchange of energy, mass and momentum leading to alterations of state properties. System characteristics can be described by universal concepts of nonlinearity, preconditioning, feedback, instability and emergent behavior. Cross-scale coupling serves to link coupling processes with system characteristics over different spatial and temporal scales. The dynamical aspects of the complex system involve the evolution of inputs, system characteristics and state properties from wave cycles to solar cycles.

Exciting results from the CEDAR program (below) provide tantalizing glimpses of complex properties of the ITM system. These, and others examples not described here, provide a rich resource for designing and focusing the *New Dimension* phase of CEDAR.

Initial Conditions, Preconditioning and Memory

The initial conditions (initial 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 all possible initial conditions that permit that state define its precondition. Preconditioning appears to be necessary for a number of important phenomena in ITM physics, which consequently require comprehensive observations and modeling to understand. 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: 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.

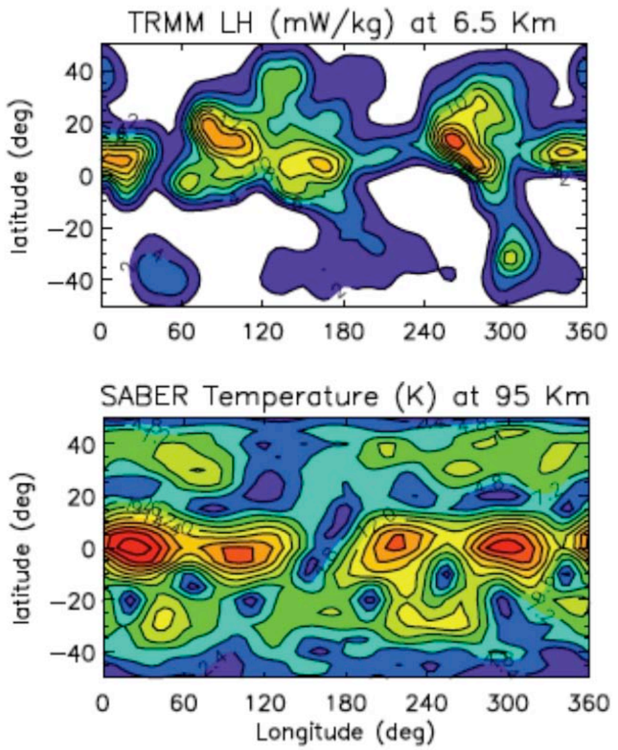
For example, the neutral atmosphere and ionosphere are key agents for preconditioning geospace. They respond strongly to both magnetospheric energy sources and solar EUV and X-ray enhancements, the responses coming over a wide range of temporal and spatial scales. Moreover, they preserve the recent history of energy inputs and introduce seasonal and solar cycle effects. Periodic, impulsive energy inputs embedded within longer active time periods may cause different dynamics within the system to emerge, so 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. Specifically, observations, theories, and models of the system must include time scales that span the complete memory of the system.

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. This provides a mechanism for transporting energy and other quantities across spatial scales.

Atmospheric waves, such as tides, planetary and gravity waves, are a prime example of nonlinearity in the system. The tides in the thermosphere appear as global scale waves in density, temperature, and wind – a whole system response to migrating and nonmigrating sources. They can be forced by the absorption of sunlight in the lower atmosphere, non-linear wave-wave interactions and by latent heat release in tropospheric clouds. These waves grow with amplitude as they propagate upward and can dominate the thermal and dynamical structure of the mesosphere-lower thermosphere.

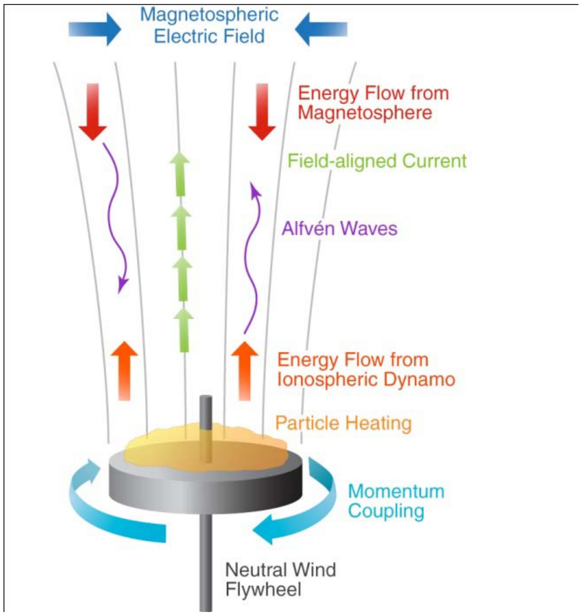
The frontier in our understanding of waves and tides in the upper atmosphere lies not in the linear theory of these waves, but in the quantification of their amplitudes and variability produced by nonlinear wave-wave and wave-mean interactions. Nonlinear breaking of gravity waves in the mesosphere is a significant momentum source for the region but the processes of converting and cascading this energy to the mean flow across a range of spatial and temporal scales is very much an area of active research. 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. Numerous other nonlinear processes prevail in the SAIR and new processes are yet to be discovered.



Nonlinearity: Latitude-longitude distributions of the diurnal component of (a) latent heating rate at 6.5 km altitude derived from TRMM satellite data and (b) the corresponding measured diurnal temperature amplitudes at 95 km derived from TIMED/SABER temperature measurements. Note the predominant wave-4 longitude distribution of land-sea difference is reflected in the latent heating rates and in the generated tides that impose a striking wave-4 longitude distribution on the lower thermosphere.

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 theory approach.



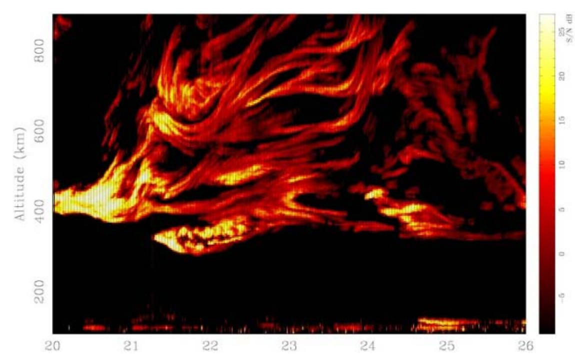
Feedback: Neutral motions driven by past forcing feedback electrodynamically on present electrical connections by driving dynamo fields.

The upper atmosphere inherently is a multi-variable system, with properties experiencing a wide range of temporal and spatial responses. Consequently the role of feedback processes in the system can occur through a range of possibilities. An interesting 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 present 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.

Instability

A characteristic property of a complex system, like the SAIR, is nonlinearity that leads to instability, a condition where one or more of the system states exhibits 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



Instability: Equatorial plasma instability forms spontaneously and regularly at low magnetic latitudes. At sunset, recombination pushes the F region ionosphere into instability. 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. At small scales, the irregularities disrupt communication signals through refraction, diffraction, and scattering.

in the ITM and 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 continued investigation if a complete systems description is to be achieved.

Emergent Behavior

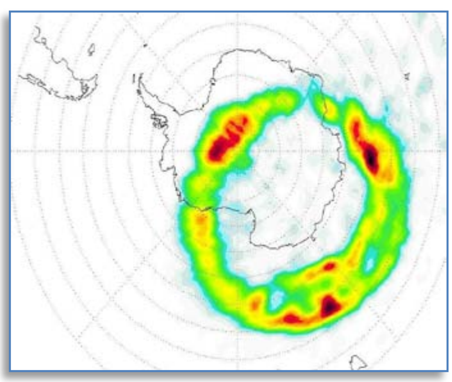
Perhaps the most interesting characteristic of complex systems is the emergence of new features. Emergent behavior results from the interaction of a large number of system components that could not have been anticipated on the basis of the properties of components acting individually. Although it is as yet unclear which features in geospace represent emergence, there are some obviously strong candidates. These include ionospheric super-fountains, great red auroras, storm enhanced densities, and enhanced NOx transport into the stratosphere during sudden stratospheric warmings. 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, the 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 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 re-established 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.

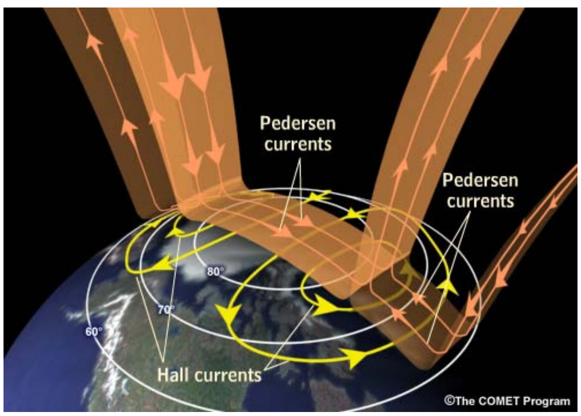
5b Cross-Scale Coupling

Cross-scale coupling provides the link between the dimensions of complexity and coupling. The SAIR inherently is a multi-scale system, with energy inputs occurring over a wide range of scales and the system response dependent on the system complexity at those scales. For example, auroral arcs occur over scales of less than 10 km, the auroral oval is typically about 5,000 km (almost 3 orders of magnitude larger), while dayside solar EUV heating spans 40,000km. These very different scales of energy input result in responses that are dependent on the characteristic conditions of the SAIR, i.e. complexity. These different scales for ionization lead to very structured ionospheric conductivity. This behavior can also produce very structured electric fields. Together this creates a tremendous challenge in ITM research that essentially leads to "missing energy" in numerical models.



Scales: The auroral oval depicts a large range of spatial as well as temporal scales.

The "missing energy" puzzle developed as increases in Joule Heating by factors of 2 to 3 were needed in global circulation models to adequately reproduce the global wind and temperature structure. Using the accepted statistical patterns of particle precipitation and plasma convection it was possible to reproduce the neutral temperature structure or the wind fields, 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 (momentum transfer between ions and neutrals) at high latitudes. This was puzzling as increasing the average electric fields or particle precipitation fluxes increased both temperature and neutral winds. Small scale variability in the high-latitude ion convection is 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.



Energy: Currents closing in the ionosphere can exhibit significant variability in time and space that alters the amount of energy deposited in the ITM.

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.

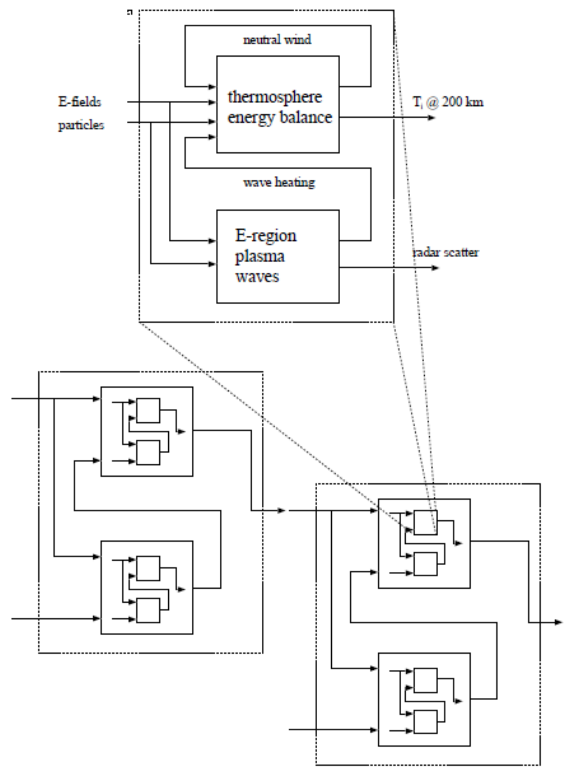
A "Cybernetic" Example

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 particle precipitating into the polar thermosphere strongly drives 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 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 nitric oxide that acts as a radiator and a dominant cooling mechanism for the thermosphere.

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 magnetosphere response to the mass loading by these heavy ions.

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 it 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 which includes the 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.

6 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 below 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.

STRATEGIC THRUST #1: 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 program 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 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 in ways that preserve their influences on 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.

STRATEGIC THRUST #2: Explore Exchange Processes at Boundaries and Transitions

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 our Interaction Region 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 amongst components are a common feature of complex systems; thus new knowledge in this area is applicable to a wide range of planetary, solar system, exo-planetary 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

STRATEGIC THRUST #3: 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 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 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

STRATEGIC THRUST #4: 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 our 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 (i.e., autonomous, reconfigurable, robust, low-power, etc.) 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

STRATEGIC THRUST #5: 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 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 system's 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

STRATEGIC THRUST #6: 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 correlations and contribute to understanding their causalities, 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 are 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