OASIS

Exploring the Interaction of Earth's Atmosphere with Space

THE OBSERVATORY FOR ATMOSPHERE SPACE INTERACTION STUDIES

An Atmospheric and Geospace Sciences Community Report

Submitted to the

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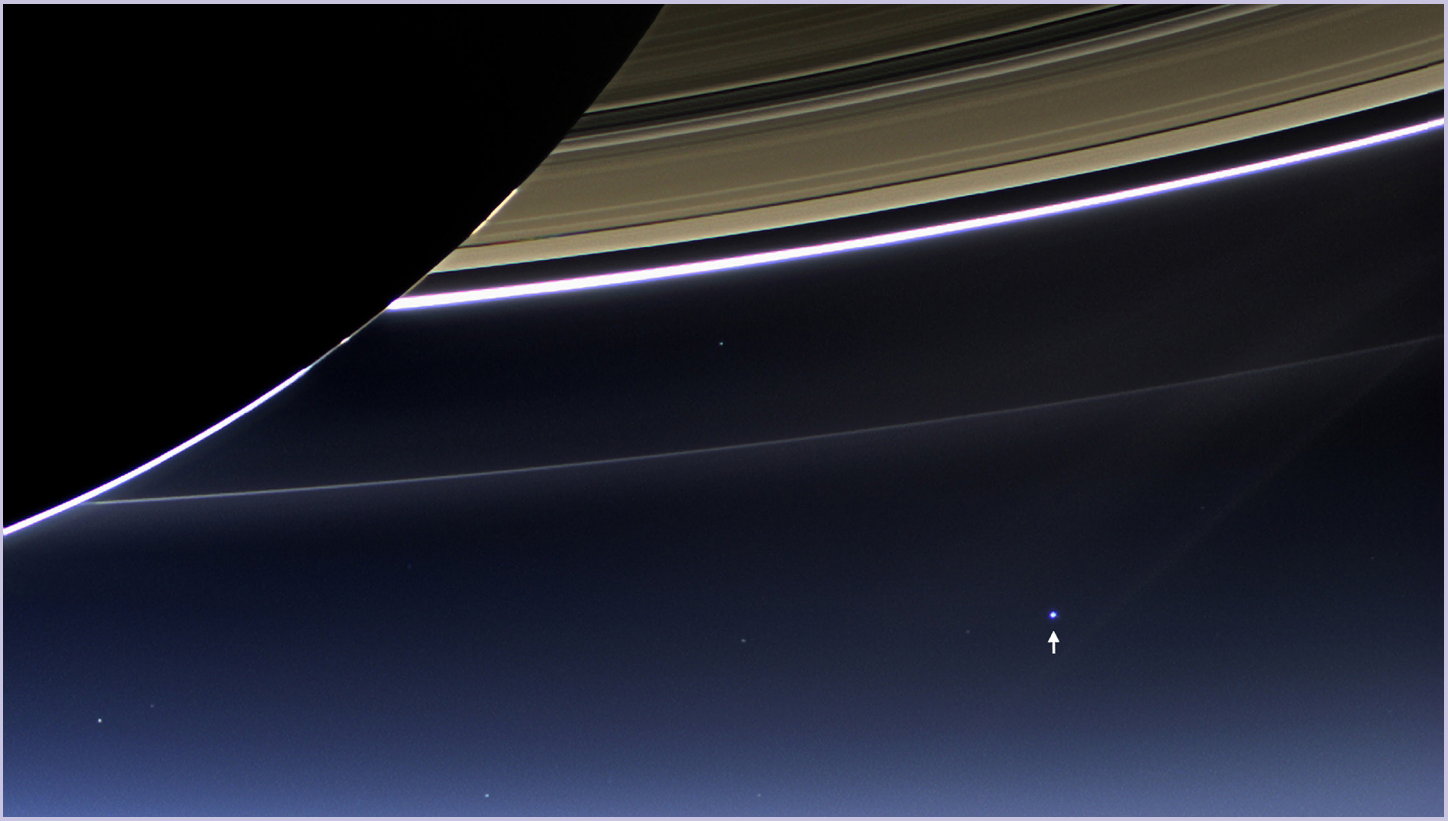
Earth from the Cassini Spacecraft on 19 July 2013



A Na laser guide star beam is projected towards the Milky Way by one of the 8.2 m diameter (53 m^2) telescopes at the European Southern Observatory's Paranal Observatory, Chile. OASIS will employ similar laser technologies and the 100 m^2 large lidar telescope (LLT) array to probe the Earth's neutral atmosphere from virtually the surface to 1000 km altitude. *(Image courtesy of ESO/Yuri Beletsky)*

This image of Earth was photographed from 900 million miles away on 19 July 2013 by NASA's Cassini spacecraft in orbit around Saturn. Although Earth appears fragile and isolated, it is now estimated that there are billions of Earth-like planets orbiting Sun-like stars in the Milky Way. The nearest may be located within 12 light years of Earth. OASIS will be used to explore fundamental atmospheric processes that have helped insure Earth's habitability for the 3.5 billion years that our planet has harbored life. This knowledge will also enhance our understanding of other Earth-like planets within the galaxy and how their atmospheres evolve.
(NASA/JPL-Caltech/Space Science Institute, Image ID PIA17171)

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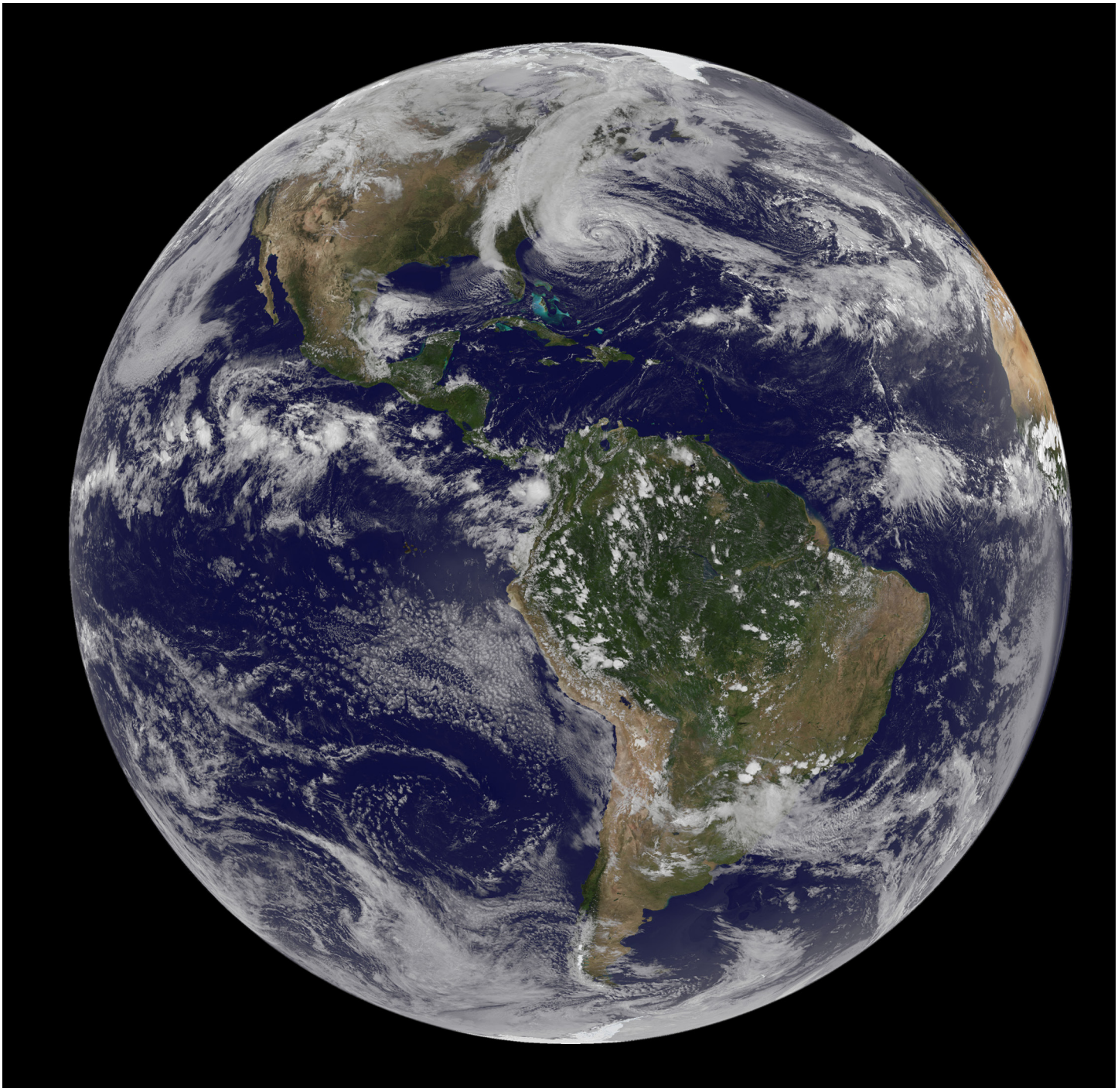

This natural-color image, acquired by the Geostationary Environmental Satellite (GOES-13), shows Hurricane Sandy approaching the East Coast of the United States on 28 October 2012. The Observatory for Atmosphere Space Interaction (OASIS) will explore crucial coupling and feedback mechanisms between the Earth's atmosphere and space that influence weather and climate and help ensure the long-term habitability of our planet. *(NASA Earth Observatory Image by Robert Simmon with data courtesy of NASA/NOAA Goes Project Science Team)*

Foreword

On 15-17 May 2012, with support from the National Science Foundation, an international group of scientists convened for two and a half days at the University Club of Chicago to discuss the scientific merits of developing a major new observational facility to explore the fundamental processes that are known to shape planetary atmospheres throughout the galaxy and govern their evolution. Participants focused primarily on Earth's middle and upper atmosphere from 50 to 1000 km altitude. They identified the science drivers for the initiative, determined what new observational capabilities were required to address them and developed a top-level design concept for the new facility. In particular, they acknowledged that there exists a serious observational gap of the Earth's neutral atmosphere above 100 km. Information on neutral winds and temperatures and on the interactions between the neutral atmosphere and plasma in the Earth's space-atmosphere-interaction region is either sparse or nonexistent. The group consensus was that the new facility must address this observational gap.

The conference participants and others spent the next eighteen months refining the scientific arguments, assessing the current state of technology and developing the design requirements and performance specifications for the new facility. The results of their careful deliberations are contained in this report and in the Engineering and Technical Supplement. Both documents have undergone several reviews by the workshop participants and other key scientists. In particular, I acknowledge the considerable efforts of the Steering Committee, who helped organize the workshop and provided overall guidance for this initiative. I also thank our NSF colleagues in the Division of Atmospheric and Geospace Sciences for their encouragement and for providing the resources to conduct the Chicago workshop and prepare this report.

Chester S. Gardner, University of Illinois
January 2014

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Executive Summary

The Earth formed 4.5 billion years (4.5 By) ago by accretion of debris from the solar nebula, the disk-like cloud of dust and gas left over from the formation of the Sun. Afterward, the Earth continued to be bombarded by large objects for perhaps the next billion years. It is now thought that planetesimals and comets, which formed beyond 2.5 AU, where it was cold enough for water ice to accumulate, were the major sources of Earth's water. They also may have been the source of the complex organic chemicals necessary for the origin of life. Volcanic outgassing and impact degassing of the mantel created the primordial atmosphere and the first primitive life emerged about 3.5 By ago, when sufficient crust had solidified and liquid water condensed on the surface. These early life forms began to modify the chemistry and composition of the oceans and atmosphere. Life capable of photosynthesis appeared around 2 By ago, dramatically increasing the atmospheric concentration of oxygen while reducing CO_2 levels. Complex multicellular life arose about 600 My ago. Throughout this long 3.5 By period, during which Earth has harbored life, the Sun's luminosity increased by more than 20%.

In spite of this large change in solar radiation and the significant modification of the atmosphere by life itself, Earth has remained habitable because of the effects of a set of key universal processes that govern the evolution of planetary atmospheres everywhere.

For example, the Earth's magnetic field shields our atmosphere from the energetic electrons and protons in the solar wind that are partially responsible for stripping Mars of its primordial atmosphere. The Earth's carbonate-silicate cycle provides a feedback mechanism that controls atmospheric CO_2 levels and climate over long time scales, preventing the runaway greenhouse effect that is responsible for the high temperatures on Venus today. However, there are many coupled mechanisms and feedback processes that are at play in a planetary atmosphere system. Many are unknown and cannot be addressed without a complete description of the atmosphere, from its lower interaction with land and oceans to its upper interaction with space. Weather and climate modeling have improved substantially by coupling predictive atmosphere models with ocean models, and large-scale ocean/atmosphere observing networks have been developed to provide crucial input data to the models. Because of the relative inaccessibility of the near-space environment, the interaction of the upper atmosphere with space is not described nearly as well, nor are its influences on the lower atmosphere understood well enough to incorporate them in weather and climate models.

The natural upward extension of a planet's atmosphere ultimately leads to its interaction with space, where atmospheric neutral gasses become entwined with the dynamic plasma of space. This space-atmosphere-interaction region (SAIR) is common to all planetary systems, yet its properties, and the processes that govern them, are not sufficiently described to fully understand its role in an atmosphere's development and evolution. However, the SAIR is known to be essential for sustaining life on Earth by absorbing extreme solar radiation, ablating meteoric material, regulating gaseous escape, dissipating energetic particles and fields from space, while balancing influences from the planet itself in the form of tsunami-like atmospheric waves propagating from below, hurricane-speed winds exceeding several hundred mph and temperatures four times that of the surface. Unfortunately, there is no set of observations that adequately captures these properties nor are there numerical models that can adequately predict upper atmosphere behavior and how it influences weather and climate on the surface.

This initiative is focused on advancing observational capabilities of the near-space environment and our understanding of key universal processes in Earth's upper atmosphere. Three basic questions that have commanded the attention of atmosphere and space scientists for generations, serve as guiding themes.

1. What are the fundamental processes that shape the Earth's upper atmosphere and govern its evolution?
2. How do these processes affect weather and climate?
3. What roles do they play on other planets?

These questions are especially relevant today as rising concentrations of greenhouse gases are changing Earth's climate and increasing numbers of extra-solar planets (exoplanets) are being discovered in our galaxy (1015 confirmed exoplanets plus 3600+ additional candidates from the Kepler Mission as of Jan 2014).

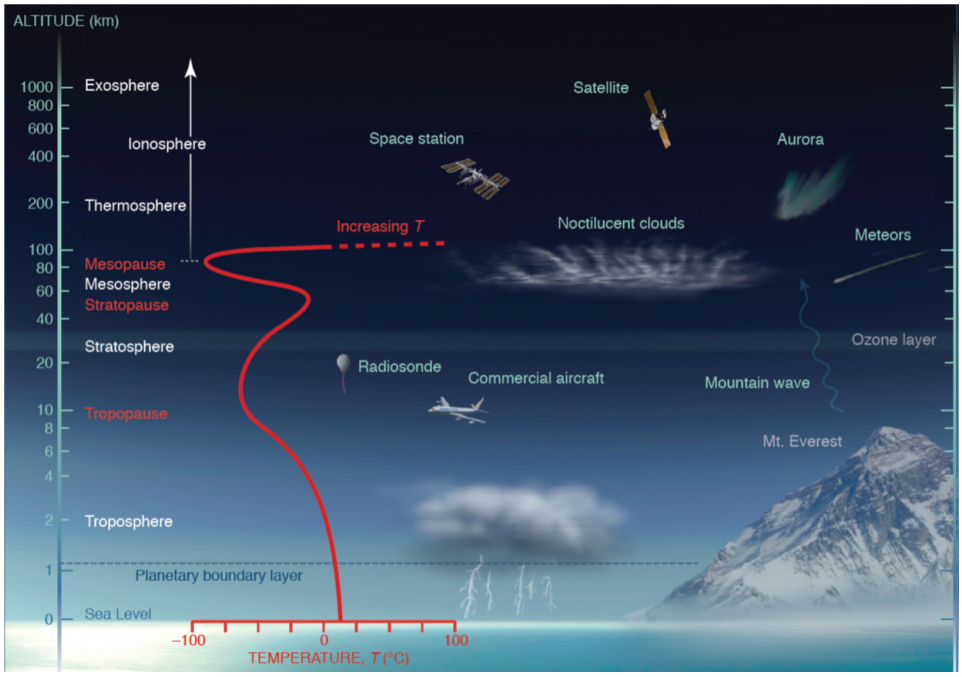
The initiative's overarching goal is to substantially advance our understanding of the fundamental, universal processes that occur in the Earth's space-atmosphere-interaction region (~50 km and above) and how they shape the atmospheres of Earth-like planets throughout our galaxy.

While it will address a broad range of processes and scientific goals, the primary focus is on three processes that have profound effects on planetary atmospheres everywhere and, in particular, on Earth:

- Plasma-neutral atmospheric coupling — What is the role of plasma-neutral coupling in establishing the predominant states of planetary atmospheres?
- Wave-induced transport and turbulence — How does wave-induced transport and turbulence influence the structure, composition and circulation of planetary atmospheres?
- Cosmic dust influx — What is the magnitude of the global cosmic dust influx and what impact does it have on Earth's atmosphere and climate?

Much of the information required, especially knowledge of the neutral atmosphere, its dynamics and its thermal structure in Earth's space-atmosphere-interaction region above 50 km altitude, is either sparse or nonexistent. Although modern radar systems and GPS technology can be used to probe the ionized atmosphere up to 1000 km altitude, observations of the neutral atmosphere above 100 km are limited because existing instruments lack the accuracy, resolution and altitude coverage necessary to address the most important scientific questions. Resonance lidar systems using tracer gases of Na, Fe and He are potentially capable of probing the neutral atmosphere to 1000 km altitude, but existing systems do not have the sensitivity to make scientifically useful measurements of winds and temperatures at the higher altitudes. Current instruments employ lasers with output powers of a few watts and small telescopes, typically less than one-meter diameter. Much higher power-aperture-product lidars are required to make the necessary observations above 100 km altitude.

The crucial information needed to achieve this initiative's overarching goal can be obtained by developing a major new atmospheric observatory, the Observatory for Atmosphere Space Interaction Studies (OASIS), to explore the Earth's neutral and ionized atmosphere from the stratosphere to 1000 km. Although OASIS will employ a variety of state-of-the-art instruments, the centerpiece will be an 11-meter class optical telescope array, the Large Lidar Telescope (LLT), that



The Earth's atmosphere is divided into regions based upon temperature structure, composition and dynamical characteristics (see Glossary for definitions). OASIS (Observatory for Atmosphere Space Interaction Studies) will explore the Earth's neutral and ionized atmosphere and the universal processes in this region that shape the atmospheres of habitable Earth-like planets throughout our galaxy. Although the primary focus for OASIS will be the region between 50 and 1000 km altitude, the Large Lidar Telescope (LLT) array, together with various state-of-the-art laser technologies, will be capable of measuring wind, temperature and atmospheric constituents from the Earth's surface to the exosphere. *(Graphic from CEDAR: The New Dimension, 2011)*

will serve as the receiving system for several powerful Doppler lidar systems (viz. Rayleigh, Na, Fe and He lidars). The LLT, in combination with modern high-power lasers, will enable observations of neutral atmosphere properties (winds, temperature and density) to 1000 km altitude with a sensitivity and resolution approximately 1000 times better than can be achieved with the most powerful lidar systems in operation today. Achieving this measurement capability will be a transformative step in the study of the Earth's upper atmosphere and near space environment. OASIS and LLT will enable significant progress by providing critical measurements of atmospheric properties and parameters at greatly enhanced resolution and at much higher altitudes than is possible today. The knowledge obtained will improve our ability to model the Earth's whole atmosphere and predict the role of the upper atmosphere in climate. It will also have direct applications to studies of other planets in the solar system and to the exploration of nearby exoplanets within our galaxy. There are no technology barriers to realizing this goal.

The LLT will consist of an array of telescopes (viz. 10x12 array of 1.03 m parabolic mirrors) yielding a total collecting area of approximately 100 square meters, the equivalent of a single mirror 11 meters in diameter. It will be designed so that each telescope can be pointed at several different zenith (0°, 6° and 30°) and azimuth angles (N, S, E and W), enabling portions of the array to be dedicated to measuring specific components of the 3-D wind field or dynamical parameters like turbulence or momentum and heat fluxes.

The LLT array will be transportable so that it can be relocated to different sites to address scientific issues that are latitude and hemisphere dependent and incorporate state-of-the-art tele-science technologies to enable autonomous operation of the instruments. The observatory will also include important companion

instruments such as radars, imagers, spectrometers and perhaps in situ measurement capabilities using balloon and rocket probes, to provide crucial supplementary measurements of key species and parameters. OASIS will cost approximately $150M and require five years to construct. Operating and maintenance costs will be about $3M per year.

Powerful multi-beam Rayleigh, Na, Fe and He Doppler lidars, sharing the large telescope aperture, will make observations of neutral temperatures and 3-D winds from 30 to almost 200 km and from 300 to 1000 km. Furthermore, to serve the broader atmospheric science community, observations of the lower atmosphere, down to the surface, can also be made with the LLT by employing aerosol, Raman and differential absorption lidar (DIAL) technologies. These lidars, with power-aperture products as large as 10^4 Wm^2, will permit researchers to explore atmospheric processes with unprecedented accuracy, resolution and altitude coverage. Other state-of-the-art instruments will provide crucial correlative observations, including observations of the ionized atmosphere above 100 km. These measurements will fill a critical knowledge gap, especially in the thermosphere, and enhance our understanding of plasma-neutral coupling and electrodynamic processes that require knowledge of both the neutral and ionized components of the atmosphere. In addition, it will be possible to directly measure key constituents, processes and parameters like meteoric smoke particles, heat, constituent and momentum transport, eddy diffusivity and the turbulent Prandtl number below the turbopause (~110 km) at resolutions comparable to the spatial and temporal scales of even the smallest scale sources of turbulence. Because LLT will be designed specifically for lidar applications and be partially steerable, active experiments involving laser modification and chemical releases from satellites and rockets will open entirely new research areas.

Although plasma-neutral coupling, wave-induced transport and turbulence and cosmic dust influx in the SAIR are the primary foci of OASIS, the facility will also be used to study other important universal processes including solar radiation influx, geomagnetic activity, electrodynamics, atmospheric escape and climate change. These processes are crucial for forming and sustaining Earth-like planetary atmospheres throughout our galaxy. The performance of the OASIS lidars, in conjunction with the correlative instruments and model development, will enable significant progress to be made in addressing the key research questions associated with these universal processes.

Furthermore, OASIS and the science it enables, will contribute directly to many of the science goals described in the *NRC 2013-2022 Decadal Strategy for Solar and Space Physics* (viz. Atmosphere-Ionosphere-Magnetosphere Interactions), *2011 NSF CEDAR Program Strategic Plan* (viz. Space-Atmosphere-Interaction Region), the *2014 NSF Report on Solar-Terrestrial Research in Polar Regions: Past, Present and Future,* and the *NASA Exobiology Roadmap 2008* (understanding the nature of habitable environments in the universe). In particular, OASIS and LLT represents one realization of the Whole Atmosphere Lidar Observatory that was advocated in the *NRC 2013-2022 Decadal Strategy* to address a wide variety of problems related to Atmosphere-Ionosphere-Magnetosphere Interactions.

Zodiacal Light over La Silla, Chile

This image of sunlight scattered by cosmic dust that orbits the sun in the ecliptic (zodiacal light), was obtained at the European Southern Observatory's La Silla Observatory, Chile in September 2009. Current estimates of the global influx of cosmic dust into the Earth's atmosphere vary by more than two-orders of magnitude (~2-270 metric tons per day). The ablated atoms and meteoric smoke particles (MSPs) are involved in a wide variety of atmospheric chemical processes, play important roles in the formation of mesospheric and stratospheric clouds and, when the iron-rich MSPs settle into the Southern Ocean around Antarctica, they fertilize the growth of phytoplankton, which impacts the atmospheric CO_2 cycle and potentially climate. OASIS lidars and radars will substantially improve our understanding of these effects and the global cosmic dust influx by characterizing the altitude distribution, physical properties, and vertical transport of the meteoric debris in the Earth's atmosphere. (*Image courtesy of ESO/Y. Beletsky*)

1 Introduction

This initiative is focused on advancing observational capabilities of the near-space environment and our understanding of key universal processes in earth's upper atmosphere. Three basic questions that have commanded the attention of atmosphere and space scientists for generations serve as guiding themes for exploring the interaction of Earth's atmosphere with space.

1. What are the fundamental processes that shape the Earth's atmosphere and govern its evolution?
2. How do these processes affect weather and climate?
3. What roles do they play on other planets?

These questions are especially relevant today as rising concentrations of greenhouse gases warm the Earth and increasing numbers of extra-solar planets (exoplanets) are being discovered within our galaxy, including at least two Earth-like planets orbiting within the habitable zone around another star (Kepler 62e and 62f).

The overarching goal is:

To substantially advance our understanding of the fundamental, universal processes that occur in the Earth's space-atmosphere-interaction region (~50 km and above) and how they shape the atmospheres of Earth-like planets throughout our galaxy.

While the initiative will address a broad range of processes and scientific goals, the primary focus is on three important processes that have profound effects on planetary atmospheres everywhere and especially on Earth:

- Plasma-neutral atmospheric coupling – What is the role of plasma-neutral coupling in establishing the predominant states of planetary atmospheres?
- Wave-induced transport and turbulence – How does wave-induced transport and turbulence influence the structure, composition and circulation of planetary atmospheres?
- Cosmic dust influx – What is the magnitude of the global cosmic dust influx and what impact does it have on Earth's atmosphere and climate?

Much of the information required to achieve this goal, especially knowledge of the neutral atmosphere, its dynamics and its thermal structure in the Earth's space-atmosphere-interaction region (SAIR) above 50 km altitude, is ether sparse or nonexistent. Although modern radar systems and GPS technology can be used to probe the ionized atmosphere up to 1000 km altitude, observations of the neutral atmosphere above 100 km have been limited because existing instruments lack the accuracy, resolution and altitude coverage necessary to address the most important scientific questions. Resonance lidar systems using tracer gases of Na, Fe and He are potentially capable of probing the neutral atmosphere to 1000 km altitude, but existing systems do not have the sensitivity to make scientifically useful measurements of winds and temperatures at the higher altitudes.

Current instruments employ lasers with output powers of a few watts and small telescopes (typically less than one meter diameter). Much higher power-aperture-product lidars are required to make the necessary observations above 100 km altitude.

This crucial information can be obtained by developing a major new atmospheric observatory, the Observatory for Atmosphere Space Interaction Studies (OASIS), to explore the interaction of Earth's atmosphere with space. OASIS will employ a variety of state-of-the-art instruments. The centerpiece is an 11-meter class optical telescope array that will serve as the receiving system for several powerful Doppler lidar systems. The large telescope array in combination with modern high-power lasers, will enable observations of the neutral atmosphere to 1000 km altitude with a sensitivity and resolution approximately 1000 times better than can be achieved with the most powerful lidar systems in operation today. Achieving this measurement capability will be a transformative step in the study of the Earth's atmosphere and near space environment. There are no technology barriers to realizing this goal.

Although plasma-neutral coupling, wave-induced transport and turbulence and cosmic dust influx in the SAIR are the primary foci of OASIS, the facility will also be used to study other important universal processes including:

- Solar radiation influx
- Geomagnetic activity
- Electrodynamics
- Neutral atmospheric dynamics
- Atmospheric escape
- Climate change

These processes are crucial for forming and sustaining Earth-like planetary atmospheres throughout our galaxy. They have been the subjects of intensive study during the past several decades because they are known to play important roles in shaping the Earth's atmosphere and climate. They will continue to be a strong focus of current and future research as articulated in several recently published community surveys and strategic plans [*National Research Council 2013-2022 Decadal Strategy for Solar and pace Physics; A Science for a Technological Society, 2013; CEDAR: The New Dimension, A Strategic Vision for the NSF Program on Coupling, Energetics and Dynamics of Atmospheric Regions, 2011; Solar Terrestrial Research in Polar Regions: Past, Present and Future, NSF Division of Polar Programs, 2013*]. We are proposing to explore these universal processes in considerably greater detail and over a much larger height range than has been accomplished to date, not only to more completely understand the structure and evolution of the Earth's atmosphere, but to also understand how they affect planetary atmospheres everywhere.

While observational and modeling capabilities are evolving, progress in characterizing these processes and their effects has been inhibited because they cannot be studied in sufficient detail and at high enough altitudes with existing instruments. This is especially true of the space-atmosphere-interaction region (50 – 1000 km), where observations of the neutral atmosphere above 100 km, its dynamics and thermal structure are either sparse or nonexistent. OASIS will enable significant progress by providing critical measurements of atmospheric constituents and parameters at greatly enhanced resolution and at much higher altitudes than is possible today. The knowledge obtained will improve our ability to model the Earth's atmosphere and predict its climate. It will also have direct applications to studies of other planets in the solar system [e.g., *Mendillo, Nagy and Waite*, 2002] and to the exploration of the nearby exoplanets within our galaxy.

1.1 OASIS – The Observatory for Atmosphere Space Interaction Studies

Experiments conducted during the past fifteen years using the 3-meter class telescopes at Air Force facilities in New Mexico (Starfire Optical Range) and Haleakala, Maui demonstrated clearly the substantial scientific advantages of employing large steerable lidar systems in combination with correlative radars, passive optical instruments and rocket probes to study the middle and upper atmosphere. This initiative builds upon that prior work by articulating the scientific rationale and design requirements for a major new facility, the Observatory for Atmospheric Space Interactions Studies (OASIS), that is capable of exploring the chemistry and dynamics of the Earth's atmosphere from virtually the surface to the exosphere (~1000 km).

The centerpiece of the observatory is an 11-meter class telescope, the Large Lidar Telescope (LLT), which will serve as the receiving system for several powerful lidar systems. It is envisioned that the facility will consist of an array of smaller telescopes (viz. 10x12 array of 1.03 m parabolic mirrors) yielding a total collecting area of approximately 100 square meters, the equivalent of a single mirror 11 meters in diameter. The array will

be designed so that each telescope can be pointed at several different zenith (0°, 6° and 30°) and azimuth angles (N, S, E and W), enabling portions of the array to be dedicated to measuring specific components of the 3-D wind field or dynamical parameters like momentum and heat fluxes. The telescope array will be transportable so that it can be relocated to different sites to address scientific issues that are latitude and hemisphere dependent. The observatory will also include other important instruments such as radars, imagers, spectrometers and perhaps in situ measurement capabilities using balloon and rocket probes, to provide supplementary measurements of key species and parameters.

Powerful multi-beam Doppler lidars (Rayleigh, Na, Fe and He), sharing the LLT aperture, will make observations of neutral temperatures and 3-D winds from 30 to almost 200 km and from 300 to 1000 km. To serve the broader atmospheric science community, observations of the lower atmosphere, down to the surface, can also be made with LLT by employing aerosol, Raman and differential absorption lidar (DIAL) technologies. The lidars, with power-aperture products as large as 10^4 Wm^2, will permit researchers to explore atmospheric processes with unprecedented accuracy, resolution and altitude coverage. Other state-of-the-art instruments, such as incoherent scatter radar (ISR), tomographic airglow imagers, airglow interferometers and meteor radars, will provide crucial correlative observations, including observations of the ionized atmosphere above 100 km. These measurements will fill a critical knowledge gap, especially in the thermosphere and enhance our understanding of plasma-neutral coupling and electrodynamic processes that require knowledge of both the neutral and ionized components of the atmosphere. In addition, it will be possible to directly measure key turbulence processes and parameters like heat, constituent and momentum transport, eddy diffusivity and the turbulent Prandtl number below the turbopause (~110 km) at resolutions comparable to the spatial and temporal scales of even the smallest scale sources of turbulence. Because the telescope will be designed specifically for lidar applications and be partially steerable, active experiments involving laser modification and chemical releases from satellites and rockets will open entirely new research areas.

1.2 Intellectual Merit and Broader Impacts

Intellectual Merit: The scientific motivation to explore the neutral properties of the middle atmosphere and thermosphere is compelling. 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 [*CEDAR: The New Dimension, Strategic Vision for the NSF Program on Coupling, Energetics and Dynamics of Atmospheric Regions, May 2011*]. This involves determining the dynamics and coupling of the Earth's atmosphere, ionosphere and magnetosphere (AIM) and their responses to solar and terrestrial inputs [*National Research Council 2013-2022 Decadal Strategy for Solar and Space Physics; A Science for a Technological Society, 2013*].

Meteorological sources of wave energy from the lower atmosphere are responsible for producing significant variability and turbulence in the upper atmosphere, while cosmic dust, energetic solar particles and fields originating from the magnetosphere regularly alter the states of the thermosphere and ionosphere. The effects of this convergence of mass and energy in the SAIR are not well understood because existing instru-

ments are not able to observe in sufficient detail, the key dynamical processes and the tight coupling between the ionosphere plasma and neutral thermosphere gas. Measurements of the neutral thermosphere are woefully incomplete and in critical need to advance our understanding of and ability to predict the SAIR. To fully explore neutral-plasma coupling in the critical region above 100 km requires measurements of the neutral atmosphere to complement radar observations of the plasma. Lidar measurements of turbulence, neutral thermospheric winds, temperatures and species can enable these explorations, an objective of highest priority for the upper atmosphere science community. The development of OASIS and LLT will do for thermosphere studies much as incoherent scatter radar systems have done for ionosphere studies.

OASIS and the science it enables, will contribute directly to many of the science goals described in the *NRC 2013-2022 Decadal Strategy for Solar and Space Physics* (viz. Atmosphere-Ionosphere-Magnetosphere Interactions), *2011 NSF CEDAR Program Strategic Plan* (viz. Space-Atmosphere-Interaction Region), the *2014 NSF Report on Solar-Terrestrial Research in Polar Regions: Past, Present and Future* and the *NASA Astrobiology Roadmap 2008* (understanding the nature of habitable environments in the universe).

In particular, OASIS and LLT represents one realization of the Whole Atmosphere Lidar Observatory that was advocated in the NRC 2013-2022 Decadal Strategy to address a wide variety of problems related to Atmosphere-Ionosphere-Magnetosphere Interactions.

Broader Impacts: The interaction region between our atmosphere and space is a pristine natural laboratory where many fundamental processes occur that are common throughout the universe. Replicating the conditions and the various inputs of energy, mass and momentum in a research lab on Earth to study these processes is impractical and cost prohibitive. Thus, as in any laboratory, techniques must be developed to measure essential properties in space and time, without disturbing the environment under study, which allow for these processes to be elucidated. OASIS, with its suite of passive and active remote sensing instruments, provides the techniques needed to properly observe the natural processes taking place in the SAIR. Like a laboratory microscope, OASIS employs enhanced but proven techniques to observe with unprecedented precision the detailed structure and evolution of the region. The design, development, deployment, operations and analysis of OASIS instruments connect the concepts of engineering with the scientific endeavor of understanding the SAIR.

By involving a range of universities that include engineering and science departments, the OASIS project will help bridge the disciplines and develop a workforce through undergraduate and graduate education that is uniquely prepared with experience in engineering design and scientific methods of inquiry.

Presented as a natural laboratory, the project will be able to attract K-12 educators and students using parallels that are invoked early on in science classrooms. The concepts of developing models, instruments, carefully conceived experiments, and interpretation of observation are rooted in every science classroom. The OASIS project takes these same concepts and applies them to the natural environment of Earth in a region that is poorly understood but critical to understanding the habitability and sustainability of our civilization. It is also a goal to more clearly introduce engineering concepts into the K-12 system through the many engineering facets of the project.

Although removed from the complex interactions that occur between anthropogenic sources and the troposphere's weather and climate, the SAIR remains susceptible to anthropogenic influences. Wave energy and chemical constituents, such as carbon dioxide and methane, can alter the region and lead to long-term changes. More directly, the exhaust from space-bound rocket systems is known to create non-natural polar mesospheric clouds and create depletions in the electron density of the ionosphere. Thus, OASIS can help better understand our impact on the whole atmosphere. Furthermore, as concepts of geoengineering are discussed to mitigate climate change, the OASIS project can help serve to better understand the impact these concepts may have on the upper atmosphere.

The capability of the OASIS project extends far beyond its primary objective and can contribute to many scientific fields. The SAIR is considered a weakly ionized gas whose complex interactions between the plasma and neutral gas lead to unique electrodynamics with far-reaching effects. Similarly, stellar atmospheres and other planetary atmospheres have gaseous regions that are weakly ionized and whose electrodynamics are not well understood. Thus, OASIS can help the sun/stellar and planetary atmosphere fields by improving understanding of neutral and plasma interactions that lead to the generation of currents and electric fields.

The detailed observations of meteoric material entering the atmosphere provided by OASIS will greatly benefit astronomers and cosmologists working on meteor science. Meteoric influx and ablation introduces dust into the Earth's ionosphere, creating what are known as *dusty plasmas*. This relatively new scientific field is demonstrating that dusty plasmas are pervasive throughout the universe and OASIS observations of the background neutral gas, ionized gas and meteoric smoke particles will advance the dusty plasma field.

The SAIR is strongly driven by waves produced locally and from below. This makes the SAIR a natural turbulence/wave laboratory where many wave processes are in action. OASIS measurements will provide the most detailed observations of waves and turbulence in our atmosphere and contribute to the broader field of fluid dynamics.

A direct benefit of the OASIS project is the unprecedented sensitivity for observing clouds, aerosols, and chemically active species in the troposphere and stratosphere. This capability is a natural by-product of OASIS because of the demanding measurement requirements to observe the upper atmosphere. By coupling other laser technologies to the LLT, OASIS will provide significantly

enhanced capabilities for measuring chemically active species such as carbon dioxide, methane, water vapor and others throughout the lower atmosphere column. This can open new opportunities of study for lower atmosphere researchers.

OASIS will advance our knowledge and understanding of the upper atmosphere in a region that is vital for tracking orbital debris and low-earth orbiting satellites. Climate changes in the upper atmosphere can also be observed by OASIS.

The relatively pristine environment of the upper atmosphere lends itself to observing changes caused by natural and man-made changes in the lower atmosphere and at the surface. This understanding will elucidate connections between the lower and upper atmosphere. Furthermore, the findings provided by OASIS will be applicable to understanding other planetary atmospheres within the solar system and the growing number of extra-solar planets being discovered within our galaxy.

1.3 Education and Public Outreach

More than fifty years after the launch of Sputnik and just as Voyager 1 and 2 are passing the edge of the heliosphere, it is ironic that there is still a region of our atmosphere only 100 kilometers above us that remains largely unexplored. This is the region beyond the reach of conventional aircraft and balloons but below the reach of satellites. Except for sounding rockets that typically spend less than 5 minutes in this region and radars that measure the low-density plasma, this altitude regime is essentially unexplored by any extensive means. Yet this is the portion of our atmosphere that interacts with space, creating such wonders as the aurora and shooting stars, and, unbeknownst to the human eye, a place where electrical currents flow, waves crash like on a beach, neutral gasses reach speeds well beyond any hurricane, and temperatures can be the coldest in our atmosphere (-160°C in summer!) and the hottest (750° C). There are many other extremes to this region that require explanation and probably more to be discovered. It is this "last frontier" so near to Earth, which makes the education and public outreach for OASIS, a natural laboratory for discovery and wonder.

Because OASIS will observe the Earth's whole atmosphere from virtually the surface to 1000 km altitude and its research encompasses processes that are known to affect planetary atmospheres throughout the solar system and Milky Way, it offers a broad spectrum of educational and outreach opportunities. OASIS will adopt the best practices of existing major atmospheric, astronomical and physics facilities to enhance K-20 education (kindergarten to graduate degree) on multiple fronts. Education and public outreach materials will be developed on topics related to OASIS science and engineering including:

- Evolution and habitability of the Earth's atmosphere
- Comparative planetary science and exoplanets
- Climate change, space weather and atmospheric modeling
- Radar and lidar engineering
- Optical imaging, tomography and interferometry engineering

OASIS observations will be made widely available through NSF-supported databases such as the OpenMadrigal Project (http://www.openmadrigal.org/). The OASIS website will include public access to both data overviews and published research results as well as real-time graphics describing ongoing observations. The OASIS web site will be modeled on successful precursors and designed specifically to serve two constituencies: 1) the public and K-20 educators and 2) researchers utilizing OASIS observations and instruments.

Undergraduate and graduate research opportunities, supported by the competitive grants of principal investigators utilizing OASIS instruments, are the most direct contributions to education. OASIS will provide state-of-the-art infrastructure for educating and training the next generation of atmospheric and geospace scientists and engineers. As part of the undergraduate and graduate educational program, OASIS management and researchers will collaborate with major universities to develop and offer college level courses on key science and engineering topics, perhaps delivered via the Internet. They will also organize short-courses for university students on contemporary topics related to OASIS research and instruments.

OASIS management and researchers will also collaborate with K-12 teachers to develop primary and secondary level educational materials on the broad range of science and engineering topics that are relevant to OASIS. These will include both written and video teaching aids. This work will be coordinated by an educational specialist that is included as part of the annual operating and maintenance budget for OASIS (see Section 4). This staff education specialist will also be responsible for leveraging OASIS education and public outreach activities by making use of existing programs within government agencies such as NSF, NASA and NOAA and by engaging private foundations.

2 Science Challenges: Key Processes Necessary for the Formation of Habitable Planetary Atmospheres

2.2 Influence of Space Processes

2.2.1 How is the Earth's upper atmosphere affected by solar radiation?

As of January 2014, 1,015 extra-solar planets have been detected orbiting 758 stars within our galaxy, including at least two Earth-like planets orbiting within the habitable zone around another star (Kepler 62e and 62f). More than 3600 additional candidates from the Kepler mission are waiting to be confirmed (http://exoplanetarchive.ipac.caltech.edu). It is estimated that the number of Earth-like planets orbiting Sun-like stars within our galaxy exceeds 3 to 4 billion. The nearest such planet may be located within 12 light years of Earth [*Petigura et al.*, 2013]. Planets with Earth-like conditions to support carbon-based life must lie within the habitable zone (HZ)—traditionally defined as *the region around a star where the incident solar flux and a planet's surface temperature supports the existence of liquid water on the planet's surface* [*Kasting et al.*, 1993]. Habitable zone limits have recently been revised establishing the inner edge at 0.99 AU and the outer

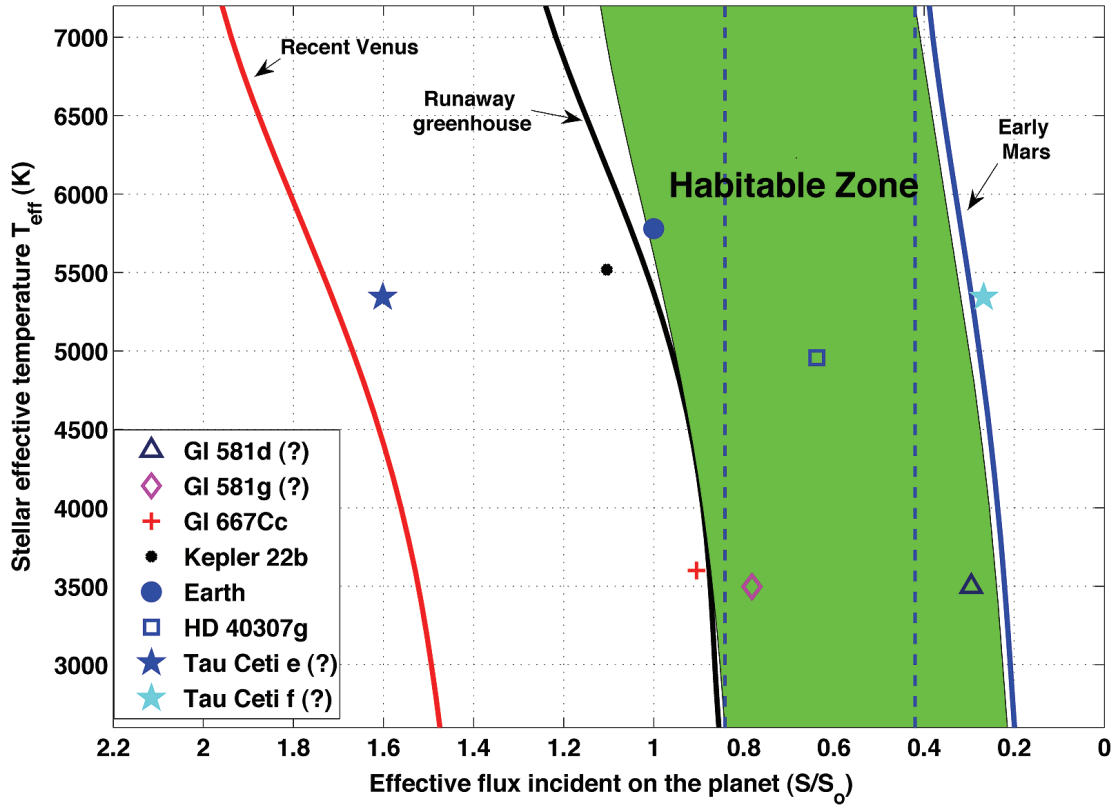


Figure 2.1.1-1 Various cloud-free habitable zone (flux) boundaries for stars with different effective temperatures (Teff). The boundaries of the green-shaded region are determined by the moist-greenhouse (inner edge, higher flux values) and maximum greenhouse (outer edge, lower flux values). A planet that receives stellar flux bounded by the two dashed vertical lines is in the HZ irrespective of the stellar type. Some of the currently known exoplanets that are thought to be in the HZ by previous studies are also shown. The (?)s for Gl 581 and Tau Ceti planet systems imply that there is an ongoing discussion about their existence. For stars with Teff < 5000 K, there is no clear distinction between runaway and moist-greenhouse limits (from *Kopparapu et al.*, 2013).

edge at 1.70 AU (see Figure 2.1.1-1 and [*Kopparapu et al.*, 2013]). Since climate systems include both positive and negative feedbacks, a planet's surface temperature is non-trivially related to incident stellar flux. Although it appears that Earth is perilously close to the inner HZ edge, in reality, cloud feedback, low upper tropospheric relative humidity, and many other atmospheric processes have yet to be included in HZ modeling. When this is done the habitable zone is likely to expand.

Of particular importance is how a planetary atmosphere deals with the extreme ultraviolet radiation portion of the stellar spectrum. Extreme ultraviolet radiation can be hazardous to life but is thought to have been instrumental in primitive Earth biogenesis processes [*Buccino et al.*, 2006]. Thus, a planet's atmosphere must be considered when evaluating the evolution and habitability of life-supporting environments. Present-day Earth's upper atmosphere acts as a shield protecting life from extreme solar radiation. Energy from the sun continuously bombards the upper atmosphere, intensifying atmospheric gaseous escape, ripping electrons from neutral molecules and atoms to form the ionosphere, energizing gas emissions in the form of airglow and auroras, and raising temperatures in the upper atmosphere 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 to fully represent the evolution of the atmosphere and its influence on life and human well being.

The irradiance, or energy flux, from the sun at wavelengths shorter than about 200 nm—called the *solar vacuum ultraviolet* (VUV)—includes the Schumann–Runge continuum (from 175 to 105 nm),

the Lyman alpha line near 121 nm, the extreme ultraviolet (EUV, from 30 to 105 nm), and the soft X-ray (XUV, from 0 to 30 nm) portions of the spectrum. The net energy flux shortward of 200 nm is ~ 4 orders of magnitude less than at visible wavelengths, and is sufficiently absorbed between 80 and 200 km altitude to protect biological systems on the surface. However, this portion of the solar spectrum is highly variable in time, which has large effects on photoionization, secondary ionization, gas excitation states, thermal dissipation and heating efficiencies.

The neutral gas heating due to VUV radiation is a fundamental, but poorly known process that determines the thermal structure of the upper atmosphere. The current lack of high spatial and temporal resolution measurements of temperatures in the height range between 100 and 1000 km, which OASIS will provide, has prevented progress in understanding the fundamental conversion of VUV radiation to thermal energy of the neutral gas in a planet's upper atmosphere. This has tremendous consequences for adequately estimating gaseous escape energetics as well as describing the energy balance of the upper atmosphere. OASIS will enhance our understanding of these heating processes by providing high spatial and temporal resolution measurements of temperatures throughout the upper atmosphere enabling the following questions to be addressed:

1. What proportion of VUV solar radiation is converted to thermal energy of the neutral gas in Earth's upper atmosphere and how does this vary with height?
2. How is the vertical thermal structure of the upper atmosphere influenced by short-term variations in the VUV flux?
3. How might the fundamental process of an upper atmosphere's absorption of solar VUV radiation contribute to improved estimates of habitable zones for candidate exoplanets?

2.1.2 How does geomagnetic activity modify the composition and temperature of the neutral atmosphere and ionosphere?

In addition to solar radiation, particles and fields emitted by the sun in the form of the solar wind can significantly impact the upper atmosphere. Although the interaction of the solar wind with the Earth's atmosphere is more complex than solar radiation, the energy deposited into the upper atmosphere by solar wind particles (mainly protons and electrons) and fields can rival the energy deposited by solar EUV radiation. Set in a strong intrinsic geomagnetic field, Earth's electrodynamically driven near-space plasma interacts with the hydrodynamically driven neutral atmosphere to dissipate solar wind energy captured by the magnetosphere. Because the dissipation processes become equally effective in influencing the action of the plasma and the neutral gas for altitudes between 100 – 1000 km, this a key region for exploring how geomagnetic storms affect the coupling of space with our atmosphere.

Geomagnetic storms occur because of enhanced coupling between the solar wind and the Earth's magnetosphere leading to a concentration of electromagnetic energy that is directed into the high latitudes. The geomagnetic storm energy is manifested in the upper atmosphere by atmospheric currents and energetic particles that can ionize, heat, and force the upper atmosphere, altering the composition, dynamics and thermal structure around the globe. The energy deposition for geomagnetic activity occurs primarily between 100 – 200 km altitude, with the more energetic precipitating electrons transferring their energy to the neutral gas between 100 – 120 km [*Fuller-Rowell and Evans,* 1987] and current dissipation transfer in the form of Joule heating occurring between 110 – 140 km [*Thayer and Semeter*, 2004].

Solar disturbances, such as coronal mass ejections where solar material is catastrophically ejected from the sun towards the Earth, can lead to major geomagnetic storms. These events are most numerous during solar maximum and typically do not persist beyond a solar rotation (~27 days at the synodic period). However, natural periodicities of solar

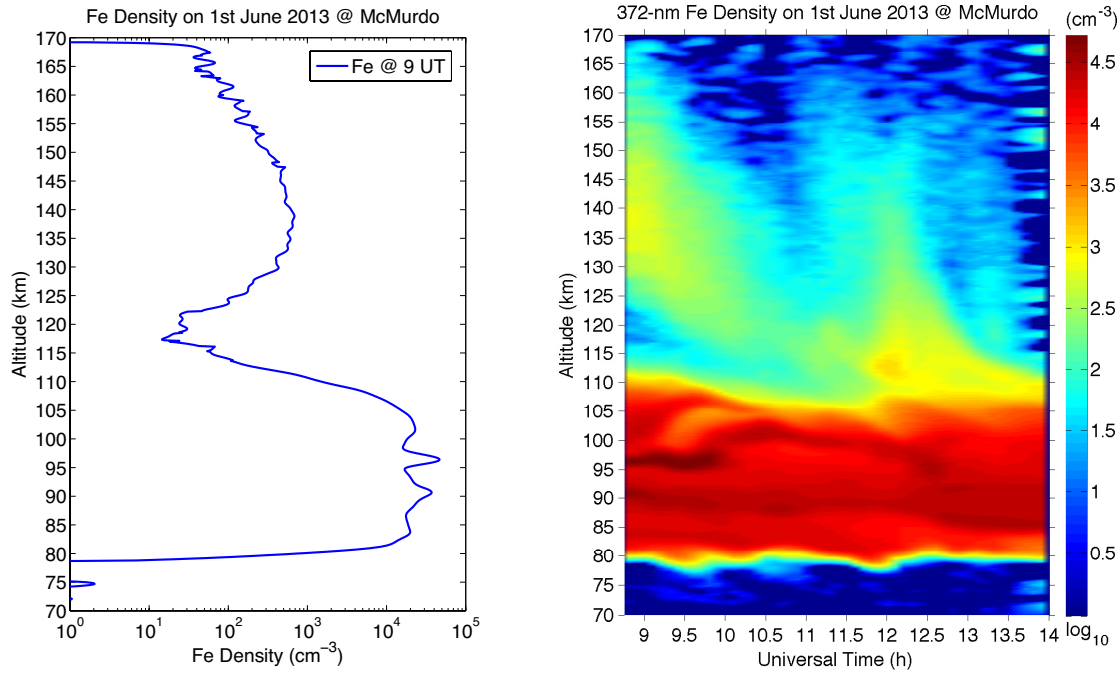


Figure 2.1.2-1 Tenuous layers of Fe, Na and K atoms exist well into the thermosphere. They can be probed with resonance fluorescence lidars to determine the temperature and wind velocity of the neutral atmosphere. Because the thermospheric densities of these metal atoms are typically 50 to 1000 times smaller than the densities at the layer peaks near 90 km, high power-aperture product lidars, like the OASIS LLT, are required to derive scientifically useful measurements. These observations, made with a modest Fe Boltzmann temperature lidar (P_{Laser}-A_{Tele}=0.5 Wm^2) at McMurdo, Antarctica, show neutral Fe layers reaching as high as 170 km on June 1, 2013. (Data courtesy of Dr. Xinzhao Chu and Mr. Weichun Fong, University of Colorado, Boulder, CO.)

disturbances (5.5, 6.75 and 9-day periods), associated with corotating interaction regions (CIRs) within the solar wind, have been detected and correlated to geomagnetic storm indices [e.g., *Lei et al.*, 2008; *Thayer et al.*, 2008]. Owing to the variable duration and intensity of geomagnetic storm events, the response of the upper atmosphere is quite diverse and poorly known—particularly between 100 – 200 km. However, the tenuous layers of meteoric metals that exist in this region can be probed with powerful Doppler lidars to measure neutral winds and temperatures (Figures 2.1.2-1 and 2.1.2-2).

To significantly enhance our understanding of how Earth's atmosphere interacts with its near-space plasma environment during geomagnetic storms requires observations of both the neutral atmosphere and plasma in the SAIR. OASIS and LLT will provide high spatial and temporal resolution measurements of temperatures and winds throughout much of the upper atmosphere capturing the dynamic response of the neutral gas to geomagnetic activity (Figure 2.1.2-2). A co-located incoherent radar will provide similar observations of the plasma and its response. This will enable the following questions to be addressed:

1. How is the upper atmosphere modified with altitude during a geomagnetic storm?
2. How does the upper atmosphere recover from a geomagnetic storm event?
3. How might the preconditioned state of the upper atmosphere modify the influence of geomagnetic storms?

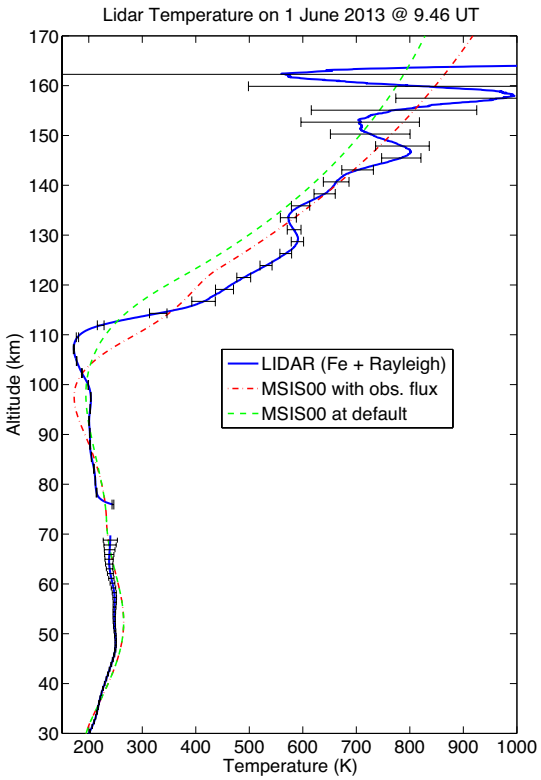


Figure 2.1.2-2 By combining Rayleigh and resonance fluorescence lidar techniques, OASIS will be able to measure neutral temperature and wind profiles from 30 to almost 200 km and from 300 to 1000 km. This temperature profile, extending from 30–165 km, was derived from the Fe Boltzmann lidar dataset shown in Figure 2.1.2-1. Because the OASIS Fe lidar will have a power-aperture product that is 2000 times larger, the OASIS measurement errors will be almost 50 times smaller. (Data courtesy of Dr. Xinzhao Chu and Mr. Weichun Fong, University of Colorado, Boulder, CO.)

2.1.3 What is the influx of cosmic dust and how does it affect the evolution of the Earth's atmosphere and climate?

The Earth formed 4.5 billion years (4.5 By) ago by accretion of debris from the solar nebula. Theoretical models suggest that the inner terrestrial planets formed on a relatively short time scale of 10–100 million years. After this initial accretion phase the Earth continued to be bombarded by large objects for perhaps the next billion years. It is now thought that planetesimals and comets, which formed beyond 2.5 AU where it was cold enough for water ice to accumulate, were the major sources of Earth's water. They may also have been the source of the complex organic chemicals necessary for the origin of life.

Today the Earth continues to accrete dust and small meteors whose global mass influx is estimated to be up to several hundred metric tons per day. Much of this mass consists of gaseous species that are ablated (evaporated) from the high-speed particles when they are heated to high temperatures caused by friction with the atmosphere. The main sources of dust in the solar system are the sublimation of comets as they approach the Sun and collisions between asteroids in a belt between the orbits of Mars and Jupiter. Dust particles from long-decayed cometary trails (in particular from comets Encke and 55P/Tempel-Tuttle) dominate the continuous sporadic input. Fresh dust trails, produced by comets that crossed the Earth's orbit recently (within the last 100 years or so), are the origin of meteor showers like the Perseids (Figure 2.1.3-2).

The significant impact of cosmic dust on the atmosphere is only now beginning to be fully appreciated [*Plane*, 2012]. Meteor deceleration and ablation between 80 and 120 km altitude deposits significant energy, substantial mass, and contributes to a complex chemistry that lead to sporadic laminae of metallic ions and neutrals. The ablated atoms are involved in a variety of ion and neutral chemical processes as the meteoric debris is transported downward by advection, eddy mixing and other wave effects. Below 85 km neutral chemistry is responsible for the formation of relatively stable chemical reservoirs of the

Figure 2.1.3-1 Noctilucent clouds (NLCs) above Oslo, Norway. These water ice clouds, the highest on Earth, occur between 80 and 86 km primarily at high latitudes during summer. First reported in 1885, they have been growing brighter and spreading to lower latitudes during much of the last century, so they are a clear signal of climate change. Meteoric smoke particles (MSPs) are widely considered to be the nuclei on which the ice crystals grow. OASIS lidars will measure the MSP profiles while the radars probe the "dusty plasmas" that result when these particles acquire charge (Image courtesy of Dr. Gerd Baumgarten, Leibniz-Institute of Atmospheric Physics e.V. at the University of Rostock, Kühlungsborn, Germany)

meteoric species. These compounds are permanently removed from the mesopause region by forming or condensing onto meteoric smoke particles (MSP). The MSPs are swept towards the winter pole by the meridional circulation system and sediment into the stratosphere, where they play an important role in the formation of stratospheric aerosols within the polar vortex and in the chemistry of ozone. Eventually the debris settles onto the Earth's surface. When MSPs, which are rich in highly soluble $Fe_2(SO_4)_3$, are deposited in the Southern Ocean around the coastal shelf of Antarctica, the bio-available Fe fertilizes the growth of phytoplankton, which impacts the atmospheric CO_2 cycle and potentially climate. The input of bio-available Fe into the Southern Ocean from MSPs is likely to be as large as, and perhaps much larger than the Aeolian dust input [*Plane*, 2012].

Current estimates of the daily influx of cosmic dust are highly uncertain. As shown in Table 2.1.3, measurements of the global input to the atmosphere vary from ~2 to 270 t d^{-1} (metric tons per day)! Zodiacal cloud observations (See page x) and space-borne dust detection (e.g., micro-crater observations on spacecraft surfaces) indicate a daily input of 100 – 300 t d^{-1} (dark blue shading in the Table), which is mostly in agreement with the accumulation rates

of cosmic elements in polar ice cores and deep-sea sediments (grey shading). In contrast, measurements of the products of meteoric ablation such as Na, Fe, ionized meteor trails and meteoric smoke particles in the middle atmosphere (light-blue shading)—by radar, lidar, high-flying aircraft and satellite remote sensing—indicate that the daily input is only 2 – 60 tons.

There are two reasons why this enormous discrepancy matters. First, if the upper range estimates are correct, then vertical transport in the middle atmosphere may be considerably faster than is generally thought to be the case, or the degree of ablation of the incoming material—which creates the atoms, ions and aerosols observed in the middle atmosphere—may be significantly overestimated. On the other hand, if the lower range estimates are correct, then our understanding of dust evolution in the solar system, and transport mechanisms from the middle atmosphere to the Earth's surface, will need substantial revision. Both situations have important implications for understanding the formation and evolution of exoplanet atmospheres, and both rely on understanding transport processes of the middle and upper atmosphere. Second, cosmic dust particles enter the atmosphere at high speeds (11–72 km s^{-1}), and their ablation injects metals into the atmosphere, which are involved in a diverse range of impacts, including the formation of layers of metal atoms and ions, nucleation of noctilucent clouds (Figure 2.1.3-1), effects on stratospheric aerosols and O_3 chemistry, and fertilization of the ocean with bio-available Fe. These impacts obviously depend on the magnitude of the cosmic dust input.

There is good evidence that the cosmic dust input has varied substantially during Earth's history and attempts have been made to link these variations to fluctuations in climate. The ^{3}He accumulation in Cretaceous limestone suggests that the cosmic dust influx varied episodically by a factor of 4 between 73 and 100 My ago. Measurements of iridium in polar ice indicate that the rate of micrometeorite deposition in Antarctica has varied by a factor of 25 in the last 120 thousand years. In fact, there is empirical evidence of a mass imbalance in the zodiacal cloud, which appears to be over-massive in relation to current sources by 1 to 2 orders of magnitude. This can be explained by the injection of dust from a large comet, which entered into a short-period near-Earth orbit, when the cosmic dust influx might have been large enough to affect terrestrial climate by changing the optical depth of the atmosphere. A survey with the Spitzer Space Telescope has shown that short-period Jupiter family comets are very likely to generate substantial debris trails. It has recently been postulated that ice age conditions lasting for a millennium

Figure 2.1.3-2 Photograph of a Perseids meteor trail taken from the International Space Station by astronaut Ron Garan on August 13, 2011. Visible Perseids meteors, like the one in this photograph, are large particles that were ejected from the comet Swift-Tuttle. Although periodic meteor showers, such as the Perseids and Leonids, can be impressive to view from Earth, the majority of the cosmic dust that enters the atmosphere is comprised of much smaller particles with individual masses less than 10 μg. Current estimates of the global cosmic dust influx vary from several metric tons per day to several hundred tons per day. OASIS lidars will help reduce this large uncertainty by measuring the meteoric smoke particles and dust in the atmosphere and by quantifying the atmospheric transport processes. (NASA Image ISS028-E-24847)

Table 2.1.3 Estimates of the global cosmic dust input rate to the Earth's atmosphere (deep blue = extra-terrestrial estimate; light blue = middle atmosphere estimate; grey = ice core/deep-sea estimate). Taken from [*Plane*, 2012].

Technique	Cosmic Dust Influx (t/d)	Reference See *Plane* [2012]	Potential problem of technique
Zodiacal dust cloud observations and modelling	270	*Nesvorný et al.* [2009]	Needs to be constrained by terrestrial meteor radars
Long Duration Exposure Facility	110 ± 55	*Love & Brownlee* [1993]	Sensitive to IDP velocity distribution
High performance radars	5 ± 2	*Mathews et al.* [2001]	Possible velocity bias/ selective mass range
Conventional meteor radars	44	*Hughes* [1978]	Extrapolation, selective mass/velocity range
Na layer modelling	20 ± 10	*Plane* [2004]	Sensitive to vertical eddy diffusion transport
Na flux obs with Doppler lidars	59 ± 11	*Gardner et al.* [2013]	Sensitive to ablation assumptions
Fe layer modelling	2	*WACCM* (see *Plane* [2013])	Depends on vertical transport
Fe/Mg in stratos. sulphate layer	22 - 104	*Cziczo et al.* [2001]	Data has limited geographic extent
Optical extinction measurements	10 - 40	*Hervig et al.* [2009]	Particle refractive indices uncertain
Fe in Antarctic ice core	15 ± 5	*Lanci et al.* [2007]	Very little wet deposition by snow
Fe in Greenland ice core	175 ± 68	*Lanci & Kent* [2006]	Uncertain atmospheric transport/deposition
Ir and Pt in Greenland ice core	214 ± 82	*Gabrielli et al.* [2004]	Uncertain atmospheric transport/deposition
Cosmic spherules in Antarctic ice	7 ± 2	*Taylor et al.* [1998]	Flux of unablated material only
Os in deep-sea sediments	101 ± 36	*Peuker-Ehrenbrink* [1996]	Focusing by ocean currents
Ir in deep-sea sediments	240	*Wasson & Kyte* [1987]	Focusing by ocean currents

around 12.9 ky ago were caused by debris from a large short-period comet, whose remnants now exist as the *Taurid Complex*. An increase in the cosmic dust influx has also been suggested as a cause of the "snowball" earth glaciations during the Neo-proterozoic era (~1000–540 My ago), probably not by direct negative radiative forcing but through indirect forcing following the nucleation of ice clouds.

Since cosmic dust plays such important roles in the composition of the Earth's atmosphere and potentially climate, reducing the uncertainty in the daily mass influx and clarifying its impact has implications for a wide range of geophysical processes including the study of exoplanets. OASIS will contribute by providing detailed measurements of meteoric species (such as Fe, Na and meteoric smoke particles) and their vertical transport throughout the middle and upper atmosphere enabling the following questions to be addressed:

1. What is the magnitude of the global cosmic dust input?
2. How do transport processes affect the distribution of cosmic dust in Earth's atmosphere?
3. What impact does cosmic dust have on the Earth's atmosphere and climate?

2.2 Influence of Planetary Processes

2.2.1 What is the role of the magnetic field in defining an Earth-like planet?

The orientation of the Earth's magnetic field lines is similar to that of a bar magnetic aligned with the axis of rotation (Figure 2.2.1-1). The field lines are nearly perpendicular to the surface near the poles and parallel to the surface near the equator. The force exerted by magnetic fields on charged particles is one of the four fundamental forces of nature and it plays a central role in organizing the plasma in the near-Earth space environment. This is obvious from optical imagery of Earth from space, which generally shows airglow from energetic particle impacts on the upper atmosphere con-

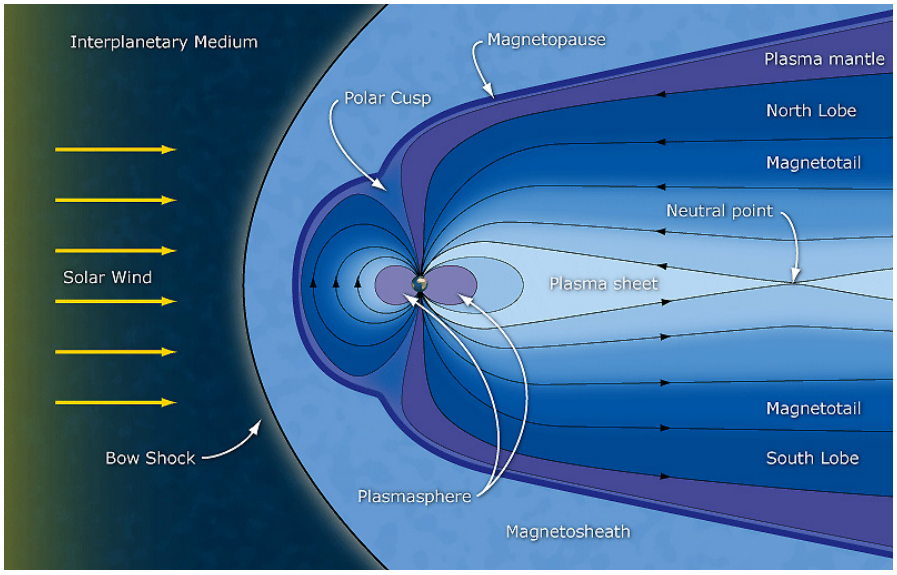


Figure 2.2.1-1 Schematic diagram of the Earth's magnetosphere. (Image courtesy of NASA)

centrated in rings near Earth's polar regions that are called the *auroral ovals* (Figures 2.2.1-2 and 2.2.7-1). If the ionosphere at middle and low latitudes were visible to the naked eye, it too would appear to be organized in latitude according to the geometry of Earth's magnetic field (Figure 2.2.1-3).

Figure 2.2.1-2 The Aurora Australis (white, green and red emissions) and airglow layers (yellow-orange emission band) observed from the International Space Station over the Indian Ocean on September 17, 2011. This aurora was excited by energetic particles that were ejected by the Sun on September 14, 2011. When these energetic electrons and protons encounter the Earth's magnetosphere, they are guided along the magnetic field lines and collide with oxygen and nitrogen molecules in the upper atmosphere (100-400 km), typically at high latitudes, causing them to glow and produce the visible aurora. The faint airglow emission band between 80 and 100 km is caused by the recombination of atoms, which were photoionized by the Sun during the day, and by chemi-luminescence caused mainly by oxygen and nitrogen reacting with hydroxyl ions. When located in the auroral zone, OASIS will probe the impact of the aurora on neutral temperatures and winds in the thermosphere. (NASA Image ISS029-E-6020)

This organized structure extends outward through the plasma sphere, the region of plasma that rotates with the Earth under the influence of its magnetic dynamo, and into the magnetosphere, with lobes that reflect the shape of the Earth's magnetic field being deformed by pressure from the solar wind (see Figure 2.2.1-1).

The presence of a background magnetic field fundamentally affects the plasma surrounding the Earth, making it a strongly anisotropic medium. The tendency for material, momentum, and energy transport along the magnetic field lines is much greater than across them. This has the effect of partially insulating the low- and middle-latitude ionosphere from magnetospheric forcing where the field lines are nearly parallel to the surface, while exposing the auroral regions at high latitudes and the polar caps to solar, magnetospheric and cosmic sources more directly. If this were not the case, energetic particle radiation from solar storms and of cosmic sources would severely threaten the habitability of the planet. As it is, energetic particles associated with solar and geomagnetic storms pose a danger mainly to passengers of aircraft (and spacecraft) flying at high latitudes.

Moreover, the transport of material, momentum, and energy goes not just from space to the Earth but also from Earth to space. For example, ions such as H^+ can be accelerated out along open magnetic field lines near each pole and lost to space. The electric fields generated by dynamo action associated with the motion of the neutral upper atmosphere are conveyed efficiently throughout the ionosphere and plasma sphere. These fields exhibit structure imposed from atmospheric solar and

lunar tides that are generated in the lower atmosphere and then propagate into the upper atmosphere.

A remarkable attribute of the magnetic field is that the Hamiltonian for charged particles can be written in a form that is magnetic-field (**B**) free. This is profound, since it implies that the equilibrium configuration of the geospace system does not depend on **B**. Indeed, the equilibrium solution for horizontal plasma drifts simply follows the drifts of the neutral upper atmosphere. That the geospace system is so clearly ordered by **B** is evidence that it is seldom in equilibrium. At high latitudes, forcing from the magnetosphere occurs on timescales too short for equilibrium to be reached. At low latitudes, the horizontal magnetic field lines inhibit vertical transport to the extent that hydrostatic balance and diffusive equilibrium cannot be achieved.

The existence of free energy associated with non-equilibrium states increases the tendency for instability. The ionosphere is much more prone to instability than the troposphere. At low, middle, and high latitudes, convective instabilities occur in the ionospheric E and F regions (~100–250 km). These give rise to irregularities with scale sizes spanning the range from hundreds of kilometers to sub-meter scales. Dynamical and streaming instabilities occur in the ionosphere as well and contribute to the irregularities, which function like diffraction screens for radio waves passing through them. The fading and scintillations that result interfere with communication and navigation systems and constitute operational hazards to critical technological services. Anticipating, forecasting, and mediating the effects of ionospheric irregularities is a central focus of the National Space Weather Program.

By observing neutral temperature and winds above 100 km, OASIS lidars, in combination with radar observations of the plasma, will enable the following questions to be addressed.

1. Where and when in the upper atmosphere is the neutral atmosphere organized by the magnetic field configuration?

2. How does the strength and configuration of an intrinsic magnetic field contribute to the evolution of a planetary atmosphere?

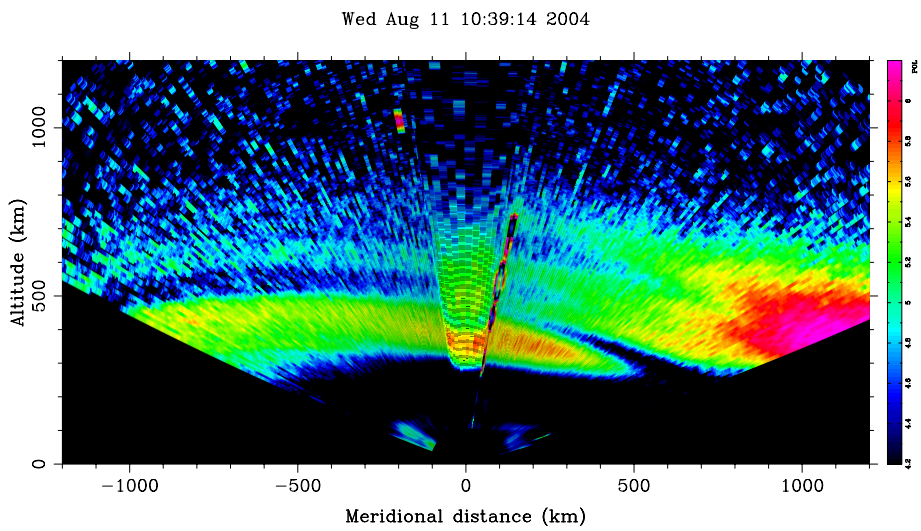


Figure 2.2.1-3 Incoherent scatter radar observations of electron densities in a meridional cut through the equatorial ionosphere showing plasma irregularities aligned with the Earth's magnetic field lines. (Image courtesy of Dr. David Hysell, Cornell University, Ithaca, NY.)

2.2.2 What is the role of plasma-neutral coupling in establishing the predominant states of planetary atmospheres?

At Earth, and for virtually every object in the Universe, there is a remarkably small transition between the sensible atmosphere of the body and the tenuous plasmas that exist above and between all such objects. The physical and chemical processes that occur between a body's atmosphere, and the fully ionized gases in regions well beyond it, involve fundamentally important processes. Plasma-neutral coupling is a fundamental process in any planetary system that supports an atmosphere. For objects with dense gases at their visible surface (Sun, stars, the giant planets of our solar system, and exoplanets), the plasma-neutral coupling includes the classic meteorological processes, photo-chemical reactions of neutrals and ionization and plasma transport to regions beyond. An additional complexity in plasma-neutral coupling occurs for worlds where surface topology also modulates upward coupling from neutrals to plasmas. Thus, Earth, Venus, Mars and Titan comprise a special challenge for understanding the diversity of coupled universal processes. Further complexity arises when an intrinsic magnetic field is present to couple external and internal electrodynamic processes with the atmosphere; a higher order of complexity realized in our solar system only by Earth.

That one of the most complex planetary atmospheres (Earth) is readily accessible to all modern research tools of ground-based and spacebased investigation offers an extraordinary opportunity to advance our understanding of our home planet, as well as the very nature of space-atmosphere-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 over vast regions of the Universe. The terrestrial atmosphere-ionosphere system offers the closest possible example of such a transformation, and yet even here we have many unanswered questions dealing with universal processes in such a concentrated occurrence region.

We now realize that the dense neutral atmosphere at Troposphere-Stratosphere heights is a domain that is strongly coupled to the upper atmosphere. Their influences define the entry point to the SAIR. Mesospheric waves, tides and winds govern the degrees of upward transport of momentum and energy. The most energetic photons and cosmic rays penetrate to the mesosphere and with them the onset of the atmosphere-ionosphere system. The density of neutrals is still so great that collisional processes govern the plasmas at mesospheric heights (<100 km), as if no magnetic field were present. The polar summer mesosphere exhibits a unique form of plasma-neutral coupling. Breaking waves in the mesosphere are a source of instability and turbulence, which can give rise to strong fluctuations in the index of refraction. The fluctuations are made much stronger still by the finite plasma density in the ionospheric D-region (75-95 km). Because of the low tempera-

tures, the presence of condensation nuclei, and a small amount of water vapor, ice crystals form and lead to the production of polar mesospheric clouds (Figure 2.1.3-1).

Along with ice crystals, meteoric dust is an important component of the D-region composition. It has only recently been appreciated that a three-component D-region plasma composed of electrons, ions, and charged aerosols exhibit extraordinary behavior in the mesosphere that is related to universal processes in dusty plasmas. One aspect is the abatement of normal diffusive processes that leads to anomalously high radar scattering cross-section due to index of refraction fluctuations. Consequently, so-called polar mesospheric summer echoes (PMSEs) occur in tandem with polar mesospheric (noctilucent) clouds and serve as telltale signs of neutral instabilities and turbulence in a medium that would otherwise be difficult to probe [*La Hoz* (2006)]. OASIS lidars, employing the LLT, will provide detailed observations of neutral temperature, turbulence and particulate matter (meteoric dust and smoke) in the mesosphere that will help advance research of dusty plasmas.

In just the next hundred kilometers of altitude (100-200 km), the fall-off in densities and the increase of ionization by solar X-rays and EUV, and energetic particle precipitation signal the onset of remarkably complex electrodynamics and plasma chemistry. This multi-component, partially ionized plasma system requires a robust theory of production, loss and transport of non-homogeneous, non-isotropic processes. Dynamo action, conductivity changes, currents, winds and waves promote plasma-neutral processes throughout the SAIR, which vary with altitude, latitude, longitude and time. Hence, describing the behavior of the SAIR is one of the most challenging aspects of characterizing the complete behavior of a planetary system.

In the E-region ionosphere (95-150 km), the plasma begins to feel the presence of the magnetic field while still being strongly influenced by neutral collisions. In this altitude regime, the neutral atmosphere clearly plays a critical role in the electrodynamics, alternating between acting as a drag and a driver. The lower E-region atmosphere is particularly critical in this context since it represents the transition where the effects of plasma forcing become increasingly important with increasing altitude and where strong current systems occur. Influxes of energetic electrons and protons produce auroral sources (ionization and aurora) and sinks of energy (Joule heating) for the atmosphere-ionosphere system to process. In spite of the critical importance of the region, direct measurements of important neutral parameters, including neutral velocities and temperatures, are almost completely lacking. Passive ground-based optical measurements have generally had significant height uncertainties because of the strong variation in the emission altitudes during disturbed conditions. Incoherent scatter radar measurements only provide indirect estimates of the neutral winds that require assumptions that are often questionable, especially in disturbed conditions. Optical remote satellite measurements can provide measurements in the lower E region with broader global coverage, but the height resolution is generally poor in the altitude range where all the neutral and plasma parameters are varying rapidly with altitude. The combination of direct wind and temperature measurements provided by OASIS lidars in the lower E region, coupled with high-resolution plasma parameter measurements from radars, will provide significant new insights into the relevant coupling processes in the SAIR.

Because the plasmas and neutrals are so heavily coupled in the thermosphere and ionosphere, it is an observational requirement to have better overlapping neutral/plasma data throughout this region, in order to constrain our understanding of their coupling mechanisms. Then observations of plasmas can provide information about neutrals, and visa versa. There are a number of plasma-neutral processes that are at play in the SAIR that display

a rich diversity with altitude, latitude, longitude and time. At low latitudes and E-region altitudes, neutral winds generate dynamo-driven electric fields that drive plasma motions whose action feeds back on neutral processes leading to a dynamic plasma-neutral exchange that is seldom in steady state. Furthermore, these processes can lead to plasma instabilities with profound consequences—as evidenced by the production of equatorial density bubbles that extend throughout the ionosphere and are believed to be seeded by neutral-plasma processes in the lower E region. At high latitudes, electrodynamic forcing imposed by external processes drives plasma through the neutral gas with global consequences on the neutral temperature and dynamics. These processes cannot be fully developed due to the lack of neutral gas measurements in the 100-200 km altitude range. OASIS measurements of neutral winds, temperature, turbulence, dust, metal atom densities, and plasma densities between 75 and 200 km will finally advance critical questions related to universal plasma-neutral processes, such as:

1. How do neutral-wind dynamo regions of Earth develop, evolve and influence plasma and neutral processes?
2. What is the morphology and consistency of dusty plasmas in the mesosphere and how do they affect the neutral gas behavior in this region?

2.2.3 What is the mean neutral circulation and thermal structure in the Earth's space-atmosphere-interaction region?

Atmospheric constituents are transported horizontally and vertically by the prevailing winds (advective transport) and through mixing processes associated with gravity waves, turbulence and molecular diffusion. Ionospheric plasma is redistributed by ExB drift, field-aligned transport, and ambipolar diffusion. Above the exobase (500-700 km), escape of atmosphere particles to outer space becomes increasingly important.

The upper atmosphere is heated by energetic processes such as absorption of ultraviolet (UV) and extreme ultraviolet (EUV) radiation and by energetic particle precipitation. These heating processes, which are generally non-uniform, are an important driver of atmospheric general circulation patterns, such as the summer to winter circulation in the stratosphere, mesosphere and lower thermosphere. The associated Coriolis force drives zonal jets including the polar vortex. In the stratosphere, quasi-stationary planetary waves can exert strong westward forcing on the winter stratospheric jet, weaken the polar vortex, and strengthen the Brewer-Dobson circulation. These waves modulate the transport of chemical species in zonal, meridional and vertical directions as exemplified by changes of ozone and NO_x during stratospheric sudden warming (SSW) events.

The middle atmosphere and lower thermosphere (MLT) circulation is driven primarily by gravity wave forcing, so much so that this region is not in radiative equilibrium. Consequently, the stratospheric jets in both hemispheres close and reverse directions, and the summer to winter meridional circulation is significantly enhanced. In addition the upward circulation in summer and downward circulation in winter are also enhanced. There is, however, still a large uncertainty in the MLT circulation, because the global distribution of gravity waves and their dynamical and thermal effects during wave breaking are only crudely parameterized in GCMs and poorly constrained by observations. Consequently, the transport by the MLT circulation, which is important for constituent exchanges between the atmosphere and near space environment (e.g., transport of NO_x, O, etc.), is not well quantified.

At lower latitudes, forcing by planetary waves and gravity waves drives equatorial oscillations, such as the quasi-biennial oscillation (QBO) and semi-annual oscillation (SAO). Apart from modulating zonal transport in the equatorial region, they also affect the thermal structure and meridional/vertical circulation and transport through thermal wind balance. Because of the aforementioned limited knowledge of gravity waves and gravity wave forcing, uncertainty also exists regarding the transport caused by these equatorial oscillations, especially above the upper stratosphere.

Waves in the stratosphere, mesosphere and thermosphere can reach very large amplitudes, and the advective transport by these waves becomes very strong. Apart from inducing a mean meridional circulation, they affect all three wind components in a highly non-uniform and complex manner, which is difficult to characterize. This is epitomized by the observed transport of water plumes released in MLT from shuttle launches, and its possible connection to tides, planetary waves and gravity waves. Wave dissipation and breaking also induces a net scalar flux, such as heat flux and constituent fluxes [*Walterscheid,* 1981; *Garcia et al.*, 2007; *Gardner and Liu*, 2010], while chemistry-wave coupling further modifies the transport of chemically active constituents. This is an area where OASIS will make a particularly significant contribution as the lidars will be capable of measuring gravity momentum, heat and constituent fluxes from 30 to at least 125 km with high accuracies and resolutions.

Turbulent diffusion caused by breaking waves is a ubiquitous feature of the atmosphere, at least up to the turbopause. Above the turbopause, molecular diffusion plays an increasing dominant role in the transport of neutral constituents. Determination of molecular diffusive transport requires accurate measurements of neutral temperature and density, which the OASIS LLT will provide, from which the mean molecular diffusion coefficient can be computed.

Accurate characterization of the mean circulation, wave advection, turbulent diffusion, and molecular diffusion is crucial for understanding and quantifying the system-wise transport of chemical species in planetary atmospheres. For example, on Earth these processes influence the pathways for transporting NO_x from the thermosphere down to the stratosphere where it can catalyze the destruction of ozone. Ion transport generally follows the neutral species in the ionosphere E-region (and lower), where the ion-neutral collision frequency is much higher than the ion gyro frequency. At higher altitudes, the ion-neutral collision frequency becomes smaller with decreasing neutral density, and the ion transport is increasingly subjected to geomagnetic forcing, field-aligned transport, ExB drifts, and ambipolar diffusion. Around the F2 peak, these become the dominant transport processes, and so the knowledge of neutral wind, ion drifts, and neutral and plasma temperatures are needed to quantify these processes. Above the exobase,

escape of hydrogen, helium and their ions through Jeans escape, polar outflow, and charge exchange becomes increasingly important.

Because of its large height coverage and sensitivity, the OASIS LLT will characterize both the mean state of the atmosphere (winds, temperature and density) as well as the smaller scale perturbations and the concomitant momentum, heat and constituent fluxes caused by waves and turbulence. These observations from 30 to almost 200 km and 300 to 1000 km will provide important data for testing theories and models with unprecedented detail and precision enabling four critical questions to be addressed.

1. What is the mean circulation and its seasonal variations in the middle and upper atmosphere?
2. What is the mean thermal structure and its seasonal variations in the middle and upper atmosphere?
3. What are dynamical and thermal effects of breaking waves and how do they impact the QBO, SAO and MLT circulation?
4. How are the various dynamical, chemical, thermal and electrodynamic processes coupled vertically to produce the observed neutral and plasma structure in the upper atmosphere?

2.2.4 How do waves across various scales control large-scale circulation in the space-atmosphere-interaction regions of Earth-like planets?

Waves are coherent atmospheric motions that are departures from the mean background state. Wave motions across a wide range of scales, from planetary waves to the smallest scale gravity waves, have profound affects on the thermal structure, composition and circulation of the Earth's atmosphere, primarily through their vertical transport of heat, constituents and horizontal momentum and through the generation of turbulence. Waves are expected to be ubiquitous in the atmosphere of any Earth-like planet, because the disturbances that produce them, such as wind blowing over mountains, convection created by heating at the surface and various instabilities of fluid motion, are similar to those on Earth. As waves propagate upward from their sources in the lower atmosphere into the SAIR, the amplitudes of their motions grow exponentially in response to decreasing atmospheric density. Eventually the motions become so large that nonlinear processes cause the waves to gradually dissipate their energy or in some cases to break. This causes energy to cascade between wave scales and generates turbulence, which enhances the mixing of chemical constituents, and accelerates the mean flow through the deposition of wave momentum.

The dynamics of the space-atmosphere-interaction region at Earth is important for several reasons. It is within this region that the major atmospheric constituents transition from being well-mixed to being

stratified according to their relative atomic and molecular weights in response to molecular diffusion and gravity. The altitude at which this occurs, near 100 km, is called the *homopause* or *turbopause*. The turbopause is thought to vary spatially and temporally, thus imposing this variability on neutral and ionized species aloft, and thereby affecting radio waves that form the basis of many communications and navigation systems and the drag experienced by satellites in low Earth orbits. In addition, neutral winds can interact with the local plasma in an intrinsic magnetic field to produce quasi-static electric fields through the so-called dynamo mechanism. These electric fields can map along magnetic field lines to much higher altitudes and redistribute plasma.

One of the most fundamental, yet least-understood processes affecting the dynamics of the SAIR concerns vertical evolution of the wave spectrum through the lower and middle thermosphere (ca. 100-200 km) where many of the waves are dissipated. Our current understanding is more qualitative than quantitative. OASIS LLT's ability to probe wave motions in this region, to almost 200 km, will provide fundamental insights on the dynamics that potentially impact the Earth's atmosphere well into the thermosphere.

The dissipation of vertically propagating gravity waves in the thermosphere, and the generation of secondary gravity waves, have been studied theoretically and through modeling, and similar processes are thought to occur at Mars [*Yiğit and Medvedev,* 2010]. The vertical propagation of tides, their dissipation, and their driving of the mean flow also have similarities at Earth and Mars [*Moudden and Forbes*, 2009]. It is likely that similar processes are occurring at other planets as well. Yet, a quantitative understanding of the dynamics of the SAIR remains a significant challenge. For instance, we still do not know the true nature of the mixing processes that result in existence of the turbopause, and whether turbulent (eddy) diffusion is the correct way to physically account for the mixing effects that are observed. We do not have a basic understanding of how instabilities occur within a population of waves, how instabilities transition to turbulence, how the turbulence evolves and feeds back to affect the waves, and how constituents respond to such processes over a range of temporal and spatial scales. We have only a limited perspective on how gravity waves interact with larger-scale and longer-period tides and planetary waves that modify their propagation and dissipation characteristics, and how the wave spectrum gives up net heat and momentum to modify the mean atmospheric state. Moreover, our ability to parameterize the above sub-grid processes in general circulation models is extremely limited. OASIS LLT's ability to probe wave motions and turbulence in exquisite detail will provide fundamental insights on the dynamics that potentially impact the Earth's atmosphere throughout the SAIR.

The current state of affairs can be described as follows. The major dynamical processes in the SAIR that are universal to all planetary atmospheres have been identified. We know these processes play important roles in planetary evolution, and we are making some theoretical and modeling progress in understanding them. However, the current lack of high resolution, spatially and temporally coincident measurements of winds, turbulence, temperatures, densities and constituents is the primary impediment to the transformative understanding of planetary SAIRs that can inform us about the evolution of planetary atmospheres within and external to our solar system. OASIS will provide that understanding by providing the observational data required to address the following questions:

1. How do nonlinear interactions and dissipation control the spatial and temporal evolution of the wave spectrum that reaches the space-atmosphere-interaction region?

2. How much does the evolving wave spectrum contribute to the mean thermal and wind structure of the space-atmosphere-interaction region?

3. How does one parameterize the transfer of heat and momentum from sub-grid wave and turbulence processes in general circulation models of the global atmosphere?

2.2.5 How does wave-induced transport influence the structure and composition of Earth-like planetary atmospheres?

In the Earth's middle and upper atmosphere, gravity waves play a major role in establishing the general circulation through their vertical transport and deposition of horizontal momentum. Momentum deposition and its effects are well known and incorporated in GCMs (atmospheric General Circulation Models) using parameterization schemes. Less known and understood are the roles that waves play in the vertical transport of heat and constituents, fundamental processes that affect the energy balance, chemistry and composition of the atmosphere below the turbopause. Recent high-resolution lidar measurements have revealed that heat and constituent transport effects are especially significant in the mesopause region (80–100 km) where the wave amplitudes are large and dissipation is strong. Because heat, constituent and momentum transport are universal consequences of wave motions, they play crucial roles in the dynamics of all planetary atmospheres.

The momentum transported upward from the Earth's lower atmosphere by gravity waves, which is then deposited in the upper mesosphere when the waves dissipate, is a global phenomenon that reverses the zonal winds and, because of the Coriolis effect, drives a strong meridional circulation towards the winter pole. To maintain mass continuity, the pole-ward motion is accompanied by upwelling in the summer hemisphere and down welling in the winter hemisphere that is strongest at the poles and negligible at the Equator [*Garcia and Solomon*, 1985]. This vertical motion exerts a significant influence on constituents and temperature at mid- and high-latitudes because the associated advection contributes to the vertical fluxes of all species, while the concomitant adiabatic heating and cooling strongly influences the temperatures. It is this wave-driven vertical motion that results in the coldest natural temperatures anywhere on Earth (~130 K) at the summer polar mesopause, even though solar radiation of this region is maximum in summer. Although the dynamical processes responsible for wave-induced forcing of global circulation are reasonably well understood, because of observational challenges, gravity wave momentum transport has not been well characterized, especially in the mesosphere and lower thermosphere. In addition, the parameterization schemes used to account for momentum transport in GCMs have not been thoroughly validated because of this lack of observational data.

Dissipating gravity waves also transport heat downward. This happens because air parcels become colder as they are perturbed upward and take in heat, which is released when air parcels are perturbed downward as they become warmer than the environment. Observational studies of the mesopause region have shown that downward heat transport is very large, resulting in local cooling rates on the order of tens of degrees per day, comparable to and sometime larger than radiative cooling. While effects of gravity wave momentum deposition are incorporated into all GCMs through parameterization, those of heat transport are not [*Akmaev*, 2007], largely due to lack of understanding

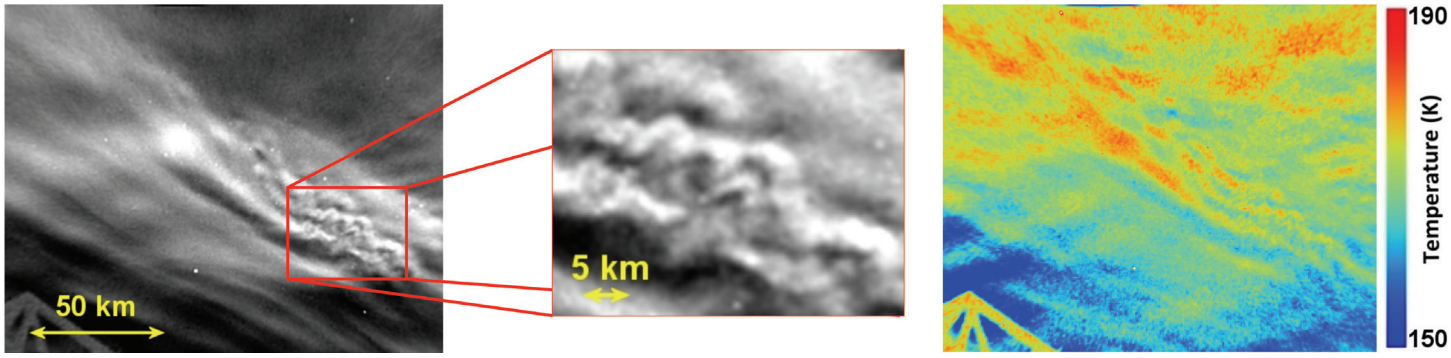


Figure 2.2.5-1 OH (3,1) band intensity image capturing the breakdown of a coherent mesospheric gravity wave into turbulence near 85 km altitude (see inset). The false color OH (3,1) rotational temperature map simultaneously reveals the thermal structure of the wave pattern and an associated sharp increase in temperature, ~20K in the region of wave breakdown. Airglow imagers will complement the observations made by the OASIS lidar systems by providing information on the small scale horizontal structure of waves and turbulence (Image courtesy of Dr. Michael Taylor, Utah State University)

of the detailed dynamical processes involved. Modeling studies have shown that the effect of gravity wave heat transport is even stronger in the thermosphere, where it could result in cooling at the rate of 150-180 K/day at high latitudes [*Yiğit and Medvedev*, 2009]. Gravity waves are ubiquitous in the atmosphere of our neighboring planet Mars. The heat transport effect is strong in the Martian atmosphere, which modeling studies have shown that it is responsible for a temperature decrease of over 45 K in the winter hemisphere, a feature that has been confirmed by measurements from the Mars Express Mission conducted by the European Space Agency [*Medvedev and Yiğit*, 2012].

Dissipating gravity waves also transport constituents vertically. There are four processes related to gravity waves that may result in vertical constituent transport; advection, turbulent mixing, dynamical transport and chemical transport. Although the physics of these four processes are fundamentally different, they can all produce substantial vertical fluxes of atmospheric constituents, which directly affect the chemistry and structure of the mesosphere and lower thermosphere. Because wave-induced transport impacts all constituents in the atmosphere, knowledge of the magnitude, geographic distribution and seasonal variability of all four mechanisms is important to a wide range of problems, including general circulation modeling, atmospheric chemistry modeling, thermal balance calculations, and the study of the mesospheric metal and airglow layers.

Unfortunately, momentum, heat and constituent transport are not yet fully understood nor have they been widely characterized, mainly because of the difficulties in acquiring reliable measurement of these quantities. In most GCMs, these effects are not explicitly included. Eddy diffusion parameterizations are commonly used to account for the vertical transport. Recent work has shown these to be inadequate for modeling mesospheric CO_2 and the meteoric metal layers because the eddy diffusion parameterization is a crude proxy for the important dynamical and chemical transport processes [*Gardner and Liu*, 2010] and because the eddy diffusivity profiles and their seasonal variations are poorly characterized [e.g. *Chabrillat et al.,* 2002*; Gardner et al.*, 2011]. Addressing this deficiency is important not only for fully understanding the impact of wave transport in the Earth's atmosphere but also for characterizing its effect on the structure and evolution of planetary atmospheres in general and of Earth-like planets in particular.

Quantifying these wave transport mechanisms requires high-resolution, high-accuracy, simultaneous measurement of vertical wind, temperature and constituent perturbations accumulated for long periods of time (tens of hours). Doppler lidar techniques, coupled with large-aperture telescopes like LLT, can make the required observations of vertical structure, while new technology airglow imagers can provide crucial information on horizontal structure (Figure 2.2.5-1). The OASIS LLT, with its very large collecting area (100 m^2) and

high power lasers (10-20 W), will achieve a significantly larger signal-to-noise ratio compared to current instruments and enable measurements down to the turbulence scale into the thermosphere. This improvement will be transformative as it will enable the direct observations of small-scale turbulent motions that are known to have an important influence on large-scale atmospheric motions and structure. Currently, such processes can only be studied using numerical models or with in situ instruments, typically only for short rocket flights.

In summary, wave-induced momentum, heat, and constituent transport processes play central roles in establishing the structure and composition of a planet's atmosphere. OASIS will provide the crucial wave and turbulence data necessary to achieve a thorough understanding of these processes and help address the following questions.

1. What are the net effects of wave-mean flow interactions and turbulence on the bulk transport and mixing of chemical constituents?

2. What are the atmospheric momentum, heat and constituent fluxes, how do they vary and how are they related to local wave activity and turbulence?

3. How do wave-induced transport mechanisms affect the circulation, thermal structure and composition of planetary atmospheres?

4. How does one parameterize the vertical transport of momentum, heat, and constituents that arise from sub-grid wave and turbulence processes in general circulation models of the global atmosphere?

2.2.6 What are the origin and nature of turbulence in the Earth's space-atmosphere-interaction region?

All planetary atmospheres are turbulent and the impact of turbulence on atmospheric structure and evolution is profound. The chaotic motion of turbulent vortices can transport significant amounts of energy, momentum and constituents, both horizontally and vertically. Turbulence affects transport at the local level by enhancing diffusion, at mesoscales by facilitating the creation of jet-streams and modulating their strength and globally, by controlling the pole-to-pole meridional circulation in the middle and upper atmosphere and the escape of light constituents, like hydrogen, to space.

Turbulence is caused by atmospheric waves that are generated largely, but not exclusively, in the lower atmosphere and then grow in amplitude as they propagate to higher altitudes. Inherent nonlinearities in fluid motions create interactions between the background flow and wave-induced fluctuations that eventually cause the waves to break and dissipate their energy as turbulence (Figure 2.2.5-1). Breaking gravity waves generate and maintain a background level of turbulence that is capable of producing substantial cooling and/or heating in the upper mesosphere and lower thermosphere.

Turbulent processes are important over a broad range of scales, from the microscale at a few meters or less to the planetary scale. At the smallest scales, the fluctuations tend to be isotropic and lead to a

transfer of flow properties from larger to smaller scales, producing a mixing effect called eddy diffusion that is more effective than molecular diffusion. Turbulence is inherently vortical, since the spin in the fluid is what leads to eddy mixing. At the largest scales, the vortical component of the atmospheric flow becomes dominant, and the statistical behavior of the fluctuation spectrum behaves as would be expected for stratified turbulence, i.e., similar to two-dimensional turbulence but with the third dimension constrained by stratification rather than geometry. While the behavior of a single vortex at those large scales can be treated deterministically, the aggregate behavior of all the vortices exhibits statistical properties that conform to the predictions of turbulence theory, although with different characteristics than at the small scales. Based upon numerical modeling studies, this feature of large-scale turbulence is predicted not only for our own atmosphere, but also for the atmospheres of other planets in our solar system. An important implication is that energy and momentum inputs at small scales can produce cascades to larger scales that lead to the generation of strong zonal flows such as large-scale jet streams. Aircraft measurements in the troposphere and stratosphere suggest that the transition from the isotropic turbulence, that operates at short spatial scales, to the larger synoptic or planetary-scale stratified turbulence, occurs at a horizontal scale size of 100 to 200 km.

Turbulent processes are complex at all altitudes, but they are even more so in the transition region between the atmosphere and space. Because of the large wave amplitudes, the Earth's upper mesosphere and lower thermosphere are characterized by unusually vigorous turbulence sources. However at altitudes near 100 km, the molecular diffusion, which also increases with altitude, eventually exceeds turbulent eddy diffusion. The boundary, where the eddy and molecular diffusion coefficients are equal, is called the *turbopause* (or *homopause*). Above the turbopause, molecular diffusion dominates, the flow becomes laminar and diffusive separation of the atmospheric constituents begins (Figure 2.2.6-1).

Near this same altitude, the effects of the ionized components of the atmosphere start to become increasingly important both in creating plasma effects and in coupling between neutrals and plasma. In particular, the Hall

Figure 2.2.6-1 Image of a trimethyl aluminum trail in the upper mesosphere and lower thermosphere photographed from the NASA Wallops Flight Facility launch site in VA on March 29, 2012 during the Anomalous Transport Release Experiment. The trail shows clear evidence of turbulence structure between 90 and 103 km altitude. Above 103 km the small-scale structure disappears abruptly and the trail becomes laminar. This transition is called the *turbopause* or *homopause*. Above the turbopause, molecular diffusion dominates, the flow becomes laminar and diffusive separation of the atmospheric constituents begins. The high signal levels and exquisite resolution provided by the OASIS lidars will significantly enhance our understanding of turbulence and its sources in the SAIR. (Image courtesy of Dr. Miguel Larsen, Clemson University, Clemson, South Carolina)

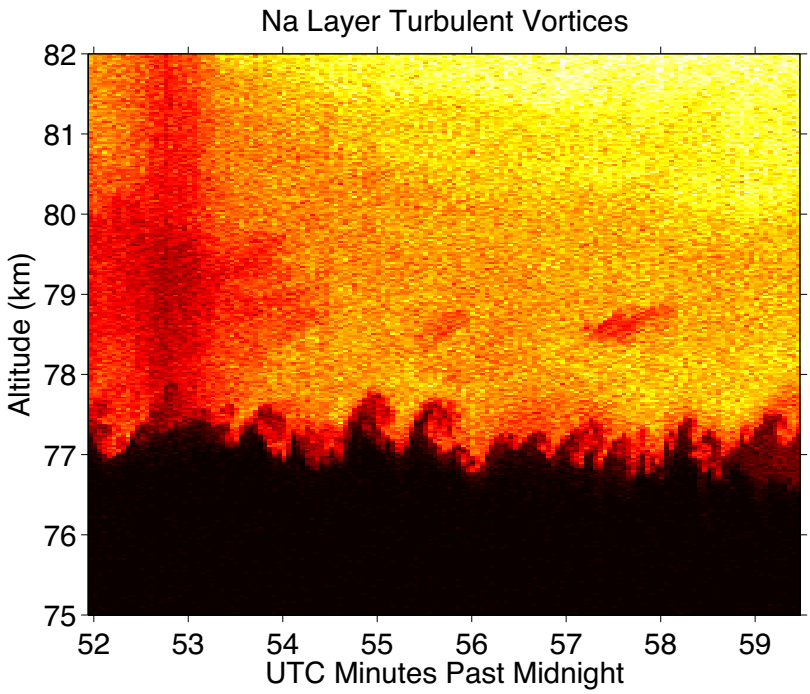


Figure 2.2.6-2 Turbulent vortices observed on the bottom side of the Na layer with a Doppler lidar ($P_{Laser}A_{Tele}$=7.5 Wm^2) on December 17, 2011 at the Table Mountain Observatory, CO. These data were acquired with resolutions of 24 m and 3 s. The large power-aperture products of the OASIS Fe and Na lidars (1000 Wm^2) will enable high-resolution measurements of the turbulent transport of heat, constituents, and momentum and the turbulent Prandtl number throughout the mesosphere and lower thermosphere to at least 130 km altitude. (Data courtesy of Dr. Xinzhao Chu and Mr. John A. Smith, University of Colorado, Boulder, CO.)

conductivity and associated Hall ion drag have a significant effect on the neutral flow at altitudes near and just above the turbopause. The Hall drag partly offsets the Coriolis force, in effect producing a local change in the planetary rotation rate, which modifies the dynamics of large-scale turbulence and mean flows in the lower thermosphere. Exploration of these effects is just beginning, but it has already been shown that Hall drag can accelerate mean flows over large areas through the cascade of energy to the larger scales associated with stratified turbulence.

The magnitude of the turbulent diffusion varies significantly with altitudes, latitudes and longitudes, and depends on the dynamical states of the atmosphere. Exactly how turbulence depends on these dynamical states, for example how it interacts with waves, and the morphology of its spatial distribution and temporal variability, is not well quantified, and is still a theoretical, observational and numerical challenge. Much of our existing empirical knowledge of turbulence has been obtained through laboratory studies, numerical modeling and in situ observations in the lower atmosphere. Measurements of turbulence in the middle and upper atmosphere are rare. In fact, current global circulation and climate models rely on wave parameterization schemes to estimate the eddy diffusivity profiles and their effects on composition and dynamics. Rocket-borne ionization gauges and chemi-luminescent smoke trails (see Figure 2.2.6-1) have provided useful in-

formation on eddy diffusion in the upper mesosphere and lower thermosphere. Unfortunately, those observations are made infrequently and they only provide snapshots in time. Hence, little is known about the diurnal, seasonal, solar cycle and geographic variability of turbulence, which has inhibited our ability to quantify its many important effects. An improved characterization of both the wave population (spectrum) that contributes significantly to the local generation of turbulence and of the turbulence itself, which OASIS will provide, is crucially important, not only for improving our understanding of the dynamics of the atmosphere, but also for characterizing the transport of energy and momentum from the lower atmosphere to the upper atmosphere and the concomitant transport of constituents.

In summary, turbulent processes are an important, universal feature of atmospheric fluid flows. Our understanding of turbulence has evolved significantly in the last decade, because of improved understanding of the theory of stratified turbulence and the ability to simulate the atmospheric flow over scale sizes covering several decades. However, progress is constrained because of the lack of detailed atmospheric measurements of turbulence and its effects, especially in the middle and upper atmosphere.

The OASIS LLT will provide critical observations of turbulent processes, including eddy and thermal diffusivities, turbulent viscosity, and the turbulent Prandtl number, that cover the range from small scales through the stratified turbulence transition, as well as the transition across the nominal turbopause and into the altitude range where plasma/neutral coupling becomes important. The anticipated discoveries made possible using the OASIS LLT (Figure 2.2.6-2) will not only have direct implications for our understanding of the space-atmosphere-interaction region but will also have much broader implications for our understanding of turbulent processes in Earth's atmosphere and predicting their effects on other planets. OASIS observations of turbulence will be used to address these crucial questions.

1. What are the eddy and thermal diffusivities in the middle atmosphere and lower thermosphere? How do they vary diurnally and seasonally and how are they related to the wave spectrum?

2. Where is the turbopause in Earth's atmosphere, how does it vary and how is it related to local wave activity?

3. What are the turbulent heating and cooling rates and how do they vary?

4. How does turbulence affect plasma/neutral coupling and large-scale flow in the space-atmosphere-interaction region?

2.2.7 How does atmospheric escape influence the evolution of planetary atmospheres?

The formation of Earth's early atmosphere, through volcanism and impact degassing of the mantel, was also accompanied by the escape of hydrogen and other heavier volatiles to space. The accumulated loss of hydrogen from Earth was important for transitioning Earth's atmosphere from a reduced to an oxidized state [*Kasting and Catlin,* 2003]. Most of Earth's hydrogen initially came from water and so when hydrogen escapes, oxygen is left behind. Water can be split into hydrogen and oxygen by non-biologic processes (e.g., thermal decomposition, electrolysis or photolysis related to volcanism, lightning and solar radiation) or by photosynthesis. Consequently, terrestrial planets become more oxidized with time even in the absence of biology. Understanding hydrogen escape is important because of the fundamental role it plays in the evolution of planetary atmospheres and because it is intimately related to the question, Is the presence of oxygen in an exoplanet atmosphere a sign of life? It is also important because hydrogen escape affects the density of the near space environment and the orbital lifetimes of satellites in low Earth orbits.

Large-scale circulation patterns and eddy diffusion in the SAIR regulate the transport of hydrogen and other species from the lower atmosphere into the upper atmosphere, thereby providing a throttle for atmospheric escape. The classical Jeans escape occurs when the individual atoms or molecules from the high-velocity tail of the thermal velocity distribution reach the escape velocity for the planet's gravity field. Hydrodynamic escape, also called *blowoff*, occurs when there is a strong thermally driven escape of lighter atoms, which through collisions, drag heavier atoms and molecules with them. Hydrodynamic escape requires high atmospheric temperatures, which may have existed early in the histories of Earth, Venus and Mars due to heat input from planetary accretion processes. Today, these planets each lose about 1 metric ton of atmosphere per hour.

Hydrogen escape played a critical role in determining how long Mars remained in a warm wet state that could have fostered some form of life [*Squyres and Kasting*, 1994; *Manga et al.*, 2012]. Hydrogen escape is also a characteristic of planets that contain organic hydrogen compounds such as CH_4, NH_3, and H_2S, and thus might have initiated life through prebiotic synthesis [*Chang et al.*, 1983]. Certainly Mars, and probably Venus, had considerable liquid water reservoirs in the past, but not today. Why Venus and Mars are essentially free of water while the Earth is not is a mystery that may depend on the role of the Earth's magnetic field. Venus and Mars have very weak magnetic fields. The atmosphere escape process is greatly accelerated by the ionization and charge exchange of the neutral

constituents and subsequent removal of ionization by the solar wind. As the magnetosphere shields the Earth from the solar wind to a large degree, it may historically have served to arrest the loss rate during times when both the solar wind and the Earth's magnetosphere were more intense and variable then they are today.

This hypothesis is controversial, as the magnetosphere does not entirely shield but more accurately redirects energy and momentum from the solar wind into the polar regions, causing heating, and through a circuitous set of processes, the acceleration and expulsion of ionospheric material, leading to significant polar ion outflow. While the magnetosphere clearly reshapes the morphology of atmospheric mass loss, it is unclear whether it retards it. New observations from Mars Express and Venus Express missions indicate that the present rates of water loss from Venus, Earth, and Mars are comparable. Launched in November 2013, the Mars Atmosphere and Volatile EvolutioN (MAVEN) mission will measure atmospheric loss rates from Mars and assess how the rate is affected by solar activity and variations in the solar wind.

For Earth today, hydrogen escape is controlled by eddy diffusion through the turbopause [*Walker*, 1977]. Once hydrogen reaches the thermosphere, it will diffuse upwards to the exobase, where the atmosphere becomes collisionless (~600 km), and eventually be lost to space, because either the upward thermal motion of the

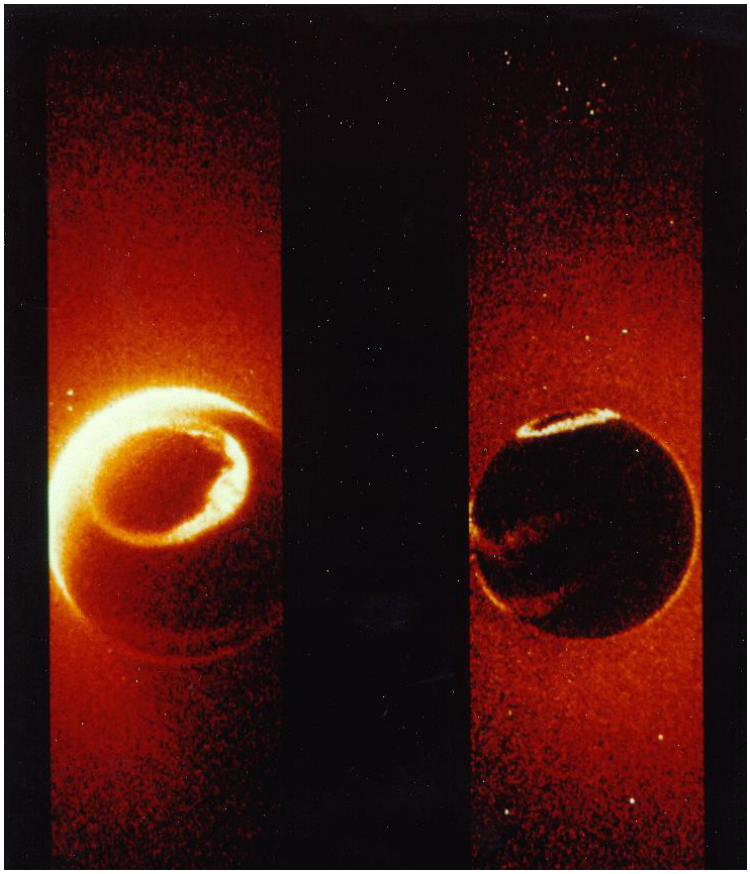


Figure 2.2.7-1 The Earth's aurora and geocorona observed by the Dynamics Explorer – 1 satellite on October 14, 1981 (left panel) and February 16, 1982 (right panel). The faint red glow extending well beyond the limb is due to resonant scattering of solar Lyman radiation by hydrogen escaping from the Earth's atmosphere. Atmospheric escape plays a central role in the evolution of planetary atmospheres. For Earth today, hydrogen escape is controlled by eddy diffusion through the turbopause. OASIS will enhance our understanding of atmospheric escape by providing measurements of the turbopause and neutral temperatures near the exobase. (Image courtesy of the NASA Goddard Space Flight Center)

hot H atoms exceeds the escape velocity or, H+ ions are accelerated out along open magnetic field lines near each pole (Figure 2.2.7-1). The escape flux is equal to the hydrogen flux at the turbopause, which is related to the turbulent eddy diffusivity. Furthermore, the efficiency of the thermal escape mechanism at the exobase is directly related to temperature, which is strongly influenced by the solar cycle. While the theoretical fundamentals of hydrogen escape from planetary atmospheres are now reasonably well understood, quantifying the contributions of each escape mechanism for today's Earth and understanding how those contributions change through the solar cycle, requires detailed observations of eddy transport near the turbopause and temperatures throughout the thermosphere at least to the exobase, which OASIS will provide.

Because wave-induced turbulence determines the turbopause levels at Earth, Mars, Jupiter and Saturn within our solar system, the study of dynamical processes that control hydrogen escape will permit us to better quantify hydrogen escape on Earth and inform us about the evolution of potentially habitable planets within and external to our solar system. Furthermore, the escape of hydrogen into the near space environment affects the drag on low Earth orbit satellites, which limits their orbital lifetimes. Thus, the OASIS LLT measurements of eddy diffusivity profiles, the height and variability of the turbopause and temperature of the thermosphere near the exobase, will make crucial contributions to our understanding of atmospheric escape on Earth, the impact on planetary atmospheres throughout our galaxy and enable us to more accurately predict satellite drag. Specifically, OASIS observations will be used to address these key questions.

1. What wave processes near the turbopause influence the limiting flux of escaping hydrogen?

2. How do processes from the turbopause to the exobase couple and vary to produce the escape of hydrogen in a planetary atmosphere?

2.2.8 How is the Earth's space-atmosphere-interaction region changing in response to rising concentrations of atmospheric greenhouse gases?

Human-induced changes in the Earth's climate system associated with increasing concentrations of CO_2 and CH_4 have begun to show environmental impacts (e.g., *IPCC*, 2007; *ACIA*, 2004). While these greenhouse gases help warm the Earth's surface and lower atmosphere by absorbing infrared radiation, they are also efficient radiators of heat so they cool the tenuous middle atmosphere and lower thermosphere. Doubling the CO_2 concentration is predicted to cool the stratopause (~50 km) by 10-12 K and the mesopause region (80-100 km) by 6-12 K [*Portman et al.*, 1995]. The circulation of the SAIR is also expected to change in response to its changing thermal structure and because changing tropospheric weather patterns will affect wave sources and modify wave-driven forcing at higher altitudes.

Temperature and wind are measured routinely throughout the troposphere and lower stratosphere by ground-based instruments including weather radars and by balloon sondes. However, acquisition of range-resolved temperature and wind from the lower stratosphere into the lower thermosphere is challenging. Although several satellite instruments are making progress, most lack absolute temperature calibration and many observations do not reach high latitudes. Thus, highly accurate "ground-truth" temperature and wind measurements are essential, not only for validating space-based measurements, but also as a key parameter in many science and climate studies. Year-round, range-resolved temperature and wind measurements in the SAIR, which OASIS will provide, are crucial for establishing the initial benchmark against which potential long-term climate changes can be compared many decades into the future. Comparison between long-term measurements and sophisticated model simulations will enhance our understanding of the processes responsible for the observed trends or changes. The improved understanding, observation and modeling will help assess and address society's needs in areas such as climate change, climate disruption and geo-engineering.

While the mean state of the SAIR is expected to change because of the rising levels of greenhouse gases, the responses are likely to be slow and challenging to observe, considering the large natural variability of this region. Measurements must be conducted with high accuracy and precision and over decadal time periods to reliably quantify the slow changes in temperature, winds, composition and wave activity. OASIS will contribute by making key measurements over a large height range with greatly enhanced sensitivity. Employing state-of-the-art spectroscopic techniques to monitor key lidar frequency parameters, which are tied to international reference standards (Sections 1 and 3.2, *Engineering and Technical Supplement*), will enable the OASIS Doppler lidars to achieve absolute temperature and wind accuracies of better than 0.05 K and 10 cm/s, respectively. This approach ensures the long-term measurement stability that is essential for climate change studies. Long-term OASIS observations of winds, temperatures and gravity wave fluxes will be used to address these important questions.

1. How are the mean circulation, thermal structure and composition in the Earth's space-atmosphere-interaction region changing in response to rising levels of atmospheric greenhouse gases?

2. How are gravity waves and their fluxes in the SAIR responding to climate change in the lower atmosphere?

2.3 Observing and Modeling Space-Atmosphere Interactions

2.3.1 What are the spatial and temporal scales involved in the key atmospheric processes and how do they drive observational and modeling requirements?

Atmospheric processes operate over large spans of spatial and temporal scales and involve complex interactions among those scales. Because lower atmospheric processes as well as solar and magnetospheric forcing influence the Earth's middle atmosphere and near space environment, the relevant temporal scales span more than eight orders of magnitude; from seconds during which turbulent mixing occurs, to decades which typifies solar cycle irradiance variations. The important spatial scales span more than seven orders of magnitude; from a few meters, the size of the smallest turbulent eddies, to several tens of thousands of km, the scale of coherent motions associated with planetary waves and tides. Furthermore, important effects occur throughout the entire range of scales.

For example, the El Nino/Southern Oscillation and Quasi-Biennial Oscillation (QBO) occur on inter-annual time scales and have a global influence. Planetary waves exhibit periods ranging from several days to several weeks with wavelengths ranging from tens of km in the vertical to more than 10,000 km in the horizontal. Tidal waves, which have periods that are related to the Earth's rotation (24 h, 12 h, 8 hr, 6 h, etc.), have spatial scales similar to planetary waves. Both planetary waves and tides have conspicuous latitudinal structures and are strongly affected by and can interact with the wind system. Gravity waves exhibit fluctuations ranging from the buoyancy period (minutes) to the inertial period (tens of hours) with vertical wavelengths as small as 1 km and horizontal wavelengths as large as the Rossby radius of deformation (thousands of km). The spatial scales of turbulence fall in a broad spectrum that is characterized by various power-laws with different indices in different regimes. The smallest eddies are a few meters in size while the largest can approach hundreds of km. Temporal variations of turbulence, which span the range from seconds to days, are related to advection, to the characteristics of sources such as breaking gravity waves and to modulation by interactions with waves and tides.

No single instrument or observing technique is capable of acquiring data over such an enormous range of spatial and temporal scales. However, OASIS can make observations over a wide altitude range from the lower stratosphere (~30 km) to beyond the exobase (1000 km) at very high spatial and temporal resolution. The OASIS lidars are capable of observations over a wide range of temporal scales (seconds to multiple days, weather permitting, and longer with long term operation) and vertical spatial scales (meters to the whole measurement range),

and provide valuable information on the temperature and wind structures associated with turbulence, gravity waves, tides, planetary waves, and the underlying mean circulation. Such information will enable these dynamical processes (especially turbulence, gravity waves and tides/planetary waves) to be quantified and lead to a better understanding of the interactions among them. It will also shed light on the day-to-day variability (i.e., weather) of the near space environment. With measurements from the lower to the upper atmosphere, the observations will also provide information on the vertical coupling of atmospheric regions and wave coherence.

The horizontal wind and its vertical shear in the region just above the mesopause can be extremely large (100-200 m/s, and ~80 m/s/km), as revealed from many decades of rocket, radar and lidar measurements. This is probably due to the high static stability of the region that enables waves to grow to large amplitudes, as supported by recent lidar observations [*Yue et al.*, 2010]. The resulting large wind velocities and wind shears affect dynamics, transport, and E-region electrodynamics, so it is highly desirable to better characterize the winds and temperatures in this region and to determine the driving mechanisms. This will be possible with the high spatial/temporal resolution, and extended temporal and vertical coverage of OASIS. Extended temporal coverage will enable the time evolution of the large wind/shear structures to be monitored, while the extended vertical coverage will provide valuable insight on the evolution of the wave spectrum as the waves propagate upward from their sources in the lower atmosphere to well into the thermosphere where they experience diffusive damping, dissipation and breaking.

Direct measurements of neutral winds and temperatures in the thermosphere are sparse, so the OASIS LLT observations, especially in combination with simultaneous measurements of the plasma by radar, will be especially valuable for studying neutral-plasma coupling in the space-atmosphere-interaction region. Above about 200 km altitude, the vertical structures of wind and temperature become less significant because of damping caused by the very large molecular viscosity and diffusion. So measurements with relative coarse vertical resolution may suffice in the middle and upper thermosphere, though it is still desirable to have a high temporal resolution to quantify high frequency waves, which are more likely to reach higher altitudes.

Vertical winds provide important information about wave dynamics and transport. The vertical wind perturbations from high frequency gravity waves can become comparable to their horizontal component, and intense auroral heating can also cause large vertical winds. On the other hand, the vertical component of the mean circulation is only a few centimeters per second, but it is crucial for quantifying global transport. Direct measurements of the vertical winds throughout the atmosphere, which OASIS lidars will provide, will be of great value.

It is likely that there will remain ambiguity in interpreting some of the observational results due to the general lack of information in the horizontal directions, which is a limitation shared by all single point ground-based observatories. For example, it will be difficult to differentiate the migrating and various non-migrating modes for tidal period oscillations. And when the vertical momentum/heat fluxes within the observational column change with altitude, there is an uncertainty about whether this is due to convergence/divergence of the wave, or by the passing of the wave across the instrument field-of-view. For the underlying background wind and temperature field, there may be aliasing from quasi-stationary waves. Thus, it will be necessary to carefully design complementary measurements using airglow imagers (Figure 2.2.5-1), instrument networks (Figure 3.2-3), and satellites and numerical modeling to take full advantage of the powerful observations that OASIS will make.

2.3.2 What are the essential observational capabilities required to address the major science goals?

To make significant progress in addressing the major science goals articulated in Sections 2.1 and 2.2, accurate and precise measurements of both the neutral atmosphere and plasma (e.g., temperature, 3-D winds and composition) are required over a large height range extending from the middle stratosphere through the exobase (~30 to 1000 km), with spatial and temporal resolutions as small as a few meters and a few seconds. The essential observational capabilities depend on the specific atmospheric process being studied. The OASIS lidars will utilize the LLT to measure neutral winds, temperature and the density of specific species (Section 3.3) from which many other important parameters can be derived. OASIS LLT measurements, including the key correlative observations from co-located instruments, required to address the key scientific questions, are summarized below for each of universal processes to be explored. To fully address the science goals, it will be necessary to make observations at high-, mid- and low-latitudes. Of course, OASIS researchers will also make use of other important datasets (e.g., satellite observations) and atmospheric models, which are not directly associated with or located at the OASIS site.

Solar Radiation Influx

- Requirement: Characterize the relationship between the thermal and plasma structures of the SAIR and the incident solar flux
- OASIS LLT Observations
  - Parameter – zonal winds (u), meridional winds (v) and temperature (T), 50 km through exobase ($\geq$ 650 km)
  - Resolution – Δz~10 - 25 km and Δt ~ 5 min - 1 h
  - Accuracy $\leq$ Precision – $\Delta T \leq 5$ K
  - Sampling – solar cycle at each location
- Correlative Observations and Models
  - Airglow spectrum, 2 μm – 300 nm (optical spectrometers)
  - Ion and electron temperatures ($\Delta T \leq 5$ K) and plasma densities ($\leq$ 10%) (incoherent scatter radar and GPS profiler)
  - TIGCM

Geomagnetic Activity

- Requirement: Characterize the relationship between geomagnetic activity and the neutral and plasma structures of the SAIR
- OASIS LLT Observations
  - Parameters – zonal winds (u), meridional winds (v), vertical winds (w) and temperature (T), 100 - 150 km and 300 - 1000 km
  - Resolution – Δz = 2 - 25 km and Δt = 2.5 - 10 min
  - Accuracy $\leq$ Precision – Δu and $\Delta v \leq 15$ m/s, $\Delta w \leq 2$ m/s, $\Delta T \leq 5$ K, Density $\leq$ 10%
  - Sampling – significant number of geomagnetic storms ($K_p > 10$), ~2 years at each location
- Correlative Observations and Models
  - Airglow spectrum, 2 μm – 300 nm (spectrometers)

- Horizontal plasma drifts ≤ 15 m/s, vertical plasma drift ≤ 2 m/s, plasma T ≤ 5 K, electron/ion densities ≤ 10% (Incoherent scatter radar and GPS profiler)
- TIGCM

Cosmic Dust Influx

- Requirement: Quantify the meteoric smoke and dust in the middle atmosphere, the vertical fluxes of Fe and Na in the upper mesosphere and lower thermosphere, and vertical constituent transport throughout the stratosphere, mesosphere and lower thermosphere
- OASIS LLT Observations
  - Parameters – Atmospheric backscatter ratio, 30 – 100 km, Fe and Na Densities and Fluxes, ~75 km to 150 km, eddy diffusivity, ~30 to ~100 km, turbopause altitude, heat and constituent fluxes, 30 – 120 km
  - Resolution – L ~ 500 m and τ ~ 2.5 min – 5 h
  - Accuracy ≤ Precision – Backscatter ratio 0.5%, Fe/Na Densities ≤ 100/cm^3, Fe/Na Fluxes ≤ 50 /cm^2/s, $\Delta K_{zz} \leq$ 10 m^2/s, $\overline{\Delta w'T'} \leq$ 0.1Km/s
  - Sampling – establish seasonal variations of measured parameters, 5 years at each location
- Correlative Observations and Models
  - Meteor trail detection rate (meteor radar)
  - WACCM

Electrodynamics and Plasma-Neutral Coupling

- Requirement: Characterize the mean state and dynamics of the thermosphere and ionosphere
- OASIS LLT Observations
  - Parameters – zonal winds (u), meridional winds (v), vertical winds (w) and temperature (T), 30 – 150 km & 300 – 1000 km
  - Resolution – Δz = 0.5 - 2 km and Δt = 2.5 - 10 min
  - Accuracy ≤ Precision – Δu and $\Delta v \leq$ 5 - 15 m/s, $\Delta w \leq$ 0.5 - 2 m/s, $\Delta T \leq$ 1 - 5 K, Density ≤ 10%
  - Sampling – establish seasonal variations of measured parameters, 5 years at each location
- Correlative Observations and Models
  - Horizontal plasma drifts ≤ 5 - 15 m/s, vertical plasma drift ≤ 0.5 - 2 m/s, plasma T ≤ 1 - 5K, electron/ion densities ≤ 10% (Incoherent scatter radar and GPS profiler)
  - Derived Parameters – Pedersen, Hall and direct conductivities, parallel and perpendicular currents, perpendicular electric fields and neutral winds ~100 km to ~1000 km
  - WACCM

Neutral Atmospheric Dynamics

- Requirement: Characterize the mean circulation, mean thermal structure and wave spectrum throughout the stratosphere, mesosphere and lower thermosphere
- OASIS LLT Observations
  - Parameters – Zonal winds (u), meridional winds (v), vertical winds (w) and temperature (T), ~30 km to ~150 km
  - Resolution – Δz = 500 m and Δt = 2.5 min
  - Accuracy ≤ Precision – Δu and $\Delta v \leq$ 5 m/s, $\Delta w \leq$ 0.5 m/s, $\Delta T \leq$ 1 K
  - Derived Parameters – wave spectra
  - Sampling – establish seasonal variations of measured parameters, 5 years at each location
- Correlative Observations and Models
  - Wave horizontal structure, Δx = 500 m and Δt = 2.5 min (airglow imager)
  - Horizontal winds (Δz = 2 km and Δt = 1 h) and momentum fluxes (Δz = 2 km and Δt = 2 wk) (meteor radar)
  - WACCM

Wave Dynamics and Transport

- Requirement: Characterize the complete spectrum of waves & their fluxes from 30 to 150 km
- OASIS LLT Observations
  - Parameters – zonal winds (u), meridional winds (v), vertical winds (w) and temperature (T), ~30 km to ~150 km
  - Resolution – Δz = 500 m and Δt = 2.5 min
  - Accuracy ≤ Precision – Δu and $\Delta v \leq$ 5 m/s, $\Delta w \leq$ 0.5 m/s, $\Delta T \leq$ 1 K

- Derived Parameters – Momentum fluxes ($\overline{w'u'}$ and $\overline{w'v'}$), Heat flux ($\overline{w'T'}$) and Constituent flux ($\overline{w'\rho'}$)
- Sampling – establish seasonal variations of measured parameters, 5 years at each location

- Correlative Observations and Models
  - Horizontal plasma drifts ≤ 5 - 15 m/s, plasma T ≤1 - 5 K, electron/ion densities ≤10% (Incoherent scatter radar and GPS profiler)
  - Wave horizontal structure, Δx = 500 m and Δt = 2.5 min (airglow imager)
  - WACCM

Turbulence

- Requirement: Quantify the eddy, thermal, and momentum diffusivity profiles from the stratosphere through the turbopause and their relationships to the wave spectrum
- OASIS LLT Observations
  - Parameters – w′, T′ and ρ′, ~ 30 km through turbopause (≥ 110 km)
  - Resolution – $\Delta z \leq 50$ m and $\Delta t \leq 10$ s
  - Derived Parameters – Eddy diffusivity (K_{zz}), Thermal diffusivity (K_H), and Turbulent viscosity (K_M)
  - Resolution – L ~ 500 m and τ ~ 2.5 min
  - Accuracy ≤ Precision – $\Delta K_{zz} = \Delta K_M \leq 10$ m^2/s
  - Sampling – establish seasonal variations of measured parameters, 5 years at each location
- Correlative Observations and Modeling
  - Wave horizontal structure, $\Delta x \leq 50$ m and $\Delta t \leq 10$ s (airglow imager)
  - WACCM

Atmospheric Escape

- Requirement: Characterize the altitude of the turbopause and quantify the temperature of the thermosphere through the exobase
- OASIS LLT Observations:
  - Parameters – Eddy diffusivity (K_{zz}) through turbopause (≤ ~110 km) and Turbopause altitude (z_{TP}), T from ~100 km through exobase (~1000 km)
  - Resolution – L ~ 500 m and τ ~ 2.5 min
  - Accuracy ≤ Precision – $\Delta K_{zz} \leq 10$ m^2/s, $\Delta z_{TP} \leq 1$ km, $\Delta T \leq 2$ - 50 K
  - Sampling – establish seasonal variations of measured parameters, 5 years at each location
- Correlative Observations and Modeling
  - Electron/ion density profiles, ≤10%, plasma T, ≤1 – 5 K (incoherent scatter radar and GPS profiler)
  - WACCM

Climate Change

- Requirement: Quantify the mean temperature, winds and gravity wave fluxes from 30 to 150 km with high accuracy and assess their changes over decadal time periods
- OASIS LLT Observations
  - Key Parameters – u, v, T and Gravity wave fluxes, ~ 30 km to ~ 150 km
  - Resolution – L = 5 km and τ ~ 1 mo
  - Accuracy – $\Delta u = \Delta v \leq 0.1$m/s, $\Delta T \leq 0.1$ K and $\overline{\Delta w'u'} = \overline{\Delta w'v'} \leq 0.05$m^2/s^2, $\overline{\Delta w'T'} \leq 0.02$ Km/s
  - Sampling – establish long-term changes of measured parameters, 2 solar cycles at each location
- Models
  - Climate models and WACCM

Studies of wave dynamics, including the evolution of the wave spectrum as the wave field propagates upward, require the most extensive altitude coverage. Measuring turbulence and its effects on mixing and transport entail the smallest spatial and temporal resolutions, while studies of climate change demand the most accurate (and precise) wind and temperature observations over decadal time periods.

3 An Observatory for Studying Universal Processes in Earth-like Planetary Atmospheres

The development and refinement of sophisticated remote sensing technologies during the past five decades have contributed enormously to our knowledge of the atmosphere, especially the region above 30 km altitude. Major radar facilities, such as AMISR, Arecibo, EISCAT, Jicamarca, Millstone Hill, MU Radar and Sondrestrom have permitted researchers to study directly the ionized atmosphere with excellent accuracy and resolution while enabling inferences of neutral gas properties and dynamics. At the time these facilities were commissioned, each represented a major step forward in observational capabilities. Today these radars continue to play central roles in many ionospheric studies.

Lidar technology has enjoyed a similar renaissance since the invention of the laser 50 years ago. The first lidars were built in the 1930s and 1940s using mechanically modulated searchlights. Today, modern laser-based systems are used to probe composition and structure throughout the atmosphere from the troposphere into the lower thermosphere. The last two decades has been a period of substantial growth in lidar capabilities and applications, principally because of advances in critical areas of laser technology. Perhaps the most important of these has been the development of high-power, ultra-stable narrowband lasers, which are now being used in Doppler lidars for middle and upper atmo-

sphere applications. Furthermore, robust tunable fiber lasers are now being used in laser guide star applications for ground-based astronomical imaging (http://www.gemini.edu/node/11603) and for sensing helium in the Earth's thermosphere [*Carlson et al.*, 2009]. Today space-borne systems such as IceSat (Ice, Cloud and Land Elevation Satellite, http://icesat.gsfc.nasa.gov/) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite, http://www-calipso.larc.nasa.gov/) are routinely providing global information on clouds and aerosols in the troposphere and lower stratosphere.

While the recent advances in lidar technology have been impressive, the accuracy, resolution and range of many systems are still limited by signal levels. Current instruments employ lasers with output powers of a few watts and small telescopes (typically less than 1 meter diameter). The OASIS Large Lidar Telescope (LLT) will achieve a 1000-fold improvement in lidar capabilities by employing modern solid-state laser technologies to increase the output powers by a factor of ~10 and a large array of fiber-coupled telescopes to increase the aperture area by a factor of ~100. With the OASIS LLT it will be possible to measure neutral winds, density, temperature and chemical composition with sensitivities approximately 1000 times better than can be achieved with the most powerful lidar systems in operation today.

3.1 Top-level Observatory Requirements

The observatory requirements are driven by the scientific goals, tempered by the realities of physics, technology and resources. The top-level requirements fall into five overarching categories.

Measurement Requirements

- Neutral atmosphere winds, temperature, density (30 – 150 km, 300 – 1000 km)
- Na and Fe densities (75 – 200 km)
- He(2^3S) density (300 – 1000 km)
- Airglow images and spectra (mesosphere and lower thermosphere)
- Plasma drifts, densities and temperatures (100 – 1000 km)

Operational Requirements

- Tele-science capabilities for all major instruments
- Absolute calibration of all major instruments, traceable to internationally recognized standards
- Simultaneous multiple lidar observations (Rayleigh, Na, Fe and He)
- Day and night lidar observations
- >80% duty cycle for lidars

Infrastructure Requirements

- Transportable, modular designs for telescope array and all instrumentation

- High-speed internet communications
- Temporary living quarters for staff and visiting scientists

Site Requirements

- Significant geophysical interest
- High percentage of clear, unpolluted skies
- Near key correlative instrumentation (incoherent scatter radar friendly site, avoid heritage sites)
- Moderately high altitude for infrared studies and low aerosol and water content
- No or minimal commercial air traffic within lidar fields-of-view
- Reasonably accessible (ITAR, shipping, open access to all)
- Access to critical services such as power and communications
- Near or able to accommodate rocket/balloon launch facilities

Facility Location by Science

- Proximity to scientific observing networks
- Gravity-wave active regions
- Location based on tidal knowledge
- Direct magnetospheric forcing
- Escape flux regions
- Internal forcing processes
- Spread F active locations

Because the OASIS LLT will be transportable, it can address a wide range of problems including those that are latitude dependent. Site selection should be explored carefully to ensure that the highest priority science questions are addressed, as well as to facilitate optimum productivity of the observatory. In addition, the initial deployment of OASIS should be chosen to enable timely and efficient commissioning of the major instruments, including the telescope array. Several candidate sites are identified in Table 3.1.

Table 3.1 Candidate Sites for OASIS

Site	Location	Altitude	Clear Skies	Comments
McMurdo, Antarctica	77.9°S, 166.7°E	~0.10 km	<50%	U.S./NSF Research Base
Resolute Bay, Canada	74.7°N, 95.0°W	*0.46 km*	<45%	Canadian ISR Site
Sondrestrom, Greenland	67.0°N, 51.0°W	~0.10 km	<60%	NSF ISR Site, Rockets
Poker Flat, AK	65.1°N, 147.5°W	1.16 km	<65%	NSF ISR Site, Rockets
Table Mountain, CO	40.1°N, 105.2°W	1.69 km	~70%	NOAA Research Site
Magdalena Ridge, NM	34.0°N, 107.2°W	3.23 km	~70%	Near White Sands Missile Range
Cerro Pachon, Chile	30.2°S, 70.7°W	2.70 km	~75%	U.S./Chile Astronomical Site
Mauna Loa, HI	19.5°N, 155.6°W	4.17 km	~75%	NOAA Research Facility
Ascension Island, UK	19.5°N, 155.6°W	~0.20 km	~65%	

3.2 Conceptual Design

Doppler Lidars and Large Lidar Telescope, LLT: The centerpiece of the Observatory for Atmosphere Space Interaction Studies will be a 100 m^2 telescope array (Large Lidar Telescope) that will serve as the receiving system for several powerful Rayleigh, Na, Fe and He(2^3S) Doppler lidar systems.

The LLT is envisioned to be a versatile 5-beam, transportable system utilizing one beam fixed pointed at zenith and four beams that can be pointed at several zenith and azimuth angles. Nominally these four beams are pointed θ degrees off-zenith (θ=30º, 6º and 0º) with azimuth angles of 0 degrees (North), 90 degrees (East), 180 degrees (South) and 270 degrees (West). The array is designed so that the telescope sub-arrays can be pointed in the same directions as the laser beams.

The system is flexible so that for each beam direction, the laser power level and the aperture area of the telescope sub-array can be selected to optimize the observations for the scientific issue being investigated.

The full array is assembled from 20 modules, each consisting of six 1.03 m diameter parabolic mirrors mounted on a rigid 3.0 m x 4.5 m platform. The total collecting area of each module is 5 m^2. An optical fiber, mounted at the prime focus of each mirror, couples the light from the telescope to its detector assembly, also mounted on the module platform. The detector assembly includes a wavelength de-multiplexer that spatially separates the backscattered light from each laser beam, and then directs each signal through a narrowband optical filter to the detector. Each detector assembly can simultaneously process the signals from as many as five different laser wavelengths. The output photon counts of each detector are range gated and accumulated by a dedicated CPU and then transferred to the main data collection processor via a local area network.

The individual mirrors comprising each module are fixed pointed, but the whole module can be pointed precisely at any of the three different zenith angles and four different azimuth angles. Each telescope module is mounted on a stable pad and enclosed in a protective housing to shield the telescopes and electronics from the elements. The roof of the housing is automatically retracted whenever the module is in operation. Also included are an office/operations center and a small optical coating facility, which is used to periodically recoat the primary surfaces of the 120 parabolic mirrors.

Lidar observations are made at the lowest altitudes using the Rayleigh scattering from air molecules. Above 80 km, the lidars employ resonance fluorescence scattering from Na, Fe and metastable He(2^3S). The key laser specifications are summarized in Table 3.2. Frequency stability is ensured by employing Doppler free spectroscopic techniques to frequency-lock each laser to one of the hyperfine lines comprising the fluorescence spectrum of the species being probed. The Nd:YAG laser used for the Rayleigh lidar is frequency-locked to a nearby iodine line. Heterodyne spectroscopic techniques are employed to monitor the absolute frequency and line width of the laser pulses. Consequently, the absolute accuracies of the wind and temperature measurements are better than ±10 cm/s and ±0.05 K, respectively. Each laser

system is installed in a dedicated laboratory module that provides the required power and cooling for the laser and maintains precise control over temperature and humidity. A laser beam director (LBD) mirror is mounted outside each laser lab to project the beam to the correct zenith and azimuth angle. The LBD is controlled by the main data collection processor.

Correlative Instruments: To fully explore the universal processes that are the scientific foci of OASIS will require supplementary measurements of certain species and parameters that can only be obtained by other remote sensing instruments and perhaps by in situ balloon and rocket probes.

In addition to the lidars, the baseline observatory will include four key correlative instruments; 1) Incoherent Scatter Radar, 2) OH Tomographic Imager Network, 3) O_2^+ Fabry-Perot Interferometer Network and 4) High-sensitivity Meteor Radars.

1 **Incoherent Scatter Radar:** The incoherent scatter radar (ISR) technique is the most comprehensive means by which to measure basic properties of the ionosphere. Similar to lidar, these radar systems are in general of large aperture and high power to achieve the necessary sensitivity to resolve in range and time properties of the Earth's ionosphere (80 -1000 km). The range-resolved signal contains information enabling electron density, electron and ion temperatures, and ion motion to be determined throughout the ionospheric column, and steering extends this capability over a wider volume of the ionosphere.

Table 3.2 Key Laser Parameters

Parameter	Rayleigh	Na	Fe	He(2^3S)
Optical Wavelength	532 nm	589 nm	372 nm	1083 nm
Average Output Power	50 W	10 W	10 W	20 W
RMS Linewidth	50 MHz	50 MHz	15 MHz	10 MHz
Pulse Repetition Rate	750 pps			150 pps
Beam Divergence (Single TEM_{00} Mode)	$\leq$0.5 *mrad FW @* e^{-2}			

The ISR measurement of plasma properties is the charged gas complement to the lidar measurement of the neutral gas. Consequently the combination of the two measurements is very powerful as the neutral gas properties of the thermosphere and the plasma properties of the ionosphere can be measured in the same volume over similar timescales. This will enable the first in-depth study of plasma-neutral interactions and address many of the questions discussed in Section 2.2.2. Modern incoherent scatter radars, such as the Advanced Modular ISR (AMISR), are technically ideal for remote and extreme locations. ISR phased array systems with no moving parts, distributed transmit power for gentle degradation, and the capability to fully operate remotely have been designed and implemented in locations like Poker Flat, Alaska and Resolute Bay, Canada. The AMISR system provides rapid electronic steering which has enabled new experiments and observations. Figure 3.2-1 is an AMISR volumetric image of an E-region auroral arc (see *Semeter et al.*, 2009) illustrating the ability to observe electron density structure within the radar volume. A more complete description of ISR is given in the Engineering and Technical Supplement.

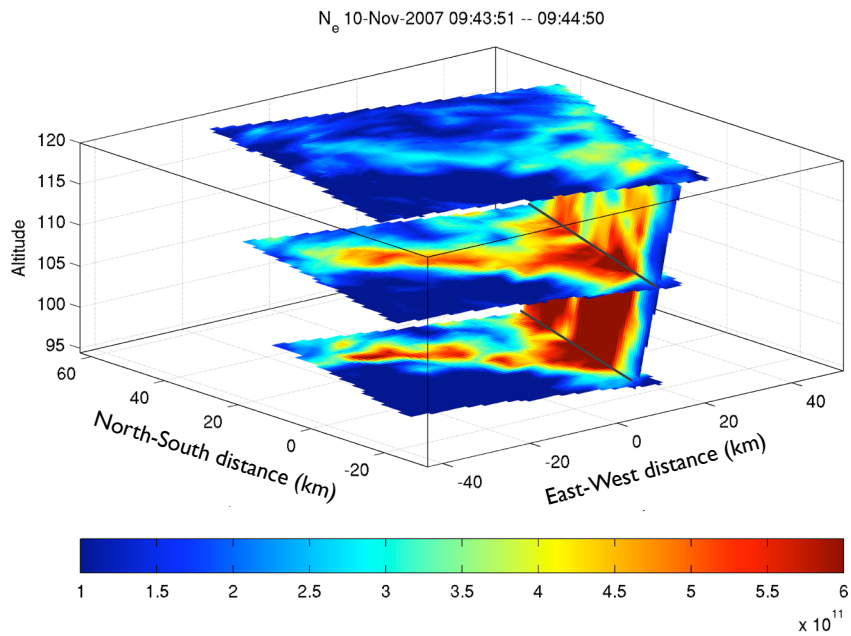


Figure 3.2-1 Volumetric image of the electron density structure showing an E-region auroral arc obtained by the Poker Flat Modular Incoherent Scatter Radar (PFISR) north of Fairbanks, AK. To study the complex dynamics of neutral-plasma coupling above 100 km altitude with OASIS, incoherent scatter radar observations of plasma densities, drifts, and temperatures will complement the lidar observations of neutral winds, densities and temperatures. (Figure from *Semeter et al.* [2009]).

2 OH Tomographic Imager Network: Airglow imagers complement the observations made by the OASIS lidar systems by providing information on the small scale horizontal structure of waves and turbulence. By adding tomographic capabilities, the 3-D structure can also be observed. Tomography has been used successfully to explore the 3-D structures in the ionosphere and aurora, in airglow emissions and in noctilucent clouds (e.g., *Raymond et al.*, 1993, *Nygren et al.,* 1997 and 2000; *Kamalabardi et al.,* 1999; *Semeter et al.,* 1999; *Dengenstein et al.,* 2004). Most conventional tomography applications, such as medical imaging, involve large amounts of data collected over a broad range of viewing angles, resulting in well-conditioned solutions and high-quality reconstructions. In contrast, atmospheric data are more difficult to obtain and are often limited to many fewer measurements and to restricted viewing angles. To overcome these limitations specific classes of algorithms have been developed and tested, enabling solutions to highly under-determined inverse problems.

Figure 3.2-2 shows how the Partially Constrained Algebraic Reconstruction Tomographic (PCART) method has been successfully applied to sparse image data to investigate 3-D gravity wave structures in the OH airglow emission layer (altitude ~87 km, half-width ~8–10 km). The figure has been sliced into 6 layers, 1.2 km apart, to reveal novel information on the internal wave structure and its vertical phase relationship within the layer (*Hart et al.*, 2012). These exploratory results were obtained using only two synchronized all-sky cameras operating on an extended (~80 km) baseline in northern Utah and southern Wyoming. A tomographic network of several imagers clustered around the LLT will provide a powerful new tool for measuring the 3-D wave field and its dynamical evolution within the lidar volume. Moreover, such height-resolved studies will be of critical importance for quantifying wave break-down dynamics and subsequent turbulent structures in unprecedented detail. These new high-resolution coordinated studies will be vital for improving our understanding of the dominant underlying mechanisms governing gravity wave energy and momentum interactions and effects in the upper atmosphere.

3 **O_2^+ Fabry-Perot Interferometer Network:** An important aspect of understanding plasma-neutral coupling is being able to decouple temporal and spatial gradients in the parameters. In order to augment the unprecedented vertical resolution of neutral parameters obtained from the OASIS lidars, a network of Fabry-Perot interferometers (FPIs) will be deployed to provide spatial coverage of the thermospheric neutral winds and temperatures with high cadence. The network will consist of three FPIs deployed around the OASIS, 300-400 km from the LLT (see Figure 3.2-3), and controlled via the Internet, as has been demonstrated for similar networks in Peru, Brazil, and the NATION network in the Midwest of the United States (e.g., *Meriwether,* 2006; *Makela et al.*, 2012). The FPIs will observe the 630.0-nm emission arising from the dissociative recombination of O_2^+, providing Doppler shift and Doppler broadening measurements of the thermospheric dynamics and temperature structure at approximately 240-250 km altitude. This capability will help fill the 200-300 km gap in OASIS lidar observations of the neutral atmosphere.

The OASIS FPI network will employ state-of-the-art imaging interferometers using the lessons learned and the advances made in the application of such instruments for the NATION FPI network. These include cloud and environmental monitoring sensors required for the proper interpretation of FPI data products (winds and temperatures). The instruments in this network will be linked together via the internet so that the observing strategy can be modified and changed depending upon the meteorological and geomagnetic activity prevailing at the time of the measurements. A variety of observing strategies can be employed, depending on the scientific goals of a specific experiment, including a survey mode of winds in the cardinal directions, a common-volume mode to deduce the three-dimensional wind vector over the OASIS lidars, and a wind-field mapping strategy to provide estimates of the two-dimensional wind field over the entire region above the FPI network.

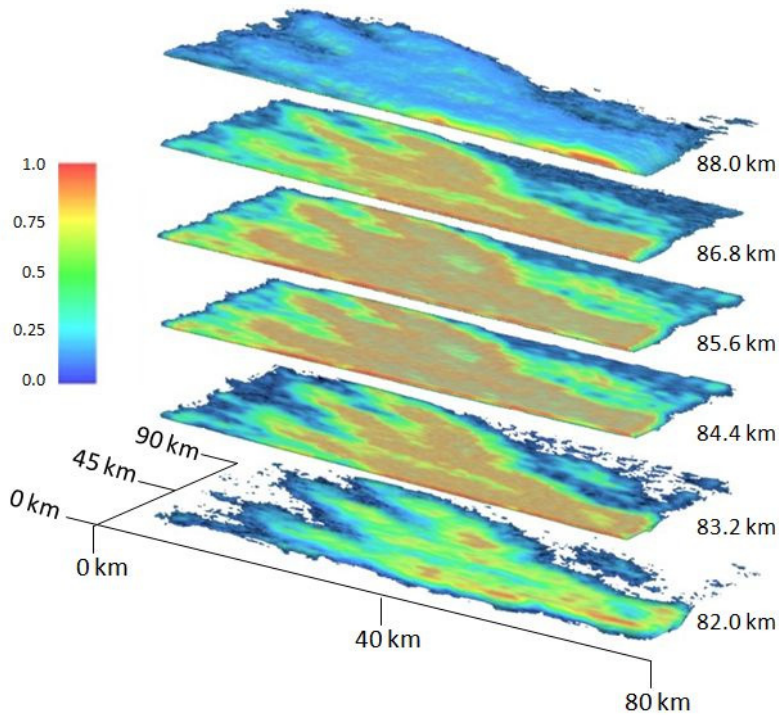


Figure 3.2-2 Tomographic image of the OH layer showing an expanded view of the 3-D volume retrieval divided into 6 horizontal slices each separated by 1.2 km. The data illustrate the gravity wave structure in the OH layer and its vertical phase relationship. OASIS will include multiple imagers positioned around the site to optimize tomographic imaging of the airglow layers and complement the LLT observations of wave phenomena and turbulence (Figure from *Hart et al.* [2012]).

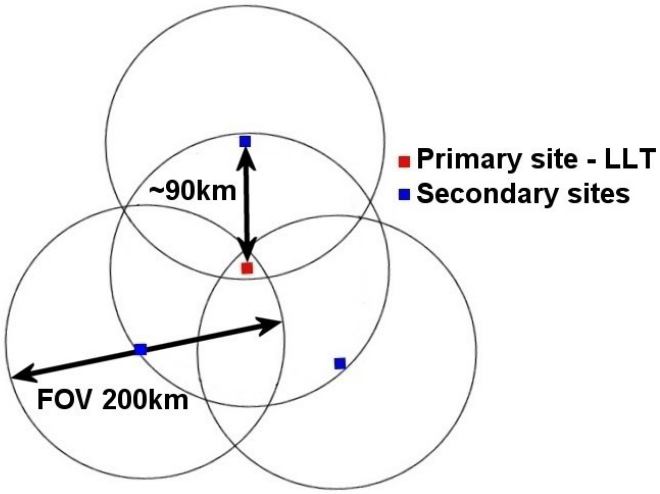


Figure 3.2-3 Schematic diagram of the OASIS OH Tomographic Imager Network. The Large Lidar Telescope (LLT) is located at the Primary Site while the airglow instruments are located at all four sites. The FOV corresponds to the OH imagers which observe the OH(3,1) band emissions (1,515-1,546 nm) from ~87 km altitude. The O_2^+ Fabry-Perot Interferometer Network will be positioned similarly but with a larger 300-400 km baseline to observe the 630 nm O_2^+ emissions from ~250 km altitude.

The aperture for the individual FPI instruments will be 10 cm with 1.5-cm spacers so that typical errors of 3 to 5 m/s and 10 to 15 K can be achieved with exposure times of 30 to 300 seconds. FPIs of this type have been operated by members of the community for the past several years and have proven to be robust and reliable, yielding high-quality measurements of thermospheric parameters.

An additional FPI, co-located with the OASIS lidars at the primary LLT site, will be equipped with a filter wheel so that a variety of wavelengths might be selected for observations. This additional FPI will have a larger aperture of 15 cm and variable gap spacers so that a variety of applications using different spectral resolutions will be possible. Examples of the low-resolution applications are observations of hydrogen alpha and helium emission lines. Examples of the high-resolution applications are the 732 nm O^+ emission, the 630.0-nm emission (to observe vertical winds with high accuracy), and the OH emission to obtain mesospheric temperatures. A second etalon designed to extend the free spectral range for extremely-high spectral resolution applications will also enable Doppler wind observations during daytime (*Gerrard and Meriwether*, 2011) and the examination of the 630-nm profile for possible O^+ contamination during geomagnetic storm events (*Makela et al.*, 2014).

4 **High-Sensitivity Meteor Radars:** Over a million times a second, radar-detectable meteoroids ablate in the lower thermosphere, leaving behind plasma trails that the neutral winds transport. The trails create intense radar echoes and so, for over 50 years, meteor radars have tracked these trails as an easy way to monitor winds in the lower thermosphere. These measurements have become important for understanding and modeling winds, tides and gravity waves in this region.

Several meteor wind-tracking techniques exist. Specular meteor radar measures the Doppler shift of meteors that pass through the atmosphere precisely perpendicular to the pointing direction of the radar. This relatively inexpensive technique can measure winds between 85 and 100 km altitude depending on the broadcast frequency. However, these radars must make many measurements to build up a wind profile, typically over the course of an hour. As a result, such measurements are averages over both space and time.

Modern specular meteor radars typically include some degree of interferometry, allowing one to determine the meteor's loca-

tion and trajectory. This allows for better resolution of wind measurements. Nevertheless, this technique produces wind profiles with a vertical resolution generally larger than 1 km and temporal resolution of 1 h. When the trail cross-sectional diameter exceeds the transmit wavelength it becomes effectively invisible to the radar. This occurs roughly when the neutral-plasma mean-free-path exceeds the same wavelength. Hence, lower frequency radars can detect higher altitude winds. However, ionospheric effects such as phase-delay and refraction more strongly modify these measurements so the upper altitude is typically limited to about 100 km. The lack of frequent, intense meteors sets the lower altitude to about 85 km.

A newer method of remotely measuring winds also takes advantage of the billions of meteors that enter the atmosphere every day, leaving behind plasma trails which the neutral wind carries along. However, instead of using a small radar to track the entire trail, this method uses large radars to follow reflections from plasma irregularities that develop in or near many trails. This requires that the radars have interferometric capabilities and can point roughly perpendicular to the geomagnetic field. Since it was first proposed in 2009, only two radars have applied this method, the Jicamarca Radio Observatory in Peru and a smaller radar in China. Both systems can infer wind velocities as a function of altitude.

By measuring winds between 93 and 110 km, this approach explores a region that overlaps the highest altitudes monitored by specular meteor radars but extends considerably higher. This technique does not require the temporal and spatial averaging typically used when obtaining winds from specular meteor radars, but instead measures detailed wind profiles with an altitude resolution of less than a few hundred meters. Further, between midnight and dawn, this method can be used to monitor winds on a nearly continuous basis.

OASIS will include both types of meteor radars, a high-sensitivity specular system to provide continuous monitoring of low-resolution wind and momentum flux profiles between 85 and 100 km and an interferometric system configured from the ISR to acquire high-resolution wind profiles between 93 and 110 km.

Key OASIS correlative instruments, including the baseline systems (denoted by @), are summarized in Table 3.3.

Table 3.3 Correlative Instrumentation

Instrument	Science Focus
Incoherent Scatter Radar@	Neutral-plasma coupling >100 km Electrodynamics >100 km
OH Tomographic Imager Network@	Wave dynamics and transport Turbulence ~87 km
O_2^+ Fabry-Perot Interferometer Network@	Neutral winds and temperatures ~250 km
High-Sensitivity Meteor Radars@	Neutral winds and large scale waves ~85-110 km
$O(^1S$, 557.7 nm) Airglow photometer/imager	Wave dynamics and transport ~97 km
O_2(A-band, 864.5 nm) Airglow photometer/imager	Wave dynamics and transport ~95 km
Na (^2P-^2S, 589 nm +589.4 nm) Airglow photometer/imager	Wave dynamics and transport ~87 km
GPS Profiler	Neutral temperatures and electron densities

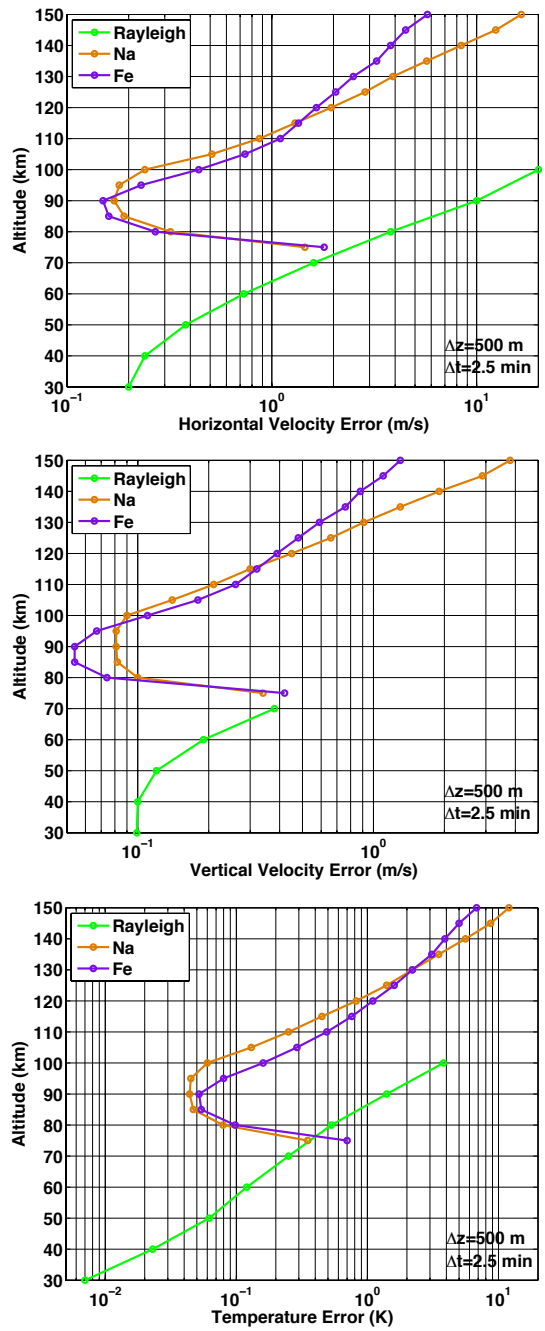


Figure 3.3-1 Profiles of the measurement accuracies of the OASIS LLT Rayleigh (green), Na (orange) and Fe (violet) Doppler lidars for nighttime observations at a vertical resolution Δz = 500 m and a temporal resolution Δt = 2.5 min; a) horizontal wind errors, b) vertical wind errors and c) temperature errors.

3.3 Lidar Observational Capabilities

Neutral Wind, Temperature and Dust: Detailed calculations of signal-to-noise-ratios (SNR) and measurement errors for the OASIS Rayleigh, Na, Fe and He (2^3S) lidars can be found in the OASIS - Engineering and Technical Supplement [*Gardner*, 2014]. The results for nighttime observations of horizontal and vertical winds and temperatures are summarized in Figures 3.3-1 and 3.3-2. In the middle atmosphere and lower thermosphere (30-150 km) for resolutions of 500 m and 2.5 min, the horizontal and vertical wind accuracies are better than about 5 m/s and the temperature accuracy is better than about 5 K. In particular, highly accurate Na and Fe lidar observations of temperatures and winds can be made in the thermosphere between 100 and 150 km at the resolution sufficient to observe the full gravity wave spectrum. Although the Na and Fe densities above 100 km are tenuous (see E&T Supplement Section 1 and references therein), the large 100 m^2 aperture provides adequate signal levels even when the densities fall below 10 cm^{-3}. Occasionally, it will be possible to extend the measurement to almost 200 km when sufficient metal densities occur at these higher altitudes (see Figure 2.1.2-1). Between 80 and 100 km where the Na and Fe densities are greatest, the absolute wind and temperature accuracies are better than a few 0.1 m/s and 0.1 K.

Dust profiles are measured by deriving the backscatter ratio using the Rayleigh lidar measurements of relative density and the Na/Fe lidar measurements of temperature. At a resolution of I km and 1 h, the OASIS

LLT can measure the backscatter ratio with an accuracy of better than 0.2% at 100 km altitude, which means it can detect a dust layer with a backscatter cross-section as small as 0.2% of the Rayleigh cross-section at 100 km.

The upper thermosphere between 300 and 1000 km is devoid of gravity waves because severe damping at lower altitudes caused by molecular diffusion eliminates them. Consequently, scientifically useful observations of this region can be made at a much coarser resolutions. For resolutions of 25 km and 5 min, the He (2^3S) Doppler lidar is capable of observing the horizontal and vertical winds with accuracies of a few tens of m/s or better and temperatures with accuracies 10 K.

Gravity Wave Momentum, Heat and Constituent Fluxes: Gravity wave flux measurements have two sources of errors; 1) photon noise errors in the fundamental wind, temperature and density measurements that are related to signal level and 2) statistical error that is related to the number of independent instantaneous flux estimates which are used to compute the mean fluxes. The OASIS LLT measures the vertical fluxes of gravity wave horizontal momentum by employing the dual-coplanar beam technique. The optimum zenith angle, which minimizes the statistical variance (error) of the momentum flux measurement, is about six degrees at mesopause heights, where gravity wave fluctuations are greatest. Because of the large telescope aperture, momentum fluxes can be measured at night with accuracies limited only by statistical noise between 30 and 135 km. The gravity wave heat and constituent fluxes are measured by employing a single zenith-pointing beam, with accuracies limited only by statistical noise between 30 and 150 km. In other words, for the OASIS gravity wave flux measurements, the lidar SNRs are so large that the effects of photon noise are negligible within these height ranges.

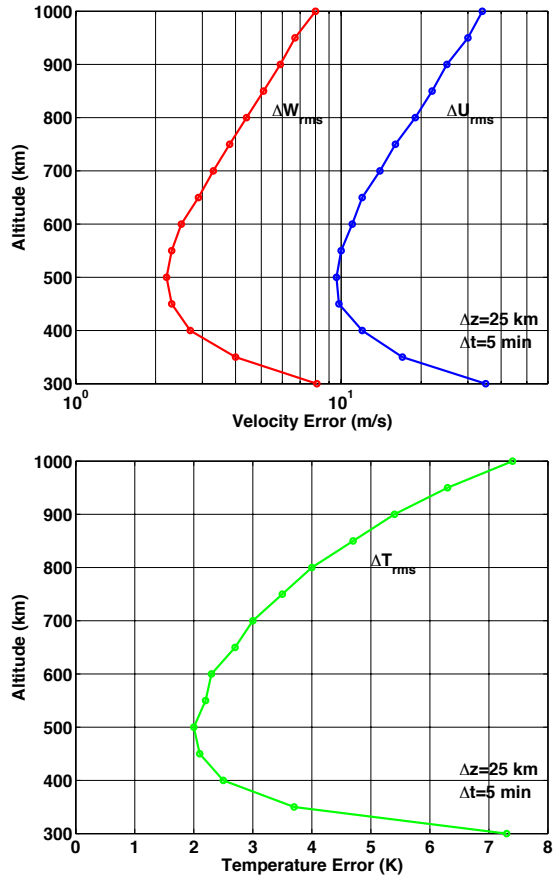


Figure 3.3-2 Profiles of the measurement accuracies of the OASIS LLT He(2^3S) Doppler lidar for nighttime observations at a vertical resolution Δz = 25 km and a temporal resolution Δt = 5 min; blue circles - horizontal wind errors, red circles - vertical wind errors and green circles - temperature errors.

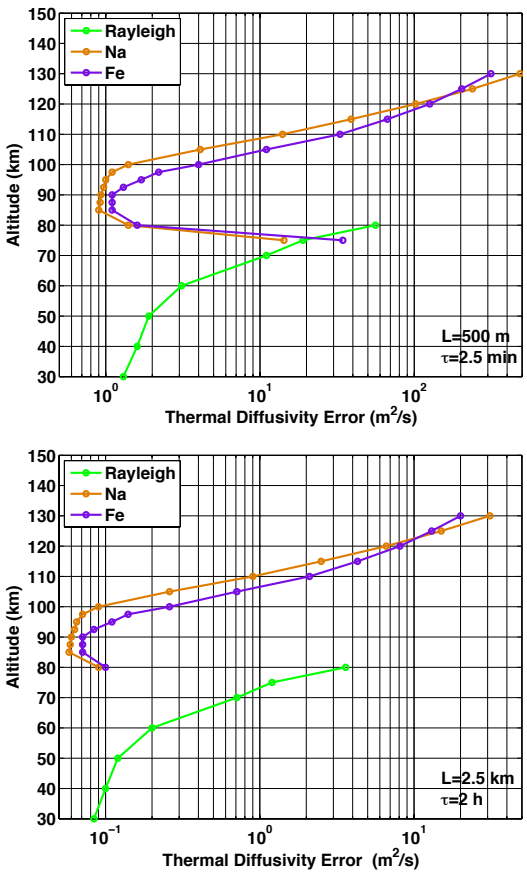


Figure 3.3-3 Profiles of the OASIS LLT Rayleigh (green), Na (orange) and Fe (violet) lidar measurement accuracies of eddy thermal diffusivity for nighttime observations at vertical and temporal resolutions of a) L = 500 m and τ = 2.5 min and b) L = 2.5 km and τ = 2 h.

Turbulent Mixing and Eddy Diffusivities: To measure turbulence and its effects, OASIS employs a single zenith-pointing beam or dual co-planer beams to measure the turbulent momentum fluxes. The lidars must be capable of observing the smaller-scale turbulent vortices, which have dimensions as small as a few tens of meters and lifetimes as short as a few seconds. The eddy heat, constituent, and momentum fluxes, associated thermal (k_H) and eddy (k_{zz}) diffusivities, turbulent viscosity (k_M), and the turbulent Prandtl number ($Pr = k_M / k_H$) can then be derived from the high resolution wind, temperature and constituent density measurements. To be most useful scientifically, the derived eddy flux, diffusivity and Prandtl number profiles should have resolutions comparable to the primary sources of turbulence such as breaking gravity waves.

To illustrate the OASIS LLT capabilities for nighttime measurements of turbulence, the accuracies the thermal diffusivity profile are plotted versus altitude in Figure 3.3-3. The fundamental wind, temperature and density observations were assumed to be collected at vertical and horizontal resolutions of $\Delta z = \Delta x = 50$ m and a temporal resolution of $t = 10$ s.

Two cases are illustrated for the vertical (L) and temporal (τ) resolutions of the derived thermal diffusivity profiles. At the highest resolution (500 m and 2.5 min), which is sufficient to observed the influence of the smallest scale gravity waves, the eddy thermal diffusivity can be measured with accuracies of about 4 m^2/s or less between 30 and 60 km and between 80 and 105 km. At the lower 2.5 km and 2 h resolution, the eddy thermal diffusivity can be measured with accuracies of 20 m^2/s or less from 30 to 130 km. Typical values for k_H in this region are thought to vary between a few tens to a few hundred m^2/s, with the largest values at the highest altitudes near the turbopause.

Daytime Observations: OASIS LLT will also yield superb lidar measurements during the daytime. However, background noise from scattered sunlight can significantly reduce the lidar SNR and measurement accuracy. Typically, coarser vertical and temporal resolutions are employed during daytime to reduce the impact of background noise and increase the SNR, thereby improving the measurement accuracies (Figure 3.3-4). Because of the very large aperture area of the LLT (100 m^2) and higher laser power levels (5–10 times larger), the daytime SNR for the OASIS lidars will be about 400 times larger, and the measurement errors about 20 times smaller, than current lidar systems that employ much smaller telescopes (0.5–0.8 m^2) and lower laser power levels (5–10 times smaller) at much lower pulse repetition rates (50 vs 750 pps). Even so, daytime errors for OASIS could be a factor of 10 larger than the nighttime values shown in Figures 3.3-1 through 3.3-3.

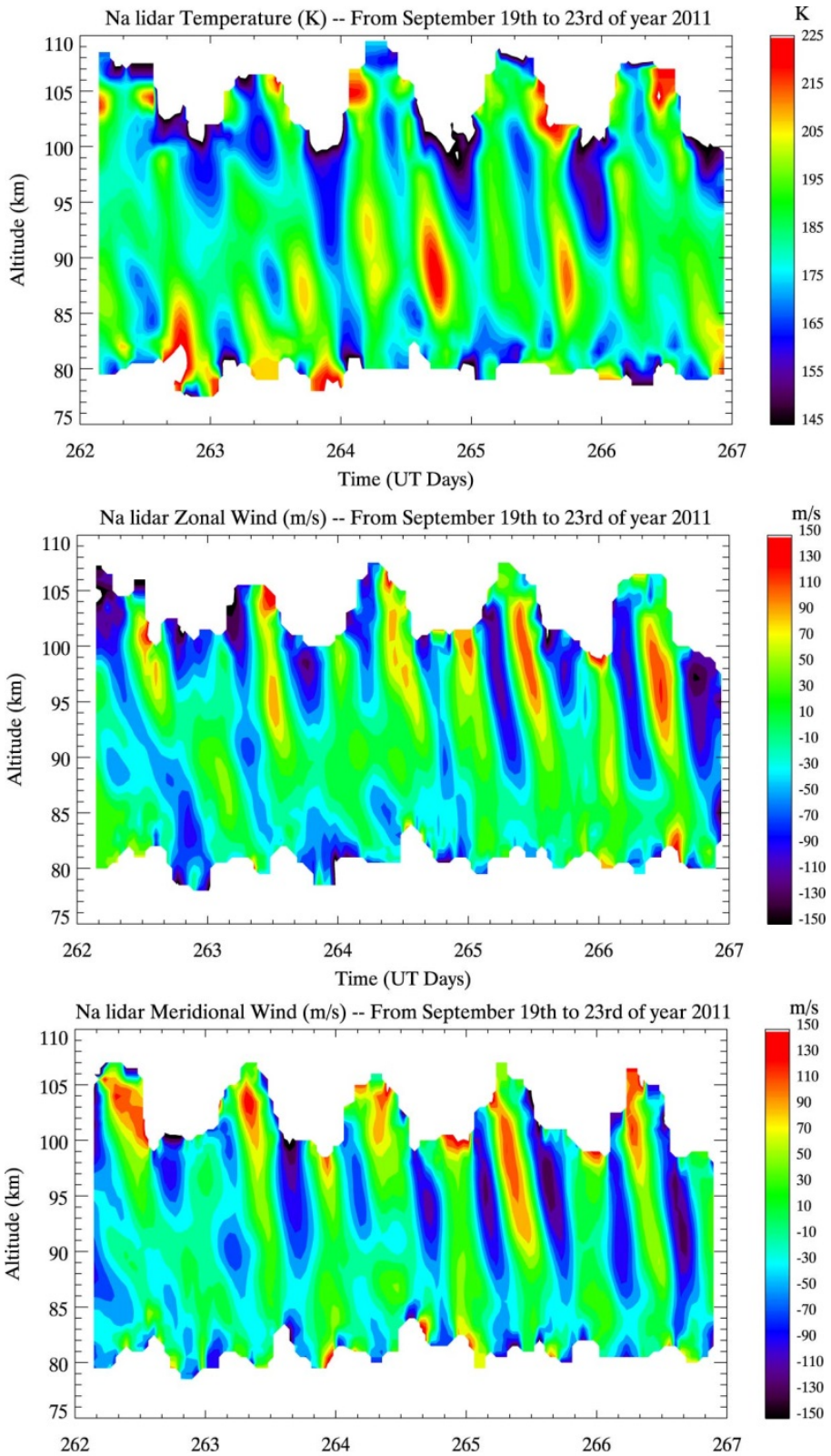


Figure 3.3-4 Continuous 5-day temperature record of the mesopause region acquired with a Na Doppler lidar in September 2011 at Utah State University. By employing modern solid-state laser technologies to enhance reliability, long-term observations, such as these, will be made routinely during both day and night by OASIS. (Data courtesy of Dr. Titus Yuan, Utah State University, Logan, UT)

3.4 Scientific Goals for OASIS

The overarching scientific goal for OASIS is to substantially advance our understanding of the fundamental, universal processes that occur in the Earth's space-atmosphere-interaction region (~50 km and above) and how they shape the atmospheres of Earth-like planets throughout our galaxy.

This goal for OASIS will be achieved by exploring ten key universal processes, at a level of observational detail and altitude coverage that is substantially better than can be realized with any existing set of instruments.

1 Solar radiation influx – How is the Earth's upper atmosphere affected by solar radiation?

What proportion of VUV solar radiation is converted to thermal energy of the neutral gas in Earth's upper atmosphere and how does this vary with height?

How is the vertical thermal structure of the upper atmosphere influenced by short-term variations in the VUV flux?

How might the fundamental process of an upper atmosphere's absorption of solar VUV radiation contribute to improved estimates of habitable zones for candidate exoplanets?

2 Geomagnetic activity – How does geomagnetic activity modify the composition and temperature of the Earth's neutral atmosphere and ionosphere?

How is the upper atmosphere modified with altitude during a geomagetic storm?

How does the upper atmosphere recover from a geomagnetic storm event?

How might the preconditioned state of the upper atmosphere modify the influence of geomagnetic storms?

3 Cosmic dust influx – What is the influx of cosmic dust and how does it affect evolution of the Earth's atmosphere and climate?

What is the magnitude of the global cosmic dust input?

How do transport processes affect the distribution of cosmic dust in Earth's atmosphere?

4 Electrodynamics – What is the role of the magnetic field in defining an Earth-like planet?

Where and when in the upper atmosphere is the neutral atmosphere organized by the magnetic field configuration?

How does the strength and configuration of an intrinsic magnetic field contribute to the evolution of a planetary atmosphere?

5 Plasma-neutral atmospheric coupling – What is the role of plasma-neutral coupling in establishing the predominant states of planetary atmospheres?

How do neutral-wind dynamo regions of Earth develop, evolve and influence plasma and neutral processes?

What is the morphology and consistency of dusty plasmas in the mesosphere and how do they affect the neutral gas behavior in this region?

6 Neutral atmospheric dynamics – What is the mean neutral circulation and thermal structure in the Earth's space-atmosphere-interaction region?

What is the mean circulation and its seasonal variations in the middle and upper atmosphere?

What is the mean thermal structure and its seasonal variations in the middle and upper atmosphere?

What are dynamical and thermal effects of breaking waves and how do they impact the QBO, SAO and MLT circulation?

How are the various dynamical, chemical, thermal and electrodynamic processes coupled vertically to produce the observed neutral and plasma structure in the upper atmosphere?

7 Wave dynamics and transport – How do waves across various scales control large-scale circulation in the space-atmosphere-interaction region of Earth-like planets? How does wave-induced transport influence the structure and composition of planetary atmospheres?

How do nonlinear interactions and dissipation control the spatial and temporal evolution of the wave spectrum that reaches the space-atmosphere-interaction region?

How much does the evolving wave spectrum contribute to the mean thermal and wind structure of the space-atmosphere-interaction region?

How does one parameterize the transfer of heat and momentum from sub-grid wave and turbulence processes in general circulation models of the global atmosphere?

What are the net effects of wave-mean flow interactions and turbulence on the bulk transport and mixing of chemical constituents?

What are the atmospheric momentum, heat, and constituent fluxes, how do they vary and how are they related to local wave activity?

How do wave-induced transport mechanisms affect the circulation, thermal structure and composition of planetary atmospheres?

How does one parameterize the vertical transport of momentum, heat and constituents that arise from sub-grid wave and turbulence processes in general circulation models of the global atmosphere?

8 Turbulence – What are the origin and nature of turbulence in the Earth's space-atmosphere-interaction region?

What are the eddy and thermal diffusivities and turbulent viscosity in the middle atmosphere and lower thermosphere? How do they vary diurnally and seasonally, and how are they related to the wave spectrum?

Where is the turbopause in Earth's atmosphere, how does it vary, and how is it related to local wave activity?

What are the turbulent heating and cooling rates and how do they vary?

How does turbulence affect plasma/neutral coupling and large-scale flow in the space-atmosphere-interaction region?

9 Atmospheric escape – How does atmospheric escape influence the evolution of planetary atmospheres?

What wave processes near the turbopause influence the limiting flux of escaping hydrogen?

How do processes from the turbopause to exobase couple and vary to produce the escape of hydrogen in a planetary atmosphere?

10 Climate change – How is the Earth's space-atmosphere-interaction region changing in response to rising concentrations of atmospheric greenhouse gases?

How are the mean circulation, thermal structure and composition in the Earth's space-atmosphere-interaction region changing in response to rising levels of atmospheric greenhouse gases?

How are gravity waves and their fluxes in the SAIR responding to climate change in the lower atmosphere?

These universal processes are crucial for forming and sustaining Earth-like planetary atmospheres throughout the universe, including our own.

The performance of the OASIS lidars, which represent a 1000-fold improvement in sensitivity over most existing systems, in conjunction with the correlative instruments and model development, will enable significant progress to be made in addressing these questions (Sections 2.3.2 and 3.3). Furthermore, the principal scientific goals of the initiative are consistent with the goals and recommendations of recent community surveys and strategic plans.

National Research Council 2013 - 2022 Decadal Strategy for Solar and Space Physics; A Science for a Technological Society

OASIS helps address three of the four key scientific goals articulated in the NRC report. They are:

Key Science Goal 1. Determine the origins of the Sun's activity and predict the variations of the space environment.

Key Science Goal 2. Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs.

Key Science Goal 4. Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe.

In addition, the OASIS scientific goals are consistent with five of the scientific goals identified by the NRC Panel on Atmosphere-Ionosphere-Magnetosphere Interactions (AIMI). They are:

AIMI Science Goal 1. Global Behavior of the Ionosphere-Thermosphere: How does the IT system respond to, and regulate magnetospheric forcing over global, regional and local scales?

AIMI Science Goal 2. Meteorological Driving of the IT System: How does lower atmosphere variability affect geospace?

AIMI Science Goal 3. Ionosphere-Thermosphere-Magnetosphere Coupling: How do high-latitude electromagnetic energy and particle flows impact the geospace system? What are the origins of plasma and neutral populations within geospace?

AIMI Science Goal 4. Plasma/Neutral Coupling in a Magnetic Field: How do neutrals and plasma interact to produce multiscale structures in the AIM system?

AIMI Science Goal 5. Planetary Change: How is our planetary environment changing over multi-decadal scales and what are the underlying causes?

Furthermore, the OASIS LLT represents one realization of the **Whole Atmosphere Lidar Observatory** that was advocated by the AIMI Panel to enable critical ground-based observational capabilities that will be necessary to achieve the AIMI science goals.

***CEDAR: The New Dimension, Strategic Vision for the NSF Program on Coupling, Energetics and Dynamics of Atmospheric Regions* [May 2011]**

OASIS is highly relevant to the NSF Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) program. The new CEDAR strategic vision, released in 2011, focused on the science of the space-atmosphere-interaction region and advocated the development of a systems perspective to study this region. OASIS contributes directly to the first four of the CEDAR Strategic Thrusts.

Strategic Thrust 1. Encourage and undertake a systems perspective of geospace to understand global connectivities and causal relationships involving the SAIR and to determine their influences on the interaction region and the whole Earth system.

Strategic Thrust 2. Explore exchange processes at boundaries and transitions in geospace 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.

Strategic Thrust 3. Explore processes related to geospace evolution to understand and predict evolutionary change in the geospace system and the implications for Earth and other planetary systems.

Strategic Thrust 4. Develop observational and instrumentation strategies for geospace system studies capable of measuring system properties necessary to examine the coupling mechanisms and complexity within the SAIR.

Because OASIS researchers will include lower and upper atmospheric dynamists and chemists, planetary aeronomers and astronomers and solar physicists who will employ both OASIS observations and other correlative datasets and models to address the key scientific questions, OASIS also contributes indirectly to the two remaining strategic thrusts.

Strategic Thrust 5. Fuse the knowledge base across disciplines to promote collaborations.

Strategic Thrust 6. Manage, mine, and manipulate geospace data and models to tap the vast resources of burgeoning geospace data.

NASA Astrobiology Roadmap 2008

While OASIS will be used to explore the Earth's atmosphere, the universal processes being studied apply to planetary atmospheres in general and to Earth-like planets in particular, anywhere in the universe. Consequently, OASIS will also contribute to the science goals of major astronomy initiatives like the NASA Astrobiology Program. The relevant science goals from the NASA Astrobiology Roadmap 2008 are:

- Understand the nature and distribution of habitable environments in the universe. Determine the potential for habitable planets beyond the Solar System, and characterize those that are observable.
- Determine how to recognize signatures of life on other worlds and on early Earth. Identify bio-signatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ or returned to Earth, and remotely measured planetary atmospheres and surfaces. Identify bio-signatures of distant technologies.

4 Cost Estimates:

Depending on correlative instruments specifically acquired for deployment with OASIS, the facility cost is estimated to be about $150 million.

The OASIS facility will require up to five years to construct. Once OASIS is fully operational, the annual operating and maintenance costs are estimated to be about $3M per year or about 2% of the cost of the facility per year. Alternatively, the construction could be phased over a period of time to minimize the cost impact. The 15-year phased construction schedule summarized below is designed to enable high-priority science issues, those that do not require the full aperture or full complement of instrumentation, to be addressed quickly. The more ambitious observations, those that require the full telescope array, would be addressed later. The cost estimates are conservative.

CY2014 through 2016 –
Cost $7M ($2.3M/yr)

- Design and test prototype 5 m^2 telescope module
- Design and test prototype wavelength demultiplexer/detector assembly
- Assemble complete telescope/detector module for Na/Fe observations
- Test and integrate existing 3-5 W flash lamp-pumped Fe laser
- Develop, test and integrate 10 W pulsed solid-state Na laser

CY2017 through 2018 –
Cost $19.5M ($9.75M/yr)

- Acquire/deploy 4 additional telescope/detector modules for Na/Fe/He obs
- Develop/test/integrate 20 W pulsed fiber He laser
- Acquire/deploy laser lab and data acquistion modules
- Acquire/deploy OH and O_2^+ airglow instrumentation and lab modules ($3.5M)
- Deploy 5-Beam 25 m^2 Na/Fe/He system to suitable ISR site

CY2019 through 2023 –
Cost $97M ($19.4M/yr)

- Acquire/deploy 15 additional telescope/det modules for Na/Fe/He
- Develop, test and deploy 10 W pulsed solid-state Fe laser
- Acquire/deploy mirror recoating module
- Acquire/deploy ISR and meteor radars and lab modules ($26M)
- Upgrade 5-Beam system for 100 m^2 + Na/He/Fe operation

CY2024 through 2028 –
Cost $23M ($4.6M/yr)

- Develop, test and deploy 20 W pulsed Nd-YAG laser for Rayleigh obs
- Upgrade all detector modules for Doppler Rayleigh obs

The operations costs include on-site personnel to maintain the instruments, telescope and tele-science communications systems, as well as off-site management of operations and science activities. The operations cost estimates, summarized below, include benefits for salaries. These cost estimates are also conservative.

- **On Site - $1.40M/yr**
  - 1 Laser engineer - $150K/yr
  - 1 ISR engineer - $150K/yr
  - 2 Telescope/detector systems engineers - $250K/yr
  - 1 Correlative instrument technician - $125K/yr
  - 1 Data acquisition/telescience communications technician - $125K/yr
  - 1 General maintenance employee - $100K/yr
  - Instrument and infrastructure maintenance - $500K/yr
- **Off Site – $1.50M/yr**
  - OASIS Director - $225K/yr
  - Clerical support - $75K/yr
  - Travel - $150K/yr
  - Education and Outreach - $250K
  - Institutional overhead (50% salaries + travel + education) - $800K

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Glossary - Atmospheric Regions

The Earth's atmosphere is divided into various regions based upon temperature structure, composition and dynamical characteristics (see Figure in Executive Summary).

Exosphere – Above the exobase the thin atmosphere merges with space. In this region collisions between atmospheric molecules and atoms are rare while their the thermal motion is sufficiently large that they can achieve escape velocity and become lost to space.

Geospace – Upper region of the atmosphere and magnetosphere where the inner boundary is the ionosphere (~75 km) and the outer boundary is the magnetopause, the interface between the Earth's magnetosphere and solar wind.

Heterosphere – The region above the turbopause where composition varies with altitude because poor mixing allows constituents to stratify based upon molecular weight. The upper region of the heterosphere is composed almost entirely of hydrogen.

Homosphere – The region below the turbopause where the atmosphere is well-mixed by turbulence and so chemical composition is relatively homogeneous.

Ionosphere – Stretching from about 75 km into the exosphere, the ionosphere is the atmospheric region containing electrons and charged atoms and molecules. The ionosphere is created by the ionization of atmospheric constituents, primarily by solar UV radiation, and is divided into four broad regions called *D (75-95 km)*, *E (95-150 km)*, *F (150-250 km)* and topside *(>250 km)*.

Lower Atmosphere – The troposphere and lower stratosphere where most weather phenomena occur (0~15 km).

Magnetosphere – The outer layer of the ionosphere above 100 km where charged particles (electrons, atoms and molecules) are controlled by the Earth's magnetic field and solar wind. The shape of the magnetosphere is quite complex and varies substantially under the influence of the solar wind.

Mesosphere – Also called the *middle atmosphere*, temperature decreases with increasing altitude in the mesosphere reaching values as low as 125-130 K over the polar regions in summer, which are the coldest natural temperatures anywhere on Earth. The mesosphere extends to about 85 km in summer and 100 km in winter. Its upper boundary is called the *mesopause*.

Middle Atmosphere – Generally considered to be the stratosphere and mesosphere between about 10 and 100 km.

Plasmasphere – Region of the inner magnetosphere consisting of low energy (cool) plasma whose motion is largely dominated by the Earth's magnetic field.

Space-Atmosphere-Interaction Region – Mesosphere, thermosphere and ionosphere from 50 to 1000 km.

Stratosphere – Located above the tropopause, temperature increases with increasing altitude in the stratosphere because of the absorption of solar UV radiation by ozone. The upper boundary of the stratosphere near 50 km is called the *stratopause*.

Thermosphere – Located above the mesopause, temperature increases with increasing altitude in the thermosphere, reaching values as high as 1000 K or more. The upper boundary, where the mean-free path is equal to the atmospheric scale height, is called the *thermopause* or *exobase*. The altitude of the exobase varies between about 500 and 700 km, depending on solar activity.

Troposphere - Lowest region of the atmosphere in which the temperature generally decreases with increasing altitude. The troposphere extends to about 15 km altitude near the Equator and to about 8-10 km near the poles. Its upper boundary is called the *tropopause*.

Turbopause – Located near 100 km, the turbopause marks the boundary between the lower atmosphere, where turbulent mixing dominates, and the upper atmosphere, where molecular diffusion dominates.

Upper Atmosphere – Region above 100 km that includes the thermosphere and exosphere.

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