CEDAR LIDAR BEYOND PHASE III;

ACCOMPLISHMENTS, REQUIREMENTS AND GOALS

A self-assessment by the CEDAR lidar community for the Division of Atmospheric Sciences of the National Science Foundation

MARCH 2004

EXECUTIVE SUMMARY

The Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) program, an element of the U.S. Global Change Program, contributes to our understanding of the whole atmosphere and its response to both natural and anthropogenic processes. The CEDAR program has seen dramatic progress in understanding the physics and chemistry of the middle atmosphere and how this region is coupled with both the lower and the upper atmosphere. Arguably, the CEDAR lidar program has been the keystone for many of the advancements made in CEDAR-related science goals related to middle-atmosphere research, and is a program whose measurement domain and capabilities are directly applicable to climate change concerns. This report highlights the scientific achievements and technical advancements made by the CEDAR lidar community, and provides recommendations and priorities for future initiatives that will lead to new scientific advances in CEDAR science.

The CEDAR lidar program has contributed at various levels to all four science areas of the CEDAR Phase III initiative. Lidar studies have addressed the outstanding scientific questions identified by the CEDAR community. The CEDAR lidar community has published over 200 peer-reviewed papers since 1985. The lidar community has demonstrated expertise in developing new technologies, exploiting unique telescope facilities, and deploying lidar systems at a wide variety of field locations.

Current lidar programs will continue to contribute to CEDAR science, improve system performance and capabilities, and ensure high-quality, high-fidelity measurements. However, to guarantee fundamental advances, the report recommends that the following actions be given the highest priority by the CEDAR community.

1. Ready access to (or development of) large-aperture telescope facilities
2. The development and deployment of robust mobile lidar systems capable of wind and temperature measurements in the in the middle atmosphere
3. The development and deployment of Doppler Rayleigh wind-temperature systems to meet the need for measurements of the atmospheric circulation below the mesopause region
4. Support for technical innovation at the level of a center of excellence for lidar research
5. The improvement of existing systems by measures such as enabling daytime capabilities and extending Rayleigh systems with Raman channels
6. The extension of lidar measurements into the thermosphere by exploring new species to serve as lidar targets for upper atmospheric research
7. the development of novel lidar technologies to explore alternative methods for studying the middle aatmosphere.

The implementation of these recommendations would allow the CEDAR lidar community to obtain

1. wind and temperature measurements over complete diurnal cycles, which are required for the understanding of tidal, planetary, and gravity wave fluxes as well as wave-wave and wave-mean flow interactions in the middle atmosphere,
2. the very high resolution measurements that are required to understand instabilities and other small-scale processes in the middle atmosphere,
3. the consistent long-term measurements that are required to study long-term trends in the middle atmosphere,
4. new measurements in the thermosphere (E and F regions), where they would provide basic measurements of thermospheric composition and circulation,
5. the species-specific measurements of both neutral and ionized species that are required for study ion-neutral coupling and MLT electrodynamics,
6. the high-resolution measurements of nanometer-size particles required for studies of cloud formation in dusty plasma environments.

These measurements are required to advance our understanding of the middle atmosphere.

This report recommends that the CEDAR lidar community engage in a formal and technical community dialog that addresses the community priorities identified above: specifically, that the CEDAR community support the following activities at the annual CEDAR meeting in 2004:

1. a dedicated session with panel discussions identifying and prioritizing scientific questions concerning the middle atmosphere that can be addressed by lidar, and
2. a dedicated session with panel discussions presenting technical approaches to developing the next-generation lidar systems that will be employed by the community.

In addition to meeting the specific needs of the CEDAR lidar, the goal of these sessions will also be to promote two other critical processes:

1. discussions between lidar and non-lidar researchers that will increase synergism in the observational programs of the CEDAR community
2. engagement of students who are already working or considering work in middle-atmosphere lidar.

Finally this report recommends that the NSF Upper Atmosphere Research Section and the CEDAR lidar community work together to accomplish the following:

1. Develop a strategy to ensure continued access to a Class-I large-aperture telescope facility for lidar research (Community Priorities 1 and 4).
2. Create a specific major proposal opportunity in support of next-generation lidar systems (Community Priorities 2, 3, and 4).
3. Support, as appropriate, extensions and improvements to current lidar systems (Community Priority 5).
4. Support as appropriate investigations of new technologies and species for middle-atmosphere lidar studies (Community Priorities 6 and 7).
5. Establish a committee, consisting of both lidar experimentalists and middle/upper atmospheric researchers, to develop an integrated research strategy for the CEDAR lidar community (Community Priorities 1–7).

PREFACE

This report was requested by Dr. Robert M. Robinson, Program Manager in the Division of Atmospheric Sciences of the National Science Foundation (NSF) for the Coupling, Energetics and Dynamics of Atmospheric Regions (CEDAR) program, during the annual CEDAR meeting in June 2003. The purpose of this report is to provide a self-assessment from the CEDAR lidar community to the NSF that could be used to assess the current status and future directions of lidar research in the CEDAR program.

The report is based on a community discussion between the members of the CEDAR lidar community. The participants in this discussion were

Arecibo Observatory: Craig Tepley, Jonathan Friedman, Shikha Raizada

Clemson University: John Meriwether, Andrew Gerrard

Colorado State University: Chiao-Yao She, David Krueger

Northwest Research Associates: Bifford Williams

Pennsylvania State University: Timothy Kane

SRI International: Jeffrey Thayer, Weilin Pan

University of Alaska: Richard Collins

University of Illinois: Chester Gardner, Gary Swenson, Xinzhao Chu, Alan Liu

Utah State University: Vincent Wickwar, David Rees.

In preparing this report, several members of the CEDAR lidar community contributed documents that reviewed scientific accomplishments, technological opportunities and challenges, and identified future scientific goals and opportunities. These contributions formed the foundation for the report and appear as a companion volume to the report in Appendix II. The contributions present the researchers of the CEDAR lidar community in their own words. These contributions were revised by their authors based on feedback from the community discussion group.

The initial draft of this report was prepared in September and October 2003. Over that two-month period, three drafts of the report were prepared and circulated to the lidar community. Maura Hagan (National Center for Atmospheric Research) and John Plane (University of East Anglia) provided informal reviews of the second draft of the report as researchers who collaborate with the CEDAR lidar community but are not members of the lidar community. The report was then presented to the CEDAR Science Steering Committee (CSSC) at their annual meeting at NSF headquarters in November 2003 and has been circulated in the community. The comments of the CSSC were circulated to the lidar discussion group and follow-up discussions were held at the Fall Meeting of the American Geophysical Union in December. The final draft of the report was prepared in February and March 2004. Christine Stensig, technical editor at SRI, edited the final copy of the report.

This final copy of the report is a revised and augmented version of the CSSC draft report.

Richard L. Collins
Geophysical Institute,
University of Alaska Fairbanks

March 2004

Cover: Photos of lidar sites at (top left to right) Utah State University, Arecibo Observatory, Maui Space Surveillance Site, (bottom left to right) Poker Flat Research Range, Colorado State University, and Sondrestrom Upper Atmosphere Research Facility.

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1. THE CEDAR PROGRAM

The Coupling Energetics and Dynamics of Atmospheric Regions (CEDAR) program has evolved through three distinct phases. Phase I was an initial phase of active planning and organization. Phase II was a phase of collaborative projects. Phase III was a new phase of scientific goals. The CEDAR Phase III Report specifically notes,

"During CEDAR Phase II, no new technology has contributed more to the science goals of CEDAR below 100 km than lidars. These include resonance lidars tuned to various alkali metals near the mesopause and Rayleigh lidars of the backscatter and Doppler type. The broad and narrow band resonance systems provide high-resolution measurements of wave dynamics and, ion-neutral chemistry, (including thin layers), temperatures, and winds in the 80–110 km region. The Rayleigh systems provide important measurements relating to vertical coupling processes. Contributions to CEDAR Phase III science goals will continue from existing instruments, especially as the power and aperture of lidar systems increase with the aid of new technologies."

The CEDAR Phase III Report identifies the following four science initiatives:

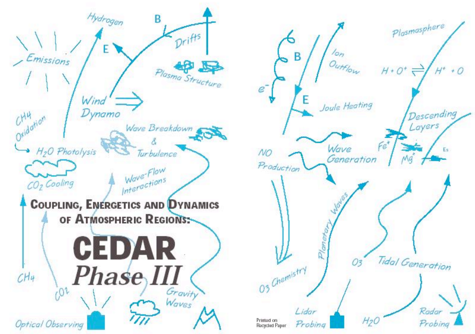
1. Coupling with Lower Altitudes (CLA)
2. Solar-Terrestrial Interactions (STI)
3. Polar Aeronomy (PA)
4. Long-Term Variations (LTV).

The report also presents 27 outstanding science questions that should be addressed by the research community. Lidar studies contribute to 19 of the 27 outstanding science questions. These questions are listed below. The outstanding science questions that CEDAR lidar studies are helping to answer are denoted by the word "***Lidar***."

1.1 COUPLING WITH LOWER ALTITUDES

1. What parts of the wave spectrum are most important in determining the thermal structure and energy and momentum budgets in the mesosphere-thermosphere-ionosphere? ***Lidar***
2. To what extent do planetary waves modulate atmospheric tides, and can such modulations of tidal motions in the dynamo region account for ionospheric signatures of planetary wave periodicities? ***Lidar***
3. What roles do waves play in driving the E- and F-region drifts and in the generation of E- and F-region dynamos. Do middle-atmosphere electrical processes such as jets and sprites affect ionospheric electrodynamics?

THE CEDAR PHASE III REPORT



The CEDAR Phase III report identifies critical scientific questions in advancing our understanding of the middle atmosphere. This community report can be found at http://cedarweb.hao.ucar.edu/commun/cedarcom.html.

4. What are the effects of wave transport on chemically active species in the mesosphere and lower thermosphere? ***Lidar***
5. Does tidal modulation of wave fluxes contribute to the observed day-to-day variability in the mesosphere and lower thermosphere? Does it control the global homogeneity in eddy mixing and minor constituent concentrations? ***Lidar***
6. What is the full role of gravity waves in creating electric fields and in seeding plasma instabilities that dominate space weather effects at equatorial and lower mid-latitudes? ***Lidar***

1.2 SOLAR-TERRESTRIAL INTERACTIONS

1. How do electric fields, composition changes and neutral dynamics interplay to determine the latitude/longitude. seasonal, local time and UT dependencies of ITM system response? ***Lidar***
2. To what degree do global ionosphere/thermosphere features, including the distribution of irregularity structures, depend on the orientation of the interplanetary magnetic field?
3. To understand the origins of local and regional features in ionospheric and thermospheric structure, what are the required spatial and temporal resolution and accuracy in the determination of energetic sources? ***Lidar***
4. What is the relative importance of thermosphere-ionosphere perturbations due to meteorological influences in comparison to those originating in the magnetosphere? How do these vary with height? ***Lidar***
5. What are the spatial scales and response times of the processes controlling the global electric field distribution?
6. How do ambient conditions influence the appearance of equatorial plasma structures and their evolution?

7. How do soft X-ray/EUV solar fluxes influence the hourly and daily variability of the ionosphere/thermosphere system?

1.3 Polar Aeronomy

1. How are composition, density and heating influenced by the auroral characteristic energy and energy flux? ***Lidar***
2. What are the magnitude and temporal variability of the polar wind?
3. What are the underlying physical causes of the inter-hemispheric differences in observed aeronomic parameters at polar latitudes? ***Lidar***
4. What are the dynamical influences on the polar MLT region from the magnetospheric, solar and meteorological sources of energy? What are the roles of chemical heating, LTE and non-LTE effects, ion-neutral chemistry, gravity wave momentum and energy deposition, Joule heating, and energy particle precipitation? ***Lidar***
5. How do the relationships between electron density, conductivity, neutral and ion composition, ion convection and neutral winds influence polar electrodynamics? How do they regulate the energy flux between the ionosphere and magnetosphere at high latitudes? ***Lidar***
6. What is the time history of electric potential voltage across the polar caps? What is the shape and size of the polar cap in response to this voltage? ***Lidar***
7. How does the interaction between large-scale circulation and gravity waves impact the presence of NLCs and PMSEs in the polar regions? ***Lidar***
8. What are the relationships between meteoric input, ionospheric plasma and minor neutral lays in the MLT region? ***Lidar***

1.4 Long-Term Variations

1. What identified long-term trends can be ascribed to inter-solar cycle variability and which to changes in the atmospheric composition at low altitudes? ***Lidar***
2. Are composition changes, temperature changes, or dynamical changes primarily responsible for changes in NLC occurrence frequency? How are these parameters related? ***Lidar***
3. What are the cloud physics issues associated with NLCs? What are the condensation nuclei, and does NLC occurrence frequency depend strongly on their variability? ***Lidar***
4. Can long-term trends in mesospheric temperatures and winds, distinct from solar cycle effects, be clearly established? ****Lidar****
5. In the thermosphere and in the F-region, can long-term trends in neutral density and temperature, peak electron density, and height of the peak be established? ***Lidar***
6. Will an apparent trend in upper thermospheric and exospheric hydrogen column abundance persist through subsequent solar cycles?

2. CEDAR LIDAR IN PHASE III

Since the publication of the Phase III Report there has been a vigorous development of lidar science in the CEDAR community. Leadership in the lidar community has been evident in three broad areas:

1. the development of new lidar technologies,
2. the utilization of unique facilities, and
3. the deployment of lidar systems at new sites.

Lidar technology offers the ability to make high-resolution measurements of wind, temperature, aerosol, and minor species (particularly the alkali metals).

The value of these range-resolved measurements has become better appreciated as the CEDAR community's understanding of the physics and chemistry of the middle atmosphere has become more sophisticated. This appreciation has grown further as community understanding of observational and analytical techniques has matured.

The NSF CEDAR program supports six lidar systems with active observation and analysis programs at sites in North America and Greenland. Three additional lidar systems are operated in collaboration with international partners. CEDAR lidars have been operated as part of instrument clusters and have supported multi-instrument campaigns that have employed ground-based, airborne, rocket, and satellite measurements (e.g., AIDA, ALOHA-90, ALOHA/ANLC-93, COQQUI-I, COQUI-II, CODA, DUSTDARTS, TOMEX, Maui-MALT, MacWAVE). CEDAR lidars have also provided critical calibration and validation data for other ground-based techniques (medium-frequency [MF] and meteor radars, airglow imagers, etc.) and for satellite observations (TIMED, ILAS, UARS, etc.) These contributions have been reported in over 200 peer-reviewed articles (see the bibliography in the Appendix). The growth in the dissemination of scientific results by the community is evident in the steady increase in published results. The following special journal issues highlight specific scientific contributions:

- "ALOHA-90: The Airborne Lidar and Observations of the Hawaiian Airglow Campaign," Geophys. Res. Lett., ALOHA-90 Special Issue, vol. 18, no 7, July 1991.
- "Arecibo Initiative in Dynamics of the Atmosphere, AIDA ACT'89," J. Atmos. Terr. Phys. Special Issue, vol. 55, no. 3, March 1992.
- "ALOHA/ANLC-93: The 1993 Airborne Lidar and Observations of the Hawaiian Airglow/Airborne Noctilucent Cloud Campaigns," Geophys. Res. Lett., ALOHA/ANLC-93 Special Section, vol. 22, no. 20,

15 October 1995.

- "ALOHA/ANLC-93 Campaigns," J. Geophys. Res.-Atmospheres, vol. 103, no. 6, 27 March 1998.
- "COQUI II," Geophys. Res. Lett., vol. 27, no. 4, 15 February 2000.
- "Layered Phenomena in the Mesopause Region," J. Geophys. Res.-Atmospheres, vol. 108, no. 6, 27 April 2003.
- "Turbulent Oxygen Mixing Experiment," J. Geophys. Res.-Atmospheres, vol 109, no. 2, 20 January 2004.

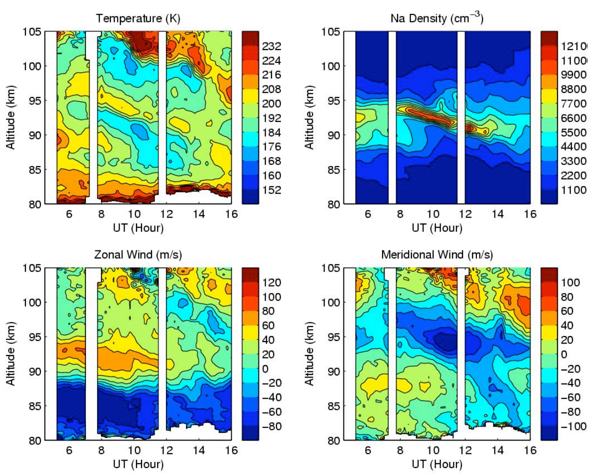
The research activities of the CEDAR lidar community have provided a wide variety of educational opportunities for graduate and undergraduate students. Lidar research allows participation by students in every phase of activity, from the design and operation of lidar systems, to the analysis of the data.

The development of lidar systems in the CEDAR community has been motivated by the need to obtain the measurements of temperature, wind, and constituents (i.e., aerosols and minor species) that are the highest resolution (in both space and time [< 1 km, < 1 min] possible. This demand for high-resolution lidar measurements has been the driver for deploying lidars at facilities with large-aperture telescopes (i.e. the Starfire Optical Range and Maui Space Surveillance Site). In parallel with this push for high-resolution studies has been the development of technologies to support daytime as well as nighttime observations. Given the capability of lidars to yield high-resolution measurements throughout the middle atmosphere (~30–80 km Rayleigh lidars, ~80–110 km resonance lidars), a strong focus of the lidar community has been studies the thermal structure and dynamics of the middle atmosphere. These studies have addressed the basic need to understand wave processes in the middle atmosphere, where waves dominate the wind amplitudes and much of the transport of momentum, heat and trace species. Recently with the launch of the TIMED satellite and the ability of lidars to make continuous daytime and nighttime measurements, complementary studies of tides and waves have been conducted where the lidar has provided understanding of the local small scales and the satellite has provided understanding of the global large scales.

Lidar studies of middle-atmosphere dynamics have generally been pursued in two distinct ways,

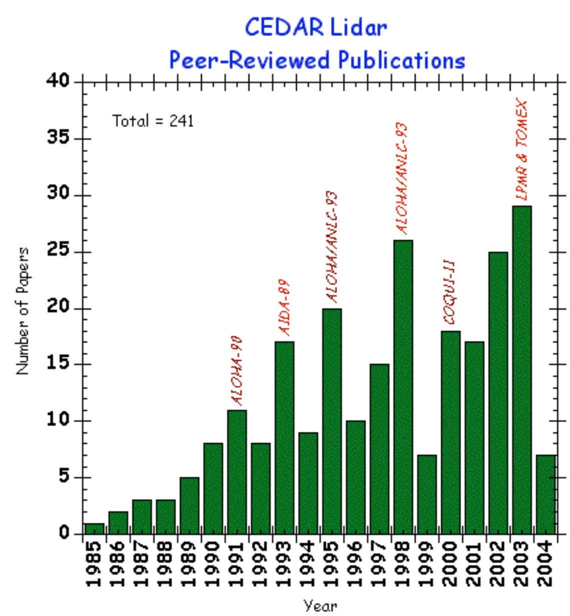
1. Case study observations that capture signatures of tidal and wave events in temperature, wind and constituent variations. These studies have yielded new measurements of
   - i. characteristics of waves and tides,
   - ii. coupling by wave activity of different altitude regions,
   - iii. scales and structures of instabilities, and

LIDAR STUDIES WITH LARGE-APERTURE TELESCOPES



Lidar measurements with large-aperture, steerable astronomical-quality telescopes (e.g., the 3 m telescope at the Starfire Optical Range and the 4 m telescope at the Maui Space Surveillance Site) have furnished high-resolution wind and temperature measurements. These observations support studies of how gravity waves transport energy in the atmosphere and contribute to the general circulation by providing measurements of the instabilities associated with breaking waves.

CEDAR LIDAR PUBLICATIONS



Number of peer-reviewed journal articles published by CEDAR lidar community each year. The years where the results of focused CEDAR campaign results are presented appear as spikes. The publication count in 2004 is only through March. The publications are listed in the Bibliography (Appendix I)

iv. wave-driven fluxes of momentum and heat.

2. Longer-term observations of temperature and constituents that provide benchmark data for circulation models. These lidar data sets allow the various model components (e.g., heating due to wave-breaking, inter-hemispheric differences in solar radiation) to be tested to match the observations and assess the influence of

   i. long-period cycles (i.e. the solar cycle),
   ii. global-scale events (i.e. volcanic eruptions), and
   iii. long-term trends (i.e. anthropogenic changes).

Furthermore, these high-resolution lidar capabilities have yielded new measurements in support of studies of

i. noctilucent clouds,
ii. distribution of minor species,
iii. coupling of ionic and neutral species,
iv. electrodynamic coupling between the thermosphere and mesosphere,
v. auroral influences, and
vi. meteors.

Lidar systems have also played an integral role in developing synergism between different measurement techniques (e.g., lidars, airglow imagers, meteor radars) and developing new insights into multi-instrument measurements.

2.1 LIDAR SCIENCE STUDIES

As discussed in Section 1, the wide variety of studies that have been enabled by lidar science have directly addressed many of the CEDAR Phase III outstanding science questions. In the accompanying figure we cross reference these specific lidar studies to the CEDAR Phase III document questions for the four science initiatives (Coupling with Lower Altitudes [CLA]; Solar-Terrestrial Interactions [STI]; Polar Aeronomy [PA]; and Long-Term Variations [LTV]). These studies include new observations (1–13) as well as analyses of new lidar techniques (14). For example, "PA4" denotes that the lidar study contributes to the fourth outstanding question of the PA initiative

2.2 CURRENT CEDAR LIDAR SYSTEMS

CEDAR lidars are currently located in all latitudes. Different lidar technologies are used to conduct a variety of studies.
In polar latitudes there are lidars at two sites.

1. Poker Flat Research Range, Chatanika, Alaska (65° N, 147° W): Broadband resonance lidar
2. Sondrestrom Upper Atmospheric Research Facility, Kangerlussuaq, Greenland (67° N, 51° W): Broadband Rayleigh lidar, Broadband resonance lidar.

In middle latitudes there are lidars at two sites.

1. Colorado State University, Fort Collins, Colorado (41° N, 105° W): Narrowband resonance lidar
2. Utah State University, Logan, Utah (42° N, 112° W): Broadband Rayleigh lidar.

In the tropics there are lidars at two sites:

1. Maui Space Surveillance Site, Maui, Hawaii (21° N, 156° W): Narrowband resonance lidar
2. National Astronomy and Ionosphere Center, Arecibo, Puerto Rico (18° N, 67° W): Broadband resonance lidar, Narrowband resonance lidar.

Three lidar systems are operated in collaboration with CEDAR researchers.

1. ALOMAR, Andoya, Norway (69° N, 16° E):

   Narrowband resonance lidar, with Institute of Atmospheric Physics and Andoya Rocket Range
2. Poker Flat Research Range, Chatanika, Alaska (65° N, 147° W):

   Broadband Rayleigh lidar, with Communications Research Laboratory
3. Rothera Research Station, Adelaide Island, Antarctica (68° S, 68° W):

   Broadband resonance lidar, with British Antarctic Service.

It is important to acknowledge that the NSF CEDAR lidar

LIDAR STUDIES AND CEDAR SCIENCE QUESTIONS

1. *Thermal and Wind Structure of the Mesosphere and Lower Thermosphere Region (MLT).* CLA2, CLA4, STI4, PA3, PA4, LTV2, LTV4
2. *The Dynamic and Convective Stability of the MLT or Mesopause Region.* CLA1, CLA6, PA4, LTV2
3. *Diurnal Thermal Structure of MLT Region.* CLA2, CLA5, PA4, LTV1, LTV4
4. *Long-Term Trends in MLT Structure.* PA3, LTV1
5. *Gravity Wave/Tidal Coupling.* CLA2, CLA5, CLA6, STI4, LTV4
6. *Dynamical Wave Cooling in the MLT Region.* CLA1, LTV1, LTV2
7. *Instability Layers, Planetary Wave and Tidal Activity.* CLA1, CLA2, CLA4
8. *Stratospheric and Mesospheric Winds.* CLA4, CLA5, STI4, LTV1
9. *Long-period gravity waves.* CLA5, STI4
10. *Noctilucent Clouds.* CLA1, PA7, PA8, LTV1, LTV2, LTV3
11. *Meteoric Metal Layers.* CLA4, PA8, LTV1
12. *Sporadic or Sudden Metal Layers.* STI1, STI3, STI4, PA4
13. *Meteors.* CLA4, PA8
14. *Thermospheric Studies.* STI3, PA1, PA5, LTV5

programs also receive support for instrument development and operation from funding programs in the National Aeronautics and Space Administration (NASA) and the U.S. Department of Defense when these efforts support common science goals (e.g., the support of middle-atmosphere satellite programs; the development of new remote sensing technologies).

Lidar systems fall in four main categories with the following measurement capabilities.

1. Broadband Rayleigh Lidars:
2. Hydrostatic temperature profiles (~30–90 km); noctilucent clouds (~83 km)
3. Broadband Resonance Lidars:
4. Mesospheric metal profiles and temperatures (~80–110 km)
5. Narrowband Rayleigh Lidars:
6. Stratospheric and mesospheric wind profiles (~30–60 km)
7. Narrowband Resonance Lidars:
8. Mesospheric temperatures, wind, and metal profiles (~80–100 km).

CEDAR lidars employ a variety of lidar technologies that yield a variety of instrument capabilities. Several of these technologies are relatively mature.

1. solid-state lasers (Nd:YAG and alexandrite),
2. dye lasers,
3. excimer lasers,
4. narrowband filters, and
5. Fabry-Perot interferometer receivers.

Several technologies have been developed by the CEDAR community:

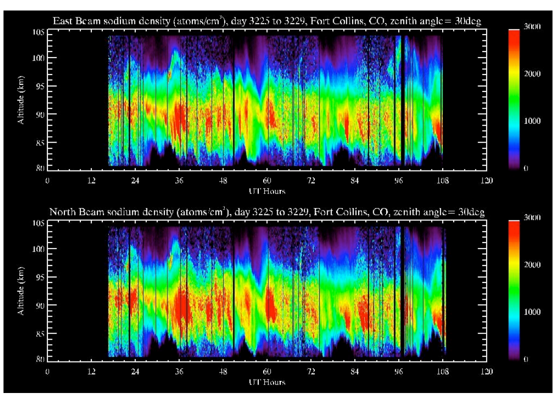
1. continuous-wave (CW)–injected hyperfine pulsed dye laser systems,
2. acousto-optic modulation tuning of lasers,
3. CW-injected and locked solid-state lasers,
4. CW solid-state mixing lasers,
5. Faraday filters, and
6. spectrally tunable receivers.

2.3 LIDAR OPERATION AND MAINTANENCE

In general terms, broadband Rayleigh and resonance lidar systems can be operated by technicians or students at the undergraduate or M.S. level. Narrowband Rayleigh and resonance lidar systems require more sophisticated operators (principal investigator: Ph.D.–level student, post-doctorate or engineer), who may in turn manage a team of trained operators. Principal investigators have developed all the current CEDAR lidar systems with teams of research staff and/or students. Staffs at these sites maintain laser safety and operate the lidar system.

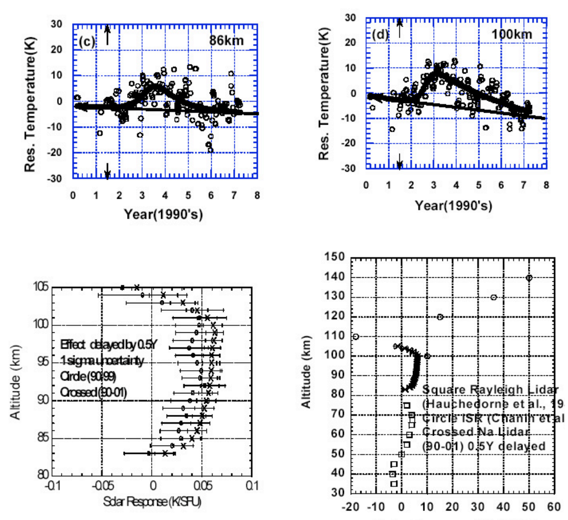
CEDAR lidar systems are generally maintained by the resident research staff. Routine maintenance costs include ongoing replacement of chemicals, gases, filters, and other consumables; annual replacement of optics and flashlamps; and biannual replacement of high-voltage parts. Annual or biannual visits by technicians from the

MULTI-DAY WIND/TEMPERATURE LIDAR MEASUREMENTS



Sodium resonance lidar observations over several days provide wind and temperature measurements for studies of tides and waves. These measurements provide data for quantifying the magnitude and variability of the atmospheric tides and planetary waves, as well as studying wave-wave interactions between different scale wave phenomena. The effort achieve these measurements has spurred a variety of developments in lidar technology.

LONG-TERM LIDAR OBSERVATIONS



CEDAR Lidar observations have yielded long-term measurements of mesopause region (~80–100 km) temperatures. Long-term lidar measurements allow the detection of global trends as well as of the response of the atmosphere to the solar cycle and to specific events (e.g., the eruption of Mt. Pinatubo).

laser vendor maintain the long-term performance of the lidar systems as well as providing training opportunities and continuity for students. The scientific laser community is relatively specialized and small, but the industry supports a variety of dealers in laser technologies: flashlamps, dyes, electronics, filter systems, and chemicals. Laser experimenters are experienced in purchasing supplies and parts at substantial savings from these dealers rather than from the laser vendors directly.

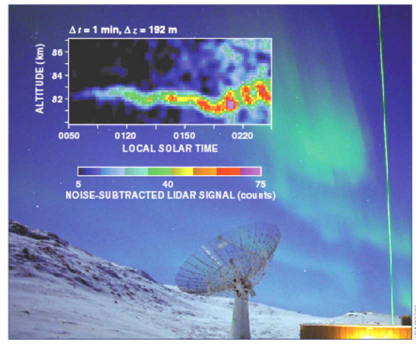
The different lidar groups of the lidar CEDAR community have collaborated in a variety of ways:

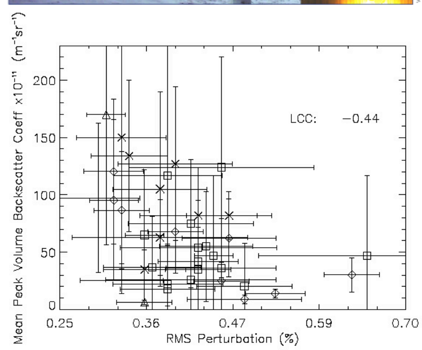
- Cooperative technical development. For example, the first sodium Doppler wind-temperature system was deployed as a collaboration between the University of Illinois and Colorado State University.
- Donation and loaning of lidar equipment. For example, lasers and telescopes have been loaned by the University of Illinois to the University of Alaska and by Clemson University to Pennsylvania State University.
- Training of personnel at different sites. For example, University of Illinois students have trained at Colorado State University for work in Maui.
- Hosting visiting students to participate in experiments at observatory sites. For example, students from Pennsylvania State University have worked at Sondrestrom and Arecibo; students from Cornell University have worked at Arecibo and Poker Flat.

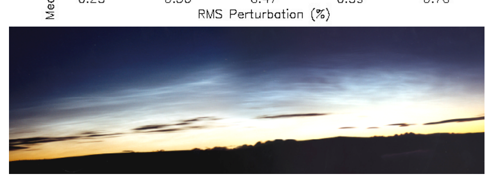
The complexity of the CEDAR lidar systems varies enormously. The operation of a single zenith pointing broadband Rayleigh lidar system at Poker Flat is considerably less challenging than the operation of resonance wind temperature measurements with the steerable 4 m mirror at the Maui Space Surveillance Site. Furthermore, the operational demands of an experimental program where seasonal measurements are made in an ongoing fashion at weekly or biweekly intervals (e.g., developing a long-term benchmark set of observations) are very different from the demands of an intensive campaign (e.g., several days of continual day and night observations for tidal studies; successive nightly observations in support of a rocket campaign or the seasonal appearance of noctilucent clouds).

Generally, lidar operators must make laboratory class

NOCTILUCENT CLOUDS

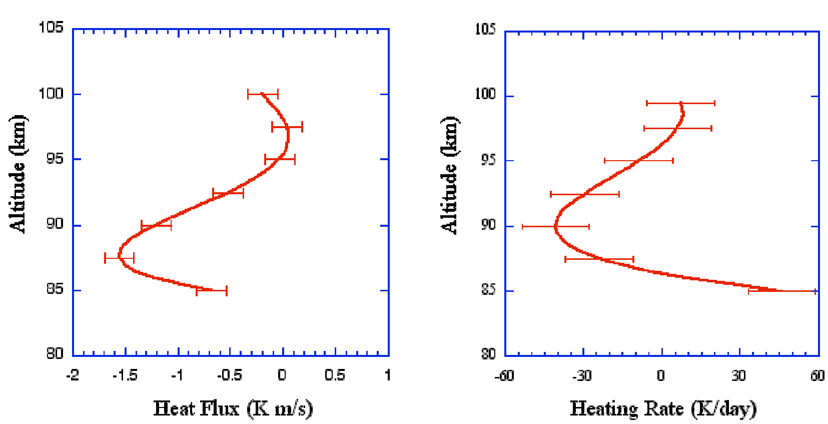






Simultaneous lidar measurements of waves in the stratosphere and mesosphere and noctilucent clouds in the mesosphere support studies of dynamic coupling across the stratopause as well as understanding the variability of noctilucent clouds. Lidar observations of noctilucent clouds also support studies of long-term change and dusty plasmas in the atmosphere.

LIDAR MEASUREMENTS OF WAVE-DRIVEN FLUXES



Estimated wave-driven fluxes of sensible heat and associated cooling rates derived from lidar measurements of wind and temperature. Such measurements allow assessment of the contribution of small-scale dynamics to the large-scale circulation of the atmosphere.

measurements in field environments under real-time conditions for long periods. These field conditions are often far removed from the campus laboratory environments envisioned by the laser manufacturer (e.g., aircraft, dry high-altitude conditions, humid tropical conditions). Narrowband lidar systems require moderate environmental control of temperature and humidity. The goal of completely unattended operation is probably beyond reach for the foreseeable future, given the electronic and laser safety issues involved in the operation of lidar systems.

2.4 MULTI-INSTRUMENT STUDIES

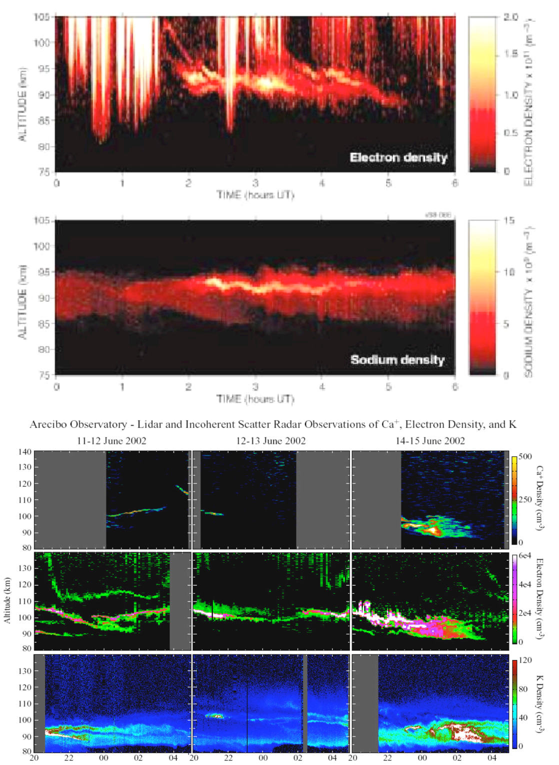
A major accomplishment of the CEDAR program has been to bring instruments together in clusters to yield new insights into the middle atmosphere. The collocation of radars, lidar, and imagers has been employed with great effect during focused campaigns (e.g., ALOHA, COQUI) to better study particular phenomena (e.g., wave-breaking events, ion-neutral coupling in sporadic layer events). The success of these campaign efforts is evidenced in the resultant publications associated with these campaigns (see CEDAR LIDAR PUBLICATIONS in Section 2).

Beyond the immediate gain from having multiple points of view of a particular phenomenon, these studies have also spurred new efforts to better combine and interpret observations from different instruments. The combination of airglow images of waves with lidar measurements of wind and temperature has yielded new insights into waves in the mesopause region. The combination of wind measurements made by of wind-temperature lidars and meteor radars has enabled new engineering analyses of these measurement methods; these analyses have improved understanding of the measurement techniques and how they can be best combined.

2.5 STUDENT PARTICIPATION

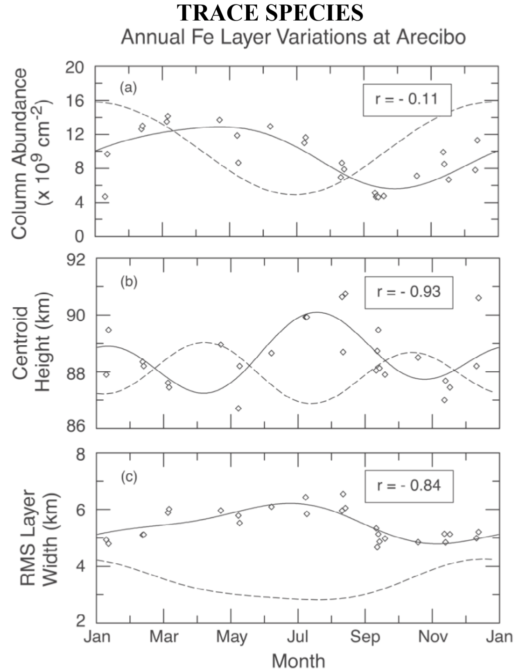
Student involvement has been a hallmark of research in the CEDAR lidar community; students have participated and provided leadership in the development, deployment, and analysis of lidar systems. Students in the CEDAR lidar programs have the opportunity to participate in the remote sensing process, from the design and operation of electro-optic systems that use basic physical principles to acquire data, to the inversion and analysis of that data to yield information about the atmosphere, and the presentation and integration of that information into current scientific understanding of the middle atmosphere. Much of the leading developments in the CEDAR lidar community have depended on the expertise of students. Their participation has been recognized and appreciated

SPECIES-SPECIFIC LIDAR STUDIES OF ION-NEUTRAL COUPLING



Resonance lidars provide high-resolution species-specific measurements of neutral and ionized metals (e.g. sodium, potassium, calcium-ion) that can be combined with radar measurements (i.e. electrons) in support of studies of ion-neutral coupling, electrodynamics and chemistry in the upper mesosphere and lower thermosphere.

LATITUDINAL VARIATION OF TRACE SPECIES



Resonance lidar measurements of the mesospheric metal layers at different sites can be combined with chemical models to determine latitudinal variations in oxygen species.

by peers in the CEDAR community, employers in electro-optics, and juries for professional prizes. Six students have been awarded the Optical Society of America's Allen prize in recognition of their contributions to optical remote sensing. Several of the CEDAR lidar programs host summer students under the NSF Research Experience for Undergraduates program.

3. CEDAR LIDAR BEYOND PHASE III

To make truly fundamental advancements to CEDAR science, the CEDAR lidar community must,

1. focus the science benefits provided by lidar on the scientific needs of the community,
2. develop, apply, and deploy technological advances, and
3. critically evaluate, maintain and improve existing lidar systems.

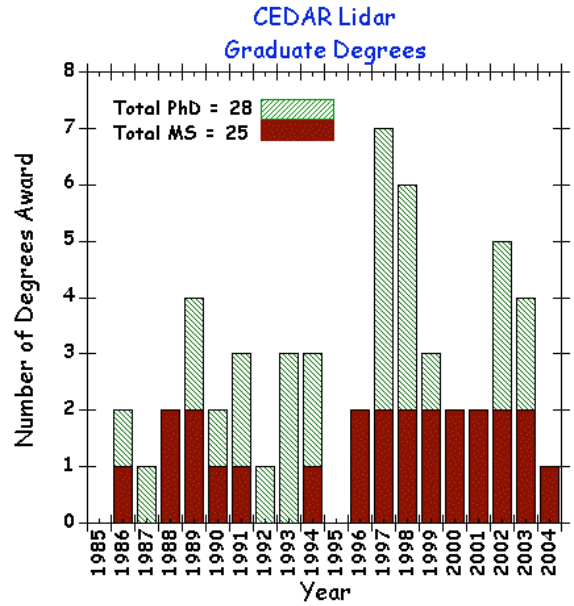
3.1 TECHNICAL CHALLENGES

The goal of wind-temperature measurements throughout the middle atmosphere in both daytime and nighttime presents challenges to both lidar transmitter and receiver technologies. The current sodium Doppler wind-temperature resonance lidars operate routinely and yield measurements of wind and temperature in daytime and nighttime with the highest resolution of CEDAR lidars. This performance reflects the efforts of the research groups at the University of Illinois and Colorado State University, who have continually fielded and continually refined these systems since they were first deployed in 1989.

These sodium Doppler wind-temperature resonance lidars are capable of making state-of-the-art high-resolution measurements that will support foreseeable studies of the mesopause region circulation. However, these lidar systems have two major limitations: they require in-house dedicated staff with technical expertise and they are limited to measurements in the altitude of the mesospheric metal layers (~80–110 km). A dedicated but moderate engineering effort would make the sodium Doppler wind-temperature systems more turn-key through a process of electronic, optical, and mechanical refurbishment and refinement. Current engineering efforts are under way to develop hybrid systems:; laser systems that replace some of the dye laser components with solid-state technology.

Resonance temperature systems that employ the hyperfine spectroscopy of potassium have been developed and operated routinely at Arecibo Observatory and by the Institute of Atmospheric Physics at Kühlungsborn, Germany. The systems operate with a lower signal-to-noise level (and hence resolution) than the sodium systems, due to the much lower abundance of mesospheric potassium. These systems could be upgraded to measure wind as well as temperature but would yield lower measurement quality than the sodium-based wind measurements. The University of Illinois developed an

GRADUATE STUDENT EDUCATION



Number of degrees awarded to students working on cedar lidar science each year. MS degrees are colored solid red and PhD degrees are dashed green. The degree count in 2004 is only through March.

iron Boltzmann lidar with twin solid-state lasers that excite a ground state and a Boltzmann populated upper state in mesospheric iron. This solid-state lidar has been deployed on aircraft as well as at remote locations in Antarctica. Like potassium-based resonance temperature systems, this system yields temperature measurements at a lower-signal-to-noise ratio than sodium. While iron Boltzmann lidar has yielded temperature studies over both poles, the lidar cannot be upgraded to measure winds.

In order to address the outstanding questions in middle atmosphere dynamics high-resolution wind-temperature Rayleigh lidar systems must be developed to provide routine measurements of wind and temperature in the stratosphere and mesosphere (~30–60 km). The primary technical challenge in Rayleigh systems is to operate highly stable laser transmitters and receivers without using the Doppler-free spectroscopic techniques that have been developed for resonance lidar systems. Rayleigh Doppler wind-temperature lidars were pioneered by lidar researchers at the National Center for Space Studies at the Observatory of Haute Provence, France, and have been operated at Arecibo Observatory and ALOMAR. The satellite community has developed a variety of technologies for measuring wind that have been integrated into lidar systems making measurements in the troposphere and stratosphere. The application of these technologies has not yet been demonstrated in CEDAR middle atmosphere lidar systems.

High-quality daytime measurements demand stable narrow-band systems with both transmitter and receiver stability and very high levels of background light rejection. While the optical quality of large subastronomical-quality telescopes is sufficient for nighttime observations, it is not sufficient for daytime work. In daytime, sub-astronomical-quality optics results in degradation of the performance of the lidar system, due to the scattering of stray light into and signal light out of the detector.

Both the lidar and wider middle- atmosphere communities have come to better appreciate the technical demands of reliable wind-temperature lidar. Certain upgrades are technically straight-forward.

- Rayleigh systems can be extended to lower altitudes via Raman scattering techniques.
- Broadband nighttime systems can be extended into twilight.
- Zenith-pointing systems can be readily upgraded with multiple telescopes to allow nighttime measurements in multiple directions.

In general, however, broadband Rayleigh and resonance systems cannot be simply upgraded to narrowband Rayleigh and resonance systems. For example, while tunable dye laser systems have demonstrated the ability to make Iron Boltzmann temperature measurements at Arecibo and Poker Flat, they are not viable systems for routine operations.

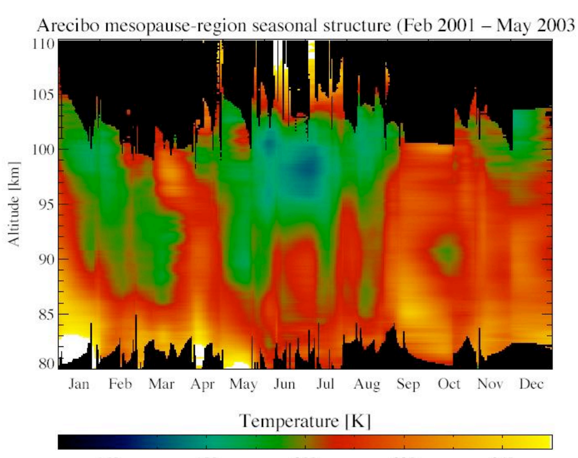
The CEDAR experience at Maui and ALOMAR illustrates that the operation of lidars with complex steerable large aperture telescope systems is not a simple "bolting-on" exercise, but requires a significant (but accomplishable) design effort to yield state-of-the-art performance. In principle there is no fundamental obstacle to the operation of a state-of-the-art lidar system at these remote centers. The challenge of operating lidars at these sites often is not due to the technical effort but to the high cost of research, lack of resident lidar expertise, competition for observing time, and security concerns about university investigators working at DoD facilities. The CEDAR lidar community has not only pushed the technical envelope by addressing new engineering and scientific challenges but also the operational and administrative envelopes by conducting new experiments at these locations.

3.2 SITE STRATEGIES

CEDAR lidar systems have been developed and deployed at sites where existing programs of middle atmosphere observations at that site or in the local region have justified the effort (e.g., Arecibo Observatory, Colorado State University, Poker Flat Research Range, Sondrestrom Upper Atmosphere Research Facility, Utah State University) or where unique experimental capabilities have justified the effort (e.g., Maui Space Surveillance Site, ALOMAR) and resulted in the development of new instrument clusters.

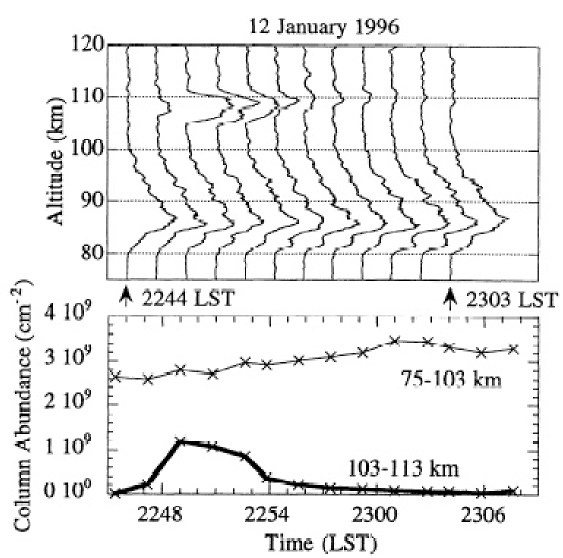
The lidar observations at each site are adapted to optimize correlative measurements with other instruments, measurements of geophysical phenomena, or seeing

SOLID-STATE LASER TECHNOLOGIES



Temperature measurements made with a solid-state potassium resonance lidar. The lidar employs hyperfine spectroscopy with an acousto-optic modulation technique to probe the mesospheric potassium at two wavelengths and so estimate temperature. The CEDAR lidar community has developed a variety of technologies in support of state-of-the-art wind and temperature measurements. High-resolution temperature measurements of this type are used in studies of the global circulation.

METEORIC MATERIAL IN THE ATMOSPHERE



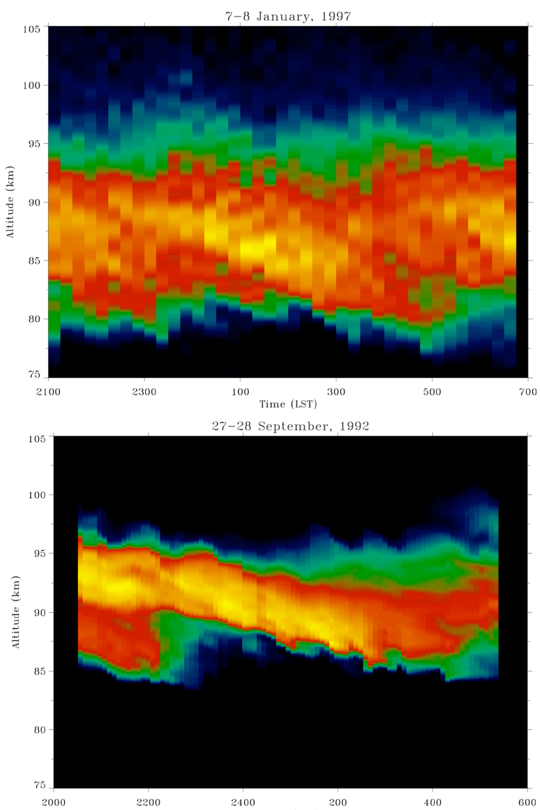
Sodium resonance lidar observations of high-altitude sporadic (or sudden) metal layers. The sporadic layer (~110 km) appears above the main mesospheric metal layer (~80–100 km), where the chemical equilibrium is expected to suppress the formation of neutral metal layers. These observations provide data for studies of the fate and transport of meteoric material in the atmosphere.

conditions (e.g., intensive observations during rocket campaigns, choice of meteoric metal species to match radar studies, intensive summertime noctilucent cloud observations, intensive springtime polar vortex observations).

While the variety of lidar capabilities makes the observational coverage less uniform than it might appear, the following complementary aspects of the current CEDAR lidar sites are worth noting.

- Resonance wind-temperature lidar systems at Maui and Fort Collins provide opportunities to compare wave activity in the middle of the Pacific Ocean and in the lee of the Rocky mountains.
- Resonance lidar temperature measurements at Maui and Arecibo provide opportunities to compare MLT structures in the tropics that are well separated in longitude.
- Rayleigh and resonance lidars at Logan and Fort Collins provide the opportunities for complementary measurements through the stratosphere and mesosphere.
- Lidar systems at ALOMAR, Sondestrom and Poker Flat provide opportunities for measuring differences in NLC structure across the Arctic and studying the role of different synoptic scale features (stratospheric vortex, Aleutian high) on the Arctic middle atmosphere.

WAVE BREAKING AND OVERTURNING



Resonance lidar measurements of the mesospheric metal layers provide high-resolution observations of wave-breaking and overturning events in the mesopause region. These observations support studies of wave breaking in the atmosphere.

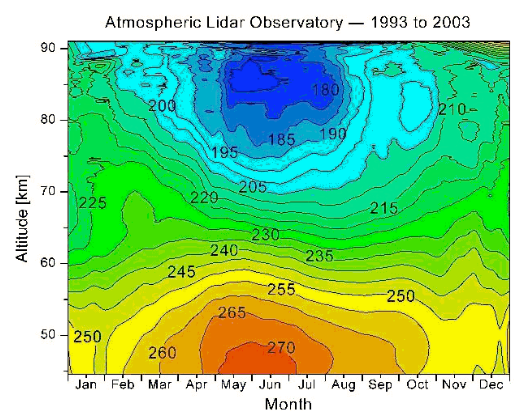
- The distribution of lidars provides opportunities for studies of latitudinal differences in wave and tidal phenomena (e.g., mesospheric inversion layers, wave observations of wave-breaking events and instabilities).
- The distribution of resonance lidars provides opportunities for studies of latitudinal variations in chemical species (e.g., odd oxygen).
- Antarctic and Arctic lidar measurements provide opportunities for inter-hemispheric comparisons in NLCs, mesospheric metal layers, and middle atmosphere temperature structure.

3.3 NEW CEDAR LIDAR SYSTEMS

A variety of new lidar systems have been suggested for development by the CEDAR lidar community. These suggestions include lidar systems that,

- Exploit resonant scattering from species in the thermosphere and would extend lidar measurements into the E- and F-region. These systems have been demonstrated in paper studies by members of the CEDAR and U.S. Air Force lidar communities. In principle, proof-of-concept experiments could be conducted with current tunable dye–laser-based lidar systems. These systems would yield measurement profiles of excited nitrogen and helium in the E and F

TEMPERATURE STUDIES OF THE MIDDLE ATMOSPHERE



Broadband Rayleigh lidar measurements of temperature at mid-latitudes. Rayleigh lidar observations yield routine measurements of the temperature profile from the mid-stratosphere to the lower thermosphere in support of studies of the structure and circulation of the middle atmosphere. Such systems can be upgraded with Raman techniques to extend the temperature measurements to lower altitudes.

regions.

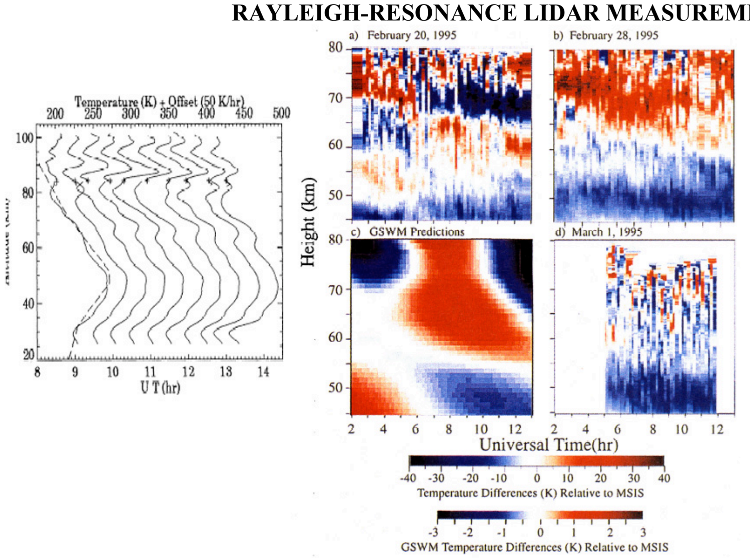
- Employ new solid-state technologies that can replace the use of dye laser technology in resonance lidar systems. A system is being developed and tested by the Colorado State University group that would use a new solid-state mixing technique to provide continuous-wave (CW) laser light for use in sodium Doppler wind-temperature lidar systems.
- Combine hyperfine spectroscopic techniques with solid-state technologies. Current acousto-optic modulation techniques could be combined with solid-state iron lidars to yield iron resonance temperature measurements. These iron lidars operating in the ultraviolet (UV) range would also yield strong Rayleigh signals for the retrieval of hydrostatic temperature.
- Employ versatile receiver technologies to allow new Rayleigh wind and temperature measurements. CEDAR resonance lidar developments have primarily focused on the combination of tunable transmitters and fixed receivers. The wider remote-sensing community has developed precision tunable receivers for a variety of applications. Initial feasibility studies are in progress to assess the use of these technologies in CEDAR lidar systems.
- Employ laser technologies with higher transmitted laser powers. Driven by applications in communications and industry, fiber-optic amplifier technologies may eventually increase laser-radiated power by a factor of three to four over current flashlamp pumped lasers. These systems, operating in the near UV range, would allow Rayleigh and Raman lidar systems to make high-resolution density profiles for studies of the troposphere, stratosphere, and mesosphere.

3.4 MOBILE MIDDLE ATMOSPHERE LIDAR SYSTEMS

The development of the Advanced Modular Incoherent Scatter Radar (AMISR) represents a new approach to observational studies in the CEDAR community. AMISR meets the need of modern state-of-the-art incoherent scatter radar that can address CEDAR science issues without being committed to one site. This approach would be of great value to the CEDAR lidar community. Like AMISR, a relocatable or mobile lidar system would allow state-of-the-art measurements at multiple sites without building up a unique capability at each and every site. The lidar could be deployed in support of a focused campaign (e.g., in support of rocket or satellite measurements) or in support of a given geophysical feature (e.g., measurements of polar summer temperatures and winds as part of a noctilucent cloud study). As global circulation models become more precise, the lidar siting strategy would also become more sophisticated. Lidar systems could be sited to confirm likely sources of gravity wave activity or where wave-driven fluxes are most active and geophysically significant and therefore most readily measured.

The development of a truly mobile lidar system demands a commitment to operational engineering issues that is not always required of static facility systems. Limiting issues relate to the size of the telescope systems that could be included in such a system and the choice of technologies that would promote reliable operation. Researchers in other lidar communities (e.g., NASA and Department of Energy (DoE) tropospheric lidar) have addressed these design issues, and several CEDAR lidar researchers feel there is much that can be learned from experience of these other lidar communities..

RAYLEIGH-RESONANCE LIDAR MEASUREMENTS OF TEMPERATURE



Combined Rayleigh and resonance lidar observations provide measurements from the lower stratosphere to the lower thermosphere (~20–100 km). These observations support studies of dynamic coupling across the stratosphere and mesosphere.

3.5 CENTERS OF LIDAR EXCELLENCE

It is widely recognized in the CEDAR community that technical leadership in the middle atmosphere lidar community has emerged at several de-facto centers of excellence: Colorado State University (Fort Collins, Colorado); the University of Illinois at Urbana Champaign (Urbana, Illinois); the Institute of Atmospheric Physics (Kuhlungsborn, Germany); and the National Center for Space Studies (Haute Provence, France). These groups have provided leadership in developing new lidar techniques and facilities and have drawn on their substantial institutional and investigator heritage in applied physics and engineering. The university-based research groups drew on a pool of talented and motivated students that were resident at the host universities. Technical progress in the community has been greatly facilitated by investigators who have pursued an interdisciplinary approach. These investigators have been committed to developing both the optical engineering techniques as well as advancing scientific questions relating to lidar. The success of the University of Illinois and Aerospace partnership in the rapid development and deployment of the iron Boltzmann lidar was based on winning a major (non-CEDAR) NSF award that resulted in a new robust and state-of-the-art temperature lidar system. The success of the Institute of Atmospheric Physics in maintaining a sustained program of lidar (and middle atmosphere) research and development has been based on its long-term planning and funding as a national center of excellence that engages young scientists of high quality.

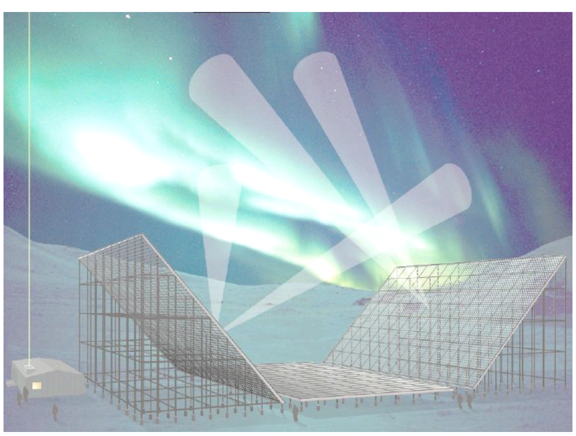
With transitions in key personnel at all these centers and the need to develop the next generation of lidar systems, the question has been raised about the need to develop a community laboratory where community resources could be focused rather than developing parallel efforts around multiple single investigators. These collaborative efforts could also include non-CEDAR research centers, for example the National Center for Atmospheric Research (NCAR). In such collaboration, NCAR could host a state-of-the-art lidar system in a programmatically stable environment, analogous to how an astronomical telescope or Class-I radar facility is operated. University collaborators could visit this facility and participate in system development, participate in and suggest observations, and pursue analysis of the data acquired at the site. Such a center would allow investigators (both professional researchers and students) to participate in state-of-the-art lidar research without the need to operate and maintain a lidar system of that caliber at their institution, and so widen the pool of active researchers in the CEDAR lidar community. A similar approach could be negotiated with the stratospheric research community, where NASA and National Oceanic and Atmospheric Administration (NOAA) researchers have established lidar facilities in support of the Network for the Detection of Stratospheric Change (NDSC). CEDAR lidar researchers could collaborate with NDSC researchers to maintain a larger-aperture lidar observatory that supported state-of-the-art observations in support of both programs.

Whether a lidar center of excellence should be established around a single investigator or a consortium of investigators, and whether such a center of excellence should be based in a large-aperture Class-I telescope facility, are open questions. Such a center will emerge naturally as collaborative efforts are initiated to address the need for a mobile lidar or next-generation lidar systems.

3.6 DATA DISTRIBUTION AND ARCHIVING

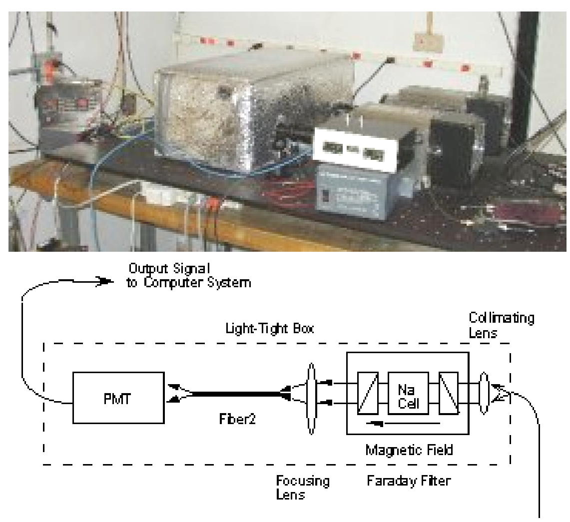
The CEDAR community infrastructure supports a

RELOCATABLE REMOTE SENSING TOOLS



The Advanced Modular Incoherent Scatter Radar will support a new approach to observational studies in solar and space physics.

DEVELOPMENT OF LIDAR TECHNOLOGIES



Magneto-optic vapor filters (or Faraday filters) are a critical technology for making high-quality daytime resonance lidar measurements of wind and temperature in the mesopause region.

database for the archiving and distribution of lidar data to members of the middle-atmosphere community. The CEDAR workshop provides a unique forum for presenting data sets and discussing and developing analysis techniques and methods. The CEDAR workshop has served as an invaluable setting for initiating collaborative studies, and is expected to continue serving this need for the foreseeable future.

4. RECOMMENDATIONS

4.1 CEDAR LIDAR COMMUNITY PRIORITIES

The existing lidar programs will continue to contribute to CEDAR science, improve system performance and capabilities, and ensure high-quality, high-fidelity measurements. However, to guarantee fundamental advances, this report recommends that the CEDAR community give the highest priority to the following seven areas.

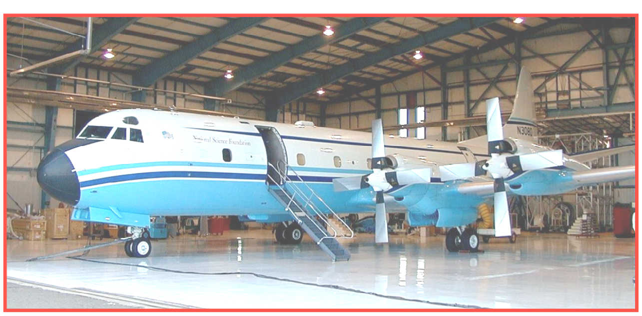
1. *Ready access to (or development of) large-aperture telescope facilities.*

   These facilities will support high-resolution wind-temperature and constituent measurements in the middle and upper atmosphere, and provide the environment for the development of new lidar systems and the refinement of measurement techniques. CEDAR lidar researchers have employed large-telescope facilities at the Starfire Optical Range (3.5 m) in New Mexico, the Maui Space Surveillance Site (4 m) in Hawaii, and the ALOMAR facility (2 × 1.8 m) in Norway under a variety of collaborative agreements with the (non-CEDAR) facility administrators. These facilities support state-of-the-art middle atmosphere research where synergism between high-resolution lidar measurements and other instruments (e.g., airglow images, meteor and MF radars) yields new studies of tides, planetary waves, and gravity waves. However, these sites are limited by logistical and programmatic considerations. No open-access large-aperture lidar facility is currently available for routine use by CEDAR lidar researchers in the United States. While these facilities will continue to support lidar-based science, over the long term the development of such a Class-I facility (in a clear-sky location) with associated CEDAR clustered radar and airglow instrumentation would provide unique opportunities for advances in middle atmosphere aeronomy, instrumental development, and student education. A community large-aperture telescope facility would support robust high-signal-to-noise measurements that also would enable the development of new lidar measurement techniques. Such a facility with resident lidar systems could support the participation of a wider pool of researchers in CEDAR lidar research, allowing researchers (both professional and student) contribute to focused developments and studies without needing to support a complete lidar program themselves. The management of such a facility could be supported by the CEDAR community alone or in collaboration with other corporations or programs (e.g., NCAR or NDSC).

2. *The development and deployment of robust mobile lidar systems capable of wind and temperature measurements in the in the middle atmosphere.*

   During CEDAR Phase III, the CEDAR lidar community has emerged as a collection of instruments associated (largely) with single investigators at specific institutions with a wide variety of measurement capabilities. Two CEDAR groups have developed robust wind-temperature lidars. These systems are based on resonance spectroscopy and are capable of high-resolution wind and temperature measurements during both day and night. The development of a community mobile wind-temperature lidar would enable the CEDAR lidar community to combine resources and expertise and would guarantee robust state-of-the-art lidar measurements. The mobile lidar system would draw on the laboratory and observatory infrastructure that has been developed at current CEDAR lidar sites. In the development of such a mobile system, consideration should be given to the possibility of deploying the mobile system in aircraft. The value of airborne lidar measurements has been demonstrated during CEDAR Phase III (e.g. ALOHA-90, ALOHA/ANLC-93). Making intensive airborne campaign measurements may be more effective than

AIRBORNE LIDAR STUDIES



CEDAR researchers have deployed resonance lidars and airglow imagers aboard the NSF/NCAR Electra aircraft to make middle atmosphere measurements during the ALOHA-90 campaign in Hawaii, the ALHOA/ANLC-93 campaigns in the Canadian Arctic and Hawaii, and the Leonids-98 campaign in Okinawa. CEDAR lidar researcher aboard the Electra made the first middle atmosphere temperature and Polar Mesospheric Cloud measurements over the North Pole. The adaptation of modern lidar technologies to the new High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) Gulfstream aircraft being developed by NCAR could enable lidar observations to be made anywhere in the world.

establishing a ground-based observatory in some locations (e.g., equatorial regions). Specific consideration should be given to the development of the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER) by NCAR. Although it can build on the extensive CEDAR research heritage, the development of truly mobile state-of-the art wind-temperature lidar systems will require significant technical effort.

3. *The development and deployment of Doppler Rayleigh wind-temperature systems to meet the need for measurements of the atmospheric circulation below the mesopause region.*

   While the CEDAR community has demonstrated excellence in the development of resonance lidar systems for routine wind and temperature measurements in the mesopause region, progress in middle-atmosphere aeronomy demands measurements throughout the coupled middle atmosphere system. Wind and temperature measurements over a wider vertical extent are critical for resolving large vertical-scale tidal and wave features as well as for understanding the propagation of waves through the middle atmosphere. Rayleigh lidar measurements have been demonstrated by CEDAR researchers using a variety of techniques, but routine operational measurements have not been established. The technical challenges of designing Rayleigh systems without the spectroscopic tools used in atomic resonance will require significant technical effort.

4. *Support of technical innovation at the level of a center of excellence for lidar research.*

   The development of a next generation of lidar systems (identified above in items 2 and 3) that are capable of state-of-the-art wind and temperature measurements will require major technical effort and innovation by CEDAR researchers. The development of these advanced systems will require electro-optic development at the level of a center of excellence where CEDAR technological heritage is consolidated, made available to the entire community, and advanced upon. During CEDAR Phase III lidar researchers have made significant advances both as single-institution investigators and as multiple-institution collaborators.

5. *Improvements of existing systems, such as enabling daytime capabilities and extending Rayleigh systems with Raman channels.*

   Current CEDAR lidar systems can be improved to extend their measurement coverage in the diurnal (and, at high-latitudes, seasonal) cycles as well as their altitude extent. Full diurnal cycle measurements are crucial for accurately characterizing the tides and planetary waves in the middle atmosphere and their influences on other phenomena (e.g., gravity waves, inversion layers). Raman capabilities could be integrated into Rayleigh systems to yield hydrostatic temperature measurements at lower altitudes where aerosols contaminate the Rayleigh lidar measurements.

6. *The extension of lidar measurements into the thermosphere by the exploration of new species to serve as lidar targets for upper atmospheric research.*

   CEDAR lidar studies to date have been focused on the lower thermosphere, mesosphere and stratosphere (~15–110 km). Several paper studies (i.e., studies of helium, aurorally-excited nitrogen, and barium) have presented designs of lidar systems for making measurements of thermospheric species. These thermospheric lidar systems have the potential to provide new insights into the composition and circulation of the upper-atmosphere and near-space environments, and to facilitate new experiments with radar, airglow, and satellite systems. While these experimental studies pose new challenges for lidar systems, initial proof-of-principle experimental studies can be attempted with current CEDAR lidar systems. These studies will support the development of operational systems that would allow routine lidar measurements of the thermosphere.

7. *Development of novel lidar technologies.*

   The CEDAR lidar community is a highly focused research community. While the CEDAR lidar community has focused on specific spectroscopic technologies to develop narrowband wind-temperature systems the wider electromagnetic research communities have explored other broadband and tunable technologies to meet needs in the development of high-energy laser systems and communication systems. While these technologies may not be mature enough to provide immediate tools and techniques for middle atmosphere lidar research, the CEDAR community needs to be able to critically assess these developments for possible future employment as they mature. Academic researchers working with students in science and engineering programs can pursue initial efforts in this area. The ability of the community to incorporate appropriate wide-application (or mainstream and presumably large-market) technologies will prove critical for the long-term viability of the field.

The implementation of these recommendations would allow the CEDAR lidar community to obtain,

1. wind and temperature measurements over complete diurnal cycles that are required to understand tidal, planetary and gravity wave fluxes, wave-wave and wave-mean flow interactions in the middle atmosphere,

2. very high-resolution measurements that are required to understand instabilities and other small-scale processes in the middle atmosphere,
3. consistent long-term measurements that are required to study long term trends in the middle atmosphere,
4. new measurements in the thermosphere (E- and F-regions), where they would provide basic measurements of thermospheric composition and circulation,
5. species-specific measurements of both neutral and ionized species that are required for study ion-neutral coupling and MLT electrodynamics, and
6. high-resolution measurements of nanometer size particles that are required for studies of cloud formation in a dusty plasma environment,.

These results are required for the advancement of our understanding of the middle atmosphere.

4.2 RECOMMENDATIONS TO CEDAR LIDAR COMMUNITY

This report recommends that the CEDAR lidar community engage in a formal and technical community dialog that addresses the community priorities identified above; specifically, we recommend that the CEDAR community support the following activities at the annual CEDAR meeting in 2004.

1. A dedicated session with panel discussions identifying and prioritizing scientific questions concerning the middle atmosphere that can be addressed by lidar. This session would invite colleagues conducting theoretical and modeling studies of the middle atmosphere to identify critical questions in middle-atmosphere aeronomy and discuss how lidar studies might contribute to answering these questions.
2. A dedicated session with panel discussions presenting technical approaches to developing the next-generation lidar systems that will be employed by the community. This session would invite lidar researchers (as individuals or representatives of consortia) to present critical technical designs for these systems. The session would educate fellow community members about different technical approaches and allow community members to assess the relative capabilities of different approaches. This session would also assist researchers in identifying the need for and scale of specific grant funding opportunities in support of these technical developments.

While meeting the specific needs of the CEDAR lidar the goal of these sessions is also to promote two other critical processes:

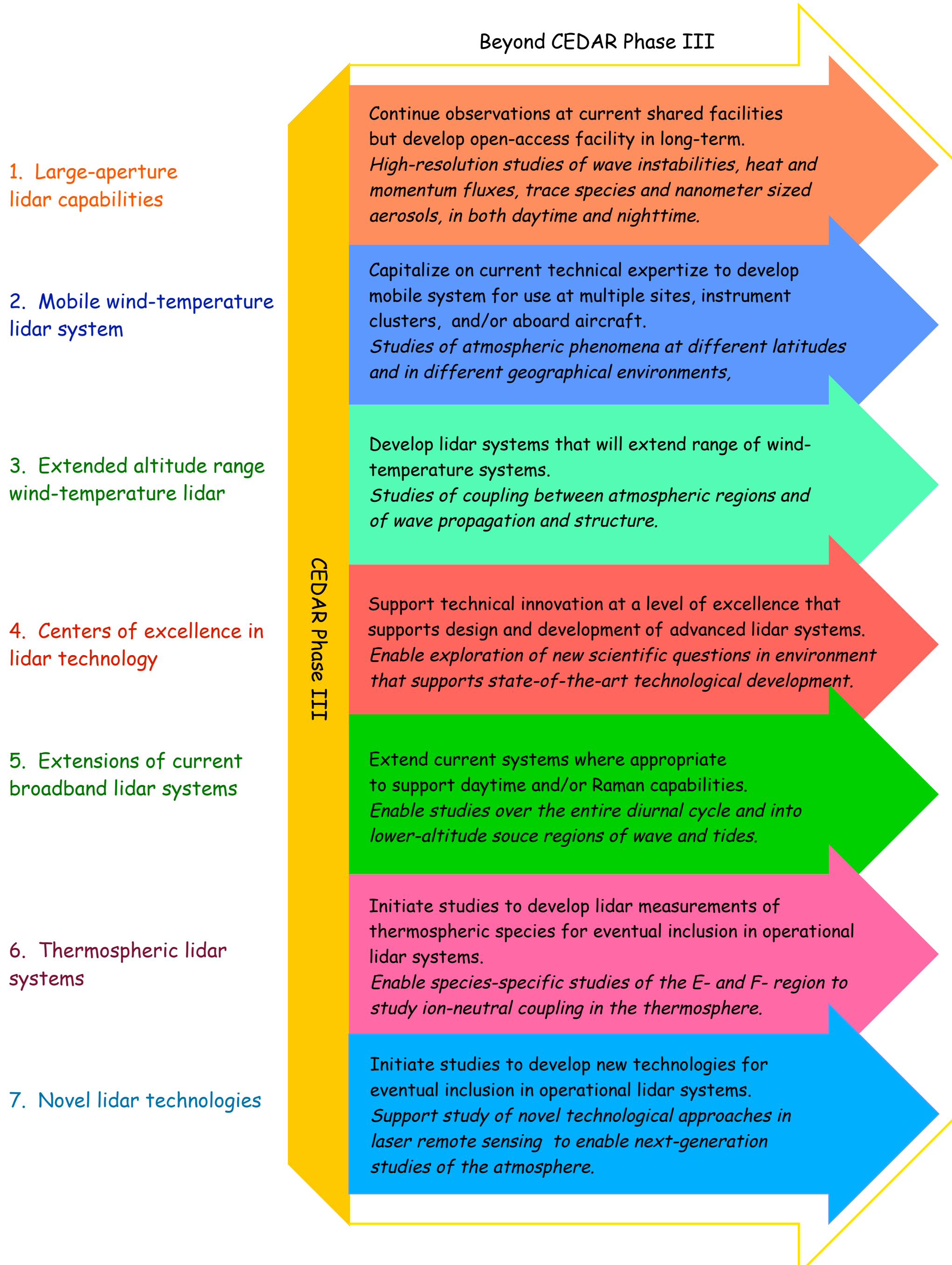
1. Discussions between lidar and non-lidar researchers that will increase synergism in the observational programs of the CEDAR community.
2. The engagement of students who are already working (or considering work) in middle atmosphere lidar.

4.3 RECOMMENDATIONS TO THE NSF UPPER ATMOSPHERE RESEARCH SECTION

This report recommends that the NSF Upper Atmosphere Research Section (NSF-UARS) and the CEDAR lidar community work together to accomplish the following:;

1. Develop a strategy to ensure continued access to a Class-I large-aperture telescope facility for lidar research (Community Priorities 1 and 4).
2. Create a specific major proposal opportunity in support of next-generation lidar systems (Community Priorities 2, 3, and 4).
3. Support, as appropriate, extensions and improvements to current lidar systems (Community Priority 5).
4. Support, as appropriate, investigations of new technologies and species for middle- atmosphere lidar studies (Community Priorities 6 and 7).
5. Establish a committee, consisting of both lidar experimentalists and middle/upper atmospheric researchers, to develop an integrated research strategy for the CEDAR lidar community (Community Priorities 1–7).

PRIORITIES FOR CEDAR LIDAR COMMUNITY



Priorities of the CEDAR lidar community that will support scientific progress in the CEDAR community. A technological recommendation (roman font) and resultant scientific outcome (italics) is identified for each priority.

APPENDIX I:
CEDAR LIDAR BIBLIOGRAPHY

1. Alvarez II, R.J., L.M. Caldwell, P.G. Wolyn, D.A. Krueger, T.B. Mckee, and C.Y. She, "Vertical atmospheric and temperature profiles using high-spectral-resolution Rayleigh-Mie lidar," *J. Atm. Oceanic Tech.* 10, 546–556, 1993.
2. Alvarez II, R.J., L.M. Caldwell, Y.H. Li, D.A. Krueger, and C.Y. She, "High Spectral Resolution Lidar Measurement of Tropospheric Backscatter-Ratio Using Barium Atomic Blocking Filter," *J. Atm. Oceanic Tech.* 7, 876–881, 1991.
3. Arnold, K. S., and C. Y. She, "Metal fluorescence lidar (light detection and ranging) and the middle atmosphere", Contemporary Physics, 44, 35-49, 2003.
4. Beatty, T.J., C.A. Hostetler and C.S. Gardner, "Lidar observations of gravity waves and their spectra near the mesopause and stratopause at Arecibo," *J. Atmos. Sci.*, vol. 49, no. 6, pp. 477–497, 15 March 1992.
5. Beatty, T.J., R.L. Collins, C.S. Gardner, C.A. Hostetler, C.F. Sechrist, and C.A. Tepley, "Simultaneous radar and lidar observations of sporadic E and Na layers at Arecibo," *Geophys. Res. Lett.*, vol. 16, no. 9, pp. 1019–1022, September 1989.
6. Beatty, T. J., R. E. Bills, K. H. Kwon and C. S. Gardner, "CEDAR lidar observations of sporadic Na layers at Urbana, Illinois," *Geophys. Res. Lett.*, vol. 15 no. 10, pp. 1137-1140, September 1988.
7. Beig, G., P. Keckhut , R. P. Lowe, R.G. Roble, M. G. Mlynczak, J. Scheer, V. I. Fomichev, D. Offermann, W.J.R. French, M. G. Shepherd, A. I. Semenov, E. E. Remsberg, C. Y. She, F. J. Lübken, J. Bremer, B. R. Clemesha, J. Stegman, F. Sigernes, and S. Fadnavis, "Review of mesospheric temperature trends", Reviews of Geophysics, Vol. 41, No. 4, 1015, 10.1029/2002RG000121, 2003.
8. Bills, R.E., C.S. Gardner and S.J. Franke, "Na Doppler/Temperature lidar: Initial mesopause region observations and comparison with the Urbana MF radar," *J. Geophys. Res.*, vol. 96, no. D12, pp. 22701–22707, December 1991.
9. Bills, R.E., C.S. Gardner, and C.Y. She, "Narrowband lidar technique for sodium temperature and Doppler wind observations of the upper atmosphere," *Opt. Eng.*, 30 (1), 13–21, 1991.
10. Bills, R.E. and C.S. Gardner, "Lidar observations of mesospheric Fe and sporadic Fe layers at Urbana, Illinois," *Geophys. Res. Lett.,* vol. 17, no. 2, pp. 143–146, February 1990.
11. Bishop, R. L., M. F. Larsen, J. H. Hecht, A. Z. Liu, and C. S. Gardner, "TOMEX; Mesospheric and lower thermospheric diffusivities and instability layers," *J. Geophys. Res., 109(D02S03),* doi:10.1029/2002JD003079, 2004.
12. Chen, S., Z. Hu, M.A. White, H. Chen, D.A. Krueger, and C.Y. She, "Lidar observations of seasonal variation of diurnal mean temperature in the mesopause region over Fort Collins, Colorado (41oN, 105oW)", J. Geophys. Res., 105 (D10), 12,371-12,380, 2000.
13. Chen, H., M. A. White, D. A. Krueger and C. Y. She, "Daytime mesopause temperature measurements using a sodium-vapor dispersive Faraday filter in lidar receiver" Opt. Lett. 21, 1003-1005, 1996.
14. Chen, H., C.Y. She and E. Korevaar, "Na Vapor Dispersive Faraday Filter," *Opt. Lett.* 18, 1019–1021, 1993.
15. Chen, H., J.R. Yu and C.Y. She, "Arrival of Pinatubo Disturbances in the Stratospheric Aerosol Layer Over Fort Collins, CO. Observed by a Lidar at 589 nm," *Appl. Phys.* B55, 159–163, 1992.
16. Chu, X., G. J. Nott, P. J. Espy, C. S. Gardner , J. C. Diettrich, M. A. Clilverd, M. J. Jarvis, "Lidar observations of polar mesospheric clouds at Rothera, Antarctica (67.5°S, 68.0°W), Geophys. Res. Letts., 31, L02114, doi:10.1029/2003GL018638, 2004.
17. Chu, X., C. S. Gardner, and R. G. Roble, "Lidar Studies of Interannual, Seasonal, and Diurnal Variations of Polar Mesospheric Clouds at the South Pole," *J. Geophys. Res.*, *108(D8),* 8447, doi:10.1029/2002JD002524, 2003.
18. Chu, X., G. J. Nott, P. J. Espy, C. S. Gardner , J. C. Diettrich, D. J. Maxfield, M. A. Clilverd, M. J. Jarvis, "Lidar observations of polar mesospheric clouds at Rothera, Antarctica (67.5°S, 68.0°W), *Geophys. Res. Letts.,* in press 2003.
19. Chu, X., G. Papen, W. Pan, C. S. Gardner, and J. Gelbwachs, "Fe Boltzmann Temperature Lidar: Design, Error Analysis, and First Results from the North and South Poles," *Applied Optics*, *41*, 4400-4410, 2002.
20. Chu, X., C. S. Gardner, and G. C. Papen, "Lidar observations of polar mesospheric clouds at South Pole: Diurnal variations," *Geophys. Res. Lett*, *Vol. 28*, No. 10, 1937-1940, 15 May 2001.
21. Chu, X., C. S. Gardner, and G. C. Papen, "Lidar observations of polar mesospheric clouds at South Pole: Seasonal variations," *Geophys. Res. Lett*, *Vol. 28*, No. 7, 1203-1206, 1 April 2001.
22. Chu, X., A. Liu, G. C. Papen, C. S. Gardner, M. C. Kelley, J. Drummond, and R. Fugate, " Lidar observations of elevated temperatures in bright chemiluminescent meteor trails during the 1998

Leonid shower ," Geophys. Res. Letts., vol. 27, no. 13, pp. 1815-1818, 1 July 2000.

23. Chu, X., W. Pan, G. C. Papen, C. S. Gardner, G. R. Swenson, and P. Jenniskens "Characteristics of Fe ablation trails observed during the 1998 Leonid meteor shower," *Geophys. Res. Letts.,* vol. 27, no. 13, pp. 1807-1810, 1 July 2000.
24. Chu, X., A. Liu, G. C. Papen, C. S. Gardner, M. C. Kelley, J. Drummond, and R. Fugate, " Lidar observations of elevated temperatures in bright chemiluminescent meteor trails during the 1998 Leonid shower ," *Geophys. Res. Letts.,* vol. 27, no. 13, pp. 1815-1818, 1 July 2000.
25. Coble, M., G. C. Papen, and C. S. Gardner, "Computing Two-Dimensional Unambiguous Horizontal Wave Number Spectra from OH Airglow Images," IEEE Trans. Geosci. & Remote Sensing, vol. 36, no. 2, pp.368-382, March 1998.
26. Collins, R.L., and R. W. Smith, Evidence of Damping and Overturning of Gravity Waves in the Arctic Mesosphere: Na Lidar and OH Temperature Observations, J. Atmos. Sol. Terr. Phys., in press, 2004.
27. Collins, R.L., M. C. Kelley, M. J. Nicolls, C. Ramos, T. Hou, T. E. Stern, K. Mizutani and T. Itabe, "Simultaneous Lidar Observations of a Noctilucent Cloud and an Internal Wave in the Polar Mesosphere," *Journal of Geophysical Research,* vol. 108, no. D8, 8435-84311, 2003.
28. Collins, R.L., D. Lummerzheim, and R. W. Smith, "Analysis of lidar systems for profiling aurorally-excited molecular species," *Applied Optics*, vol. 36, no. 24., 6024-6034, August, 1997.
29. Collins, R.L., D. Thorsen, and S. J. Franke, "Comparative MF radar and Na lidar measurements of fluctuating winds in the mesopause region," *Journal of Geophysical Research*, vol. 102, no. D14, 16583-16591, July 1997.
30. Collins, R.L., T. J. Hallinan, R. W. Smith and G. Hernandez, "Lidar observations of a large high-altitude sporadic Na layer during active aurora," *Geophysical Research Letters*, vol. 23, no. 24, 3655-3658, December, 1996.
31. Collins, R.L., X. Tao, and C. S. Gardner, "Gravity Wave Activity in the Upper Mesosphere over Urbana, Illinois: Lidar Observations and Analysis of Gravity Wave Propagation Models," *Journal of Atmospheric and Terrestrial Physics*, vol. 58, no. 16, 1905-1926, December 1996.
32. Collins, R.L., and C.S. Gardner, "Gravity wave activity in the stratosphere and mesosphere at the South Pole," *Reviews of Space Physics*, *Adv. Space Res.* vol. 16, no. 5, 81–90, 1995.
33. Collins, R.L., A. Nomura and C.S. Gardner, "Gravity Waves in the Upper Mesosphere over Antarctica: Lidar Observations at the South Pole and Syowa," *J. Geophys. Res.*, vol 99, number D3, pp. 5475–5485, March 20, 1994.
34. Collins, R.L., K.P. Bowman, and C.S. Gardner, "Polar Stratospheric Clouds at the South Pole in 1990: Lidar Observations and Analysis," *J. Geophys. Res.*, vol. 98, no. D1, pp. 1001–1010, January 1993.
35. Collins, R.L., D.C. Senft and C.S. Gardner, "Observations of a 12 h wave in the mesopause region at the South Pole," *Geophys. Res. Lett.*, vol. 19, no. 1, pp. 57–60, January 1992.
36. Collins, S. C., J. M. C. Plane, M. C. Kelley, T. G. Wright, P. Soldán, T. J. Kane, A. J. Gerrard, B. W. Grime, R. J. Rollason, J. S. Friedman, S. A. González, Q. Zhou, M. P. Sulzer, and C. A. Tepley, A study of the role of ion-molecule chemistry in the formation of sporadic sodium layers, *J. Atmos. Terr. Phys.*, *64* , 845-860, 2002.
37. Collins, S.C., T.D. Wilkerson, V.B. Wickwar, D. Rees, J.C. Walling, and D.F. Heller, The alexandrite ring laser: A spectrally narrow lidar light source for atmospheric fluorescence and absorption observations, in *Advances in Atmospheric Remote Sensing with Lidar*, edited by A. Ansmann, R. Neuber, P. Rairoux, and U. Wandinger, pp. 577–580, Springer Verlag, Berlin, 1997.
38. Cutler, L. J, R. L. Collins, K. Mizutani, and T. Itabe, "Rayleigh Lidar Observations of Mesospheric Inversion Layers at Poker Flat, Alaska 65 °N, 147° W," *Geophysical Research Letters*, vol. 28, no. 8, 1467-1470, April, 2001.
39. Dao, P. D., R. Farley, X. Tao , and C. S. Gardner, "Lidar observations of the temperature profile between 25 and 103 km : Evidence of tidal perturbation," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2825-2828, October, 15, 1995.
40. Drob, D. P., J. M. Picone, S. D. Eckermann, C. Y. She, J. F. Kafkalidis, D. A. Ortland, R. J. Niciejewski, and T. L. Killeen, Mid-latitude temperature at 87 km: Results from multi-instrument Fourier analysis, Geophys. Res. Lett. 27, 2109-2112, 2000.
41. Drummond, J. D., B. W. Grime, C. S. Gardner, A. Z. Liu, X. Chu, M. C. Kelley, C. Kruschwitz, T. J. Kane, "Observations of persistent Leonid meteor trails 3. The Glowworm," J. Geophys. Res., 107(A8), doi:10.1029/2001JA000223, 2002.
42. Drummond, J. D., S. Milster, B. W. Grime, D. Barnaby, C. S. Gardner, A. Z. Liu, X. Chu, M. C. Kelley, C. Kruschwitz, and T. J. Kane, 'Persistent Leonid meteor trails. Types I and II', Proc.

Meteoroids 2001 Conf., ESA SP-495, 215-220, Kiruna, Sweden, 2001.

43. Drummond, J. D., B. W. Grime, C. S. Gardner, A. Z. Liu, X. Chu, and T. J. Kane, "Observations of persistent meteor trails 1: Advection of the Diamond Ring," J. Geophys. Res., Vol. 106, No. A10, 21,517-21,524, 1 October 2001.

44. Drummond, J. D., C. S. Gardner, and M. C. Kelley, "Catching a falling star," Sky & Telescope, 99(6), 46-49, 2000.

45. Franke, P. M., and R. L. Collins, "Evidence of gravity wave breaking in lidar data from the mesopause region," Geophys. Res. Letts., 30(4), 1155, doi:10.1029/2001GL014477, 2003.

46. Franke, S.J., E. Stoll, R. J. States, and C. S. Gardner, "Comparison of Na Doppler Lidar and MF Radar Measurements of Meridional Winds in the Mesosphere above Urbana, IL," *J. Atmos. Solar-Terr. Phys., vol. 63,* 1789-1796, 2001.

47. Franke, S.J, T.J. Beatty, D. Thorsen, C.H. Liu, C.S. Gardner, F.L. Roesler, and J. Harlander, "Simultaneous Na lidar and HF radar observations of vertical velocities in the mesosphere above Urbana, IL.," *Geophys. Res. Lett.*, vol. 17, no. 1, pp. 69–72, January 1990.

48. Friedman, J. S., Tropical Mesopause Climatology over the Arecibo Observatory, *Geophys. Res. Lett.*, *30* (12), 1642, doi:10.1029/2003GL016966, 2003.

49. Friedman, J. S., C. A. Tepley, S. Raizada, Q. H. Zhou, J. Hedin, and R. Delgado, Potassium Doppler-resonance lidar for the study of the mesosphere and lower thermosphere at the Arecibo Observatory, *J. Atmos. Solar Terr. Phys.*, *in press*, 2003.

50. Friedman, J. S., S. C. Collins, R. Delgado, and P. A. Castleberg, Mesospheric potassium layer over the Arecibo Observatory, *Geophys. Res. Lett.*, *29* , 15-1–15-4, 2002.

51. Friedman, J. S., S. A. González, C. A. Tepley, Q. Zhou, M. P. Sulzer, S. C. Collins, and B. W. Grime, Simultaneous atomic and ion layer enhancements observed in the mesopause region over Arecibo during the Coqui II sounding rocket campaign, *Geophys. Res. Lett.*, *27* , 449-452, 2000.

52. Friedman, J. S., C. A. Tepley, P. A. Castleberg, and H. Roe, Middle-atmospheric Doppler lidar using an iodine-vapor edge filter, *Optics Letters*, *22* , 1,648-1,650, 1997.

53. Gao, X., J.W. Meriwether, V.B. Wickwar, T.D. Wilkerson, and S.C. Collins, Rayleigh lidar measurements of the temporal frequency and vertical wavenumber spectra in the mesosphere over the Rocky Mountain region, *J. Geophys. Res.*, *103*, 6405–6416, 1998.

54. Gardner, C. S., Y. Zhao, and A. Liu, "Atmospheric stability and gravity wave dissipation in the mesopause region," J. Atmos. Solar-Terr. Phys., vol. 64, 923-929, 2002.

55. Gardner, C.S., G. C. Papen, X. Chu, and W. Pan, "First Lidar Observations of Middle Atmosphere Temperatures, Fe Densities, and Polar Mesospheric Clouds Over the North and South Poles," *Geophys. Res. Letts., Vol. 28*, No. 7, 1199-1202, 1 April 2001.

56. Gardner, C.S., "Na Laser Guide Star Technologies for Adaptive Imaging". *Rev. Laser Eng.,Laser Society of Japan, Vol. 28,* No. 12, 792-795, December 2000 (Invited Paper).

57. Gardner, C.S., K. Gulati, Y. Zhao, and G. Swenson, "Measuring gravity wave momentum fluxes with airglow imagers," *J. Geophys. Res.*, vol. 104, D10, pp. 11903-11915, 27 May 1999.

58. Gardner, C.S. and W. Yang, "Measurements of the Dynamical Cooling Rate Associated with the Vertical Transport of Heat by Dissipating Gravity Waves in the Mesopause Region at the Starfire Optical Range, NM, *J. Geophys. Res.-Atmospheres,* vol. 103, no. D14, pp. 16909-16927, 27 July 1998.

59. Gardner, C.S., S. F. Franke, W. Yang, X. Tao, and J. R. Yu, "Interpretation of Gravity Waves Observed in the Mesopause Region at the Starfire Optical Range, NM: Strong Evidence for Nonseparable Intrinsic *(m, w)* Spectra," *J. Geophys. Res.-Atmospheres,* vol. 103, no. D8, pp.8699-8713, 27 April 1998.

60. Gardner, C. S., "Theoretical Models for Gravity Wave Horizontal Wave Number Spectra: Effects of Wave Field Anisotropies," J. Geophys. Res.-Atmospheres, vol. 103, no. 6, pp.6417-6426, 27 March 1998.

61. Gardner, C.S. and M. J. Taylor, "Observational Limits for Lidar, Radar, and Airglow Imager Measurements of Gravity Wave Parameters," *J. Geophys. Res.-Atmospheres,* vol. 103, no. 6, pp.6427-6438, 27 March 1998.

62. Gardner, C. S., M. Coble, G. C. Papen, and G. R. Swenson, "Observations of the Unambiguous 2-Dimensional Horizontal Wave Number Spectrum of OH Intensity Perturbations," Geophys. Res. Letts., vol. 23, no. 25, pp. 3739-3742, 15 December 1996.

63. Gardner, C.S., "Sporadic Metal Layers in the Upper Mesosphere," Proceedings of the *Faraday Discussion No. 100: Atmospheric Chemistry: Measurements, Mechanisms and Models*, pp. 431-439, The Faraday Division of the Royal Society of Chemistry, London 1996.

64. Gardner, C.S., "Testing Theories of Atmospheric Gravity Wave Saturation and Dissipation," *J. Atmos. Terr. Phys.,* vol. 58, no. 14, pp. 1575-1590, October 1996.

65. Gardner, C.S., M. Coble, G. C. Papen, and G. R. Swenson, "Observations of the Unambiguous 2-Dimensional Horizontal Wave Number Spectrum of OH Intensity Perturbations," *Geophys. Res. Letts.,* vol. 23, no. 25, pp. 3739-3742, 15 December 1996.

66. Gardner, C.S. and G. C. Papen, "Mesospheric Na Wind/Temperature Lidar," *Japanese Review of Laser Engineering*, vol. 23, No. 2, pp. 131-134, February 1995.

67. Gardner, C. S., X. Tao, and G. C. Papen, "Simultaneous lidar observations of vertical wind, temperature, and density profiles in the upper mesosphere: Evidence for nonseparability of atmospheric perturbation spectra," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2877-2880, October, 15, 1995.

68. Gardner, C. S., "Introduction to ALOHA/ANLC-93 : The 1993 Airborne Lidar and Observations of the Hawaiian Airglow/Airborne Noctilucent Cloud Campaigns," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section*, vol. 22, no. 20, pp. 2789-2792, October, 15, 1995.

69. Gardner, C. S., X. Tao, and G. C Papen, "Observations of strong wind shears and temperature enhancements during several sporadic Na layer events above Haleakala," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2809-2812, October, 15, 1995.

70. Gardner, C. S., J. Qian, M. R. Coble, G. C. Papen and G. R. Swenson, "High resolution horizontal wave number spectra of mesospheric wave perturbations observed during the October 21 triangular flight of ALOHA-93," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2869-2872, October, 15, 1995.

71. Gardner, C.S., and N. F. Gardner, "Measurement distortion in aircraft, space shuttle and balloon observations of atmospheric density and temperature perturbation spectra," *J. Geophys. Res.*, vol. 98, no. D1, pp. 1023-1033, January 1993.

72. Gardner, C.S., C. A. Hostetler and S. J. Franke, "Gravity wave models for the horizontal wave number spectra of atmospheric velocity and density fluctuations," *J. Geophys. Res.*, vol. 98, no. D1, pp. 1035-1049, January 1993.

73. Gardner, C.S., T.J. Kane, D.C. Senft, J. Qian, and G. Papen, "Simultaneous observations of sporadic E, Na, Fe and Ca^{+} layers at Urbana, Illinois; Three Case Studies," *J. Geophys. Res.*, vol 98, number D9, pp. 16,865–16,873, September 1993.

74. Gardner, C.S., C. A. Hostetler and S. Lintelman, "Influence of the mean wind field on the separability of atmospheric perturbation spectra," *J. Geophys. Res.*, vol 98, number D5, pp. 8859–8872, May 1993.

75. Gardner, C.S., "Introduction to ALOHA-90: The Airborne Lidar and Observations of the Hawaiian Airglow Campaign," *Geophys. Res. Lett., ALOHA-90 Special Issue,* vol. 18, no 7, pp. 1313–1316, July 1991.

76. Gardner, C.S., T.J. Kane, J.H. Hecht, R.L. Walterscheid, J.H. Yee, R.J. Niciejewski, R.P. Lowe, and D.N. Turnbull, "Formation characteristics of sporadic Na layers observed simultaneously by lidar and airglow instruments during ALOHA-90," *Geophys. Res. Lett., ALOHA-90 Special Issue,* vol. 18, no. 7, pp. 1369–1372, July 1991.

77. Gardner, C.S., B.M. Welsh and L.A. Thompson, "Design and performance analysis of adaptive optical telescopes using laser guide stars," *Proc. IEEE,* vol. 78, no. 11, pp. 1721–1743, November 1990.

78. Gardner, C.S., M.S. Miller and C.H. Liu, "Rayleigh lidar observation of gravity wave activity in the stratosphere and lower mesosphere," *J. Atmos. Sci.*, vol. 46, no. 12, pp. 1838–1854, June 1989.

79. Gardner, C.S., "Sodium resonance fluorescence lidar applications in atmospheric science and astronomy," *Proc. IEEE,* vol. 77, no. 3, pp. 408–418, March 1989.

80. Gardner, C.S., D.C. Senft and K.H. Kwon, "Lidar observations of substantial sodium depletion in the summertime Arctic mesosphere," *Nature,* vol. 332, pp. 142-144, March 10, 1988.

81. Gardner, C.S., and D.G. Voelz, "Lidar studies of the nighttime sodium layer over Urbana, Illinois, 2. Gravity Waves," *J. Geophys. Res.*, vol. 92, pp. 4673-4694, May 1, 1987.

82. Gardner, C.S., D.G. Voelz, C.F. Sechrist, Jr., and A.C. Segal, "Lidar studies of the nighttime sodium layer over Urbana, Illinois, 1. Seasonal and Nocturnal Variations," *J. Geophys. Res.,* vol. 91, no. A12, pp. 13,659–13,673, December 1, 1986.

83. Gardner, C.S, C.R. Philbrick, D.G. Voelz, and D. Sipler, "Simultaneous lidar measurements of the sodium layer structure at the Air Force Geophysics Laboratory and the University of Illinois," *J. Geophys. Res.*, vol. 91, no. A11, pp. 12131–12136, 1 November 1986.

84. Gardner, C.S., and D. Voelz, "Lidar measurements of gravity wave saturation effects in the sodium layer," *Geophys. Res. Letts.*, vol. 12, no. 11, pp. 765–768, November 1985.

85. Gelinas, L. J., K. A. Lynch, M. C. Kelley, S. Collins, S. Baker, Q. Zhou, and J. S. Friedman, First observation of meteoritic charged dust in the tropical mesosphere, *Geophys. Res. Lett.*, *25*, 4,047-4,050, 1998.

86. Gerding M., G. Baumgarten, U. Blum, J.P. Thayer, K. H. Fricke, U. von Zahn, R. Neuber, J. Fiedler, "Observation of an unusual 38-km aerosol layer in

the Arctic: possible sources and implications for polar vortex dynamics," Annales Geophysicae, accepted, 2003.

87. Gerrard, A.J., T.J. Kane, J. P. Thayer, T.J. Duck, J. Whiteway, "Synoptic-scale study of the arctic polar vortex's influence on the middle atmosphere," J. Geophys. Res., 107 (D16), doi 10.1029/2001JD000681, pp ACL1,1-15, 2002.

88. Gerrard, A. J., J. P. Thayer, and T. J. Kane, Mesospheric clouds and the duality of gravity waves, Eos Transactions of the American Geophysical Union, 83(43), 488, 2002.

89. Gerrard, A. J., T. J. Kane, J. P. Thayer, T. J. Duck, J. A. Whiteway, and J. Fiedler, Synoptic-scale study of the Arctic polar vortex's influence on the middle atmosphere: I. Observations, J. Geophys. Res., 107(D16), 4276, doi: 10.1029/2001JD000681, 2002.

90. Gerrard, A.J., T.J. Kane, J.P. Thayer, C.S. Ruf, and R.L. Collins, "Consideration of non-Poisson distributions for lidar applications," Applied Optics, Vol. 40, No. 9, pp. 1488-1492, 2001.

91. Gerrard, A. J., T. J. Kane, and J. P. Thayer, Year-round temperature and wave measurements of the Arctic middle atmosphere for 1995-1998, Atmospheric Science Across the Stratopause, D. E. Siskind, S. D. Eckermann, and M. E. Summers, Eds., Geophysical Monograph Series 123, American Geophysical Union, Washington, D.C., 2000.

92. Gerrard, A.J., T.J. Kane , and J.P.Thayer, "Noctilucent clouds and wave dynamics: Observations at Sondrestrom, Greenland," Geophys. Res. Lett. Vol. 25 , No. 15 , p. 2817, 1998.

93. Gerrard, A.J., T.J. Kane, D.D. Meisel, J.P. Thayer, R.B. Kerr, "Investigation of a resonant lidar for measurement of ionospheric metastable helium," Journal of Atmospheric and Solar-Terrestrial Physics, Vol. 59, No. 16, pp. 2023-2035, 1997.

94. Grime, B. W., T. J. Kane, A. Lui, G. C. Papen, C. S. Gardner, M. C. Kelley, C. Kruschwitz, and J. Drummond, "Meteor trail advection observed during the 1998 Leonid shower," Geophys. Res. Letts., vol. 27, no. 13, pp. 1819-1822, 1 July 2000.

95. Grime, B. W., T. J. Kane, S. C. Collins, M. C. Kelley, C. A. Kruschwitz, J. S. Friedman, and C. A. Tepley, Meteor trail advection and dispersion: Preliminary lidar observations, *Geophys. Res. Lett.*, *26*, 675-678, 1999.

96. Gu, Y.Y., C. S. Gardner, P. A. Castleberg, G. C. Papen, and M. C. Kelley, "Validation of LITE Stratospheric Temperature and Aerosol Measurements," *Applied Optics*, vol. 36, no. 21, pp. 5148-5157, 20 July 1997.

97. Hair, J. W., L. M. Caldwell, David A. Krueger and Chiao-Yao She, High-spectral-resolution lidar with iodine-vapor filters: measurement of atmospheric-state and aerosol profiles, Appl. Opt. 40, 5280-5294, 2001.

98. Hammond, M.R., T.D. Wilkerson, and V.B. Wickwar, High-resolution spectra of atmospheric water vapor in the near-IR using a Raman-shifted alexandrite laser, in *Lidar Remote Sensing for Industry and Environment Monitoring II*, edited by U.N. Singh, pp. 103–111, Proceedings of SPIE, 4484, 2002.

99. Hecht, J.H., A. Z. Liu, R. L. Bishop, J. H. Clemmons, C. S. Gardner, M. F. Larson, R. G. Roble, G. R. Swenson, and R. L. Walterscheid, "An overview of observations, of unstable layers during the Turbulent Oxygen Mixing Experiment (TOMEX)," J. Geophys. Res., 109(D02S01), doi:10.1029/2002JD003123, 2004.

100. Hecht, J. H., A. Z. Liu, R. L. Walterscheid, R. G. Roble, M. F. Larsen, and J. H. Clemmons,, Airglow Emissions and Oxygen Mixing Ratios from the Photometer Experiment on TOMEX, *J. Geophys. Res*., in press, 2003.

101. Hecht, J.H., R.L. Walterscheid, M.P. Hickey, R.J. Rudy, and A.Z. Liu, An observation of a fast external atmospheric acoustic-gravity wave, J. Geophys. Res., 107 (D20), 4444, doi:10.1029/2001JD001438, 2002.

102. Hecht, J. H., S. Collins, C. Kruschwitz, M. C. Kelley, R. G. Roble, and R. L. Walterscheid, The excitation of the Na airglow from Coqui Dos rocket and ground-based observations, Geophys. Res. Letters, 27(4), 453–456, 2000.

103. Hecht, J.H., R. L. Walterscheid, R. G. Roble, R. S. Lieberman, E. R. Talaat, S. K. R. Howat, R. P. Lowe, D. N. Turnbull, C. S. Gardner, R. States, and P. Dao, "A Comparison of Atmospheric Tides Inferred from Observations at the Mesopause during ALOHA-93 with the Model Predictions of the TIME-GCM,"*J. Geophys. Res.-Atmospheres,* vol. 103, no. 6, pp.6307-6322, 27 March 1998.

104. Hecht, J.H., J.P. Thayer, D.J. Gutierrez, and D.L. McKenzie, "Multi-instrument zenith observations of noctilucent clouds over Greenland on July 30/31, 1995," J. Geophys. Res., Vol. 102, No. D2, pp. 1959-1970, 1997.

105. Hecht, J.H., R. L. Walterscheid, D.C. Fritts, J. R. Isler, D. C. Senft, C. S. Gardner, S. J. Franke, "Wave breaking signatures in OH airglow and sodium densities and temperatures, Part 1: Airglow imaging and Na lidar observations," *J. Geophys. Res.-Atmospheres,* vol. 102, no. D6, pp.6655-6668, 27 March 1997.

106. Hecht, J.H., T.J. Kane, R.L. Walterscheid, C.S. Gardner and C.A. Tepley, "Simultaneous nightglow and Na lidar observations at Arecibo during the

AIDA-89 campaign," *J. Atmos. Terr. Phys.*, vol. 55, no. 3, pp. 409–423, March 1993.

107. Heinselman, C.J., J.P. Thayer, and B.J. Watkins, "A high-latitude observation of sporadic sodium and sporadic E layer formation," Geophys. Res. Lett. Vol. 25 , No. 16 , p. 3059, 1998.

108. Helmer, M, John M. C. Plane, Jun Qian, and Chester S. Gardner, "A Model of Meteoric Iron in the Upper Atmosphere," *J. Geophys. Res.-Atmospheres,* vol. 103, no. D9, pp.10,913-10,926, 20 May 1998.

109. Hickey, M.P., M. J. Taylor, C. S. Gardner, "Full-Wave Modeling of Small-Scale Gravity Waves using ALOHA-93 O(^{1}S) Images and Coincident Na Wind/Temperature Lidar Measurements," *J. Geophys. Res.-Atmospheres,* vol. 103, no. 6, pp.6439-6454, 27 March 1998.

110. Hou, T., T. E. Stern, J. Breese, M. A. Peshave, R. L. Collins, Experimental analysis of iron Boltzmann technique for lidar studies of the middle atmosphere*, Lidar Remote Sensing in Atmospheric and Earth Sciences, Reviewed and revised papers presented at the twenty-first International Laser Radar Conference (ILRC),* Quebec, Canada, 8-12 July, 477-479, 2002.

111. Hostetler, C.A. and C.S. Gardner, "Observations of Horizontal and Vertical Wave Number Spectra of Gravity Wave Motions in the Stratosphere and Mesosphere over the Mid-Pacific," *J. Geophys. Res.*, vol 99, number D1, pp. 1283–1302, 20 January 1994.

112. Hostetler, C.A., C.S. Gardner, D. Lesicar and R. Vincent, "Spectra of gravity wave density and wind perturbations observed during ALOHA-90 on the 25 March flight from Maui to Christmas Island," *Geophys. Res. Lett., ALOHA-90 Special Issue,* vol. 18, no. 7, pp. 1325–1328, July 1991.

113. Hu, X., A. Liu, C. S. Gardner, and G. R. Swenson, "Characteristics of Quasi-Monochromatic Gravity Waves Observed with Lidar in the Mesopause Region at Starfire Optical Range, NM," Geophys. Res. Lett., 29(24), 2169, doi:10.1029/2002GL014975, 2002.

114. Isham, B., C. A. Tepley, M. P. Sulzer, Q. H. Zhou, M. C. Kelley, J. S. Friedman, and S. A. González, Upper atmospheric observations at the Arecibo Observatory: Examples obtained using new capabilities, *J. Geophys. Res.*, *105* (A8), 18,609-18,637, 2000.

115. Kane, T., B. Grime, S. Franke, E. Kudeki, J. Urbina, M. Kelley, and S. Collins, Joint observations of sodium enhancements and field-aligned ionospheric irregularities, Geophys. Res. Letters, 28(7), 1375–1378, 2001.

116. Kane, T.J. and C.S. Gardner, "Structure and seasonal variability of the nighttime mesospheric Fe layer at mid-latitudes," *J. Geophys. Res.*, vol 98, number D9, pp. 16,875–16,886, September 1993.

117. Kane, T.J., C.S. Gardner, Q. Zhou, J.D. Mathews and C.A. Tepley, ""Lidar, radar and airglow observations of a prominent sporadic Na/sporadic *E* layer event at Arecibo during AIDA 89," *J. Atmos. Terr. Phys.*, vol. 55, no. 3, pp. 499–511, March 1993.

118. Kane, T.J. and C.S. Gardner, "Lidar observations of the meteoric deposition of mesospheric metals," *Science,* vol. 259, no. 5099, pp. 1297–1300, 26 February 1993.

119. Kane, T.J., P. Mui and C.S. Gardner, "Evidence for substantial seasonal variations in the structure of the mesospheric iron layer," *Geophys. Res. Lett.*, vol. 19, no. 4, pp. 405–408, 21 February 1992.

120. Kane, T.J., C. A. Hostetler and C. S. Gardner, "Horizontal and vertical structure of the major sporadic sodium layers observed during ALOHA-90," *Geophys. Res. Lett., ALOHA-90 Special Issue,* vol. 18, no. 7, pp. 1365-1368, July 1991.

121. Kawahara, T., C. S. Gardner, and A. Nomura, "Observed temperature structure of the atmosphere above Syowa Station, Antarctica (69^{O}S, 39^{O}E)," *J. Geophys. Res.,* in press 2003.

122. Kelley, M.C., C. A. Kruschwitz, C. S. Gardner, J. D. Drummond, and T. J. Kane, "Mesospheric turbulence measurements from persistent Leonid meteor trains," J. Geophys. Res., 108(D8), 8454, doi:10.1029/2002JD002392, 2003.

123. Kelley, M.C., C. S. Gardner, J. Drummond, T. Armstrong, A. Liu, X. Chu, G. C. Papen, C. Kruschwitz, P. Longhmiller, B. Grimes, J. Engelman, R. Fugate, R. Ruane, " First observations of long-lived meteor trains with resonance lidar and other optical instruments," Geophys. Res. Letts., vol. 27, no. 13, pp. 1811-14, 1 July 2000.

124. Krueger, D. A., and C. Y. She, Observed "long-term" temperature change in a midlatitude mesopause region in response to external perturbation, Earth, Planets and Space, 51, 809-814, 1999.

125. Krueger, D.A., L.M. Caldwell, R.J. Alvarez II, and C. Y. She, "Self-consistent method for determining vertical profiles of aerosol and atmospheric properties using high-spectral-resolution Rayleigh-Mie lidar," *J. Atm. Oceanic Tech.* 10, 533-545, 1993.

126. Kruschwitz, C. A., M. C. Kelley, C. S. Gardner, G. Swenson, A. Z. Liu, X. Chu, J. D. Drummond, B. W. Grime, W. T. Armstrong, J. M. C. Plane, and P. Jenniskens, "Observations of persistent Leonid meteor trails 2. Photometry and numerical modeling," J. Geophys. Res., Vol. 106, No. A10, 21, 525-21,541, October 1, 2001.

127. Kwon, K.H., and C.S. Gardner, "Airborne sodium lidar measurements of gravity wave intrinsic

parameters," *J. Geophys. Res.*, vol. 95, no D12, pp. 20,457–20,467, November 1990.

128. Kwon, K.H., D.C. Senft and C.S. Gardner, "Airborne sodium lidar observations of horizontal and vertical wavenumber spectra of mesopause density and wind perturbations," *J. Geophys. Res.*, vol. 95, no. D9, pp. 13,723–13,736, August 1990.

129. Kwon, K.H., C.S. Gardner, S.K. Avery, and J.P. Avery, "Correlative radar and airborne sodium lidar observations of the vertical and horizontal structure of gravity waves and tides near the mesopause," *J. Geophys. Res.,* vol. 95, no. D9, 13,737–13,748, August 1990.

130. Kwon, K. H., D. C. Senft and C. S. Gardner, "Lidar observations of sporadic sodium layers above Mauna Kea Observatory, Hawaii," *J. Geophys. Res.*, vol. 93, no. D11, pp. 14,199–14, 208, 20 November 1988.

131. Kwon, K. H., C. S. Gardner, D. C. Senft, F. Roesler and J. Harlender, "Daytime lidar measurements of tidal winds in the mesospheric sodium layer," *J. Geophys. Res.,* vol. 92, no. A8, pp. 8781-8786, August 1, 1987.

132. Larsen, M.F., A. Z. Liu, C. S. Gardner, M. C. Kelley, S. Collins, J. Freidman, and J. H. Hecht, "Observations of overturning in the upper mesosphere and lower thermosphere," J. Geophys. Res., 109(D02S04), doi:10.1029/2002JD003067, 2004.

133. Larsen, M. F., A. Z. Liu, R. Liu Bishop, J. H. Hecht, "TOMEX: A comparison of lidar and sounding rocket chemical tracer wind measurements," Geophys. Res. Lett., 30, doi:10.1029/2002GRL015678, 2003.

134. Leblanc, T., I.S. McDermid, P. Keckhut, A. Hauchecorne, C.Y. She, and D.A. Krueger, Temperature Climatology of the Middle Atmosphere from Long-Term Lidar Measurements at Mid- and Low-Latitudes, J. Geophysical Research 103, 17,191 - 17, 204, 1998.

135. Lintelman, S. and C.S. Gardner, "Observation and Interpretation of the Spectra of Atmospheric Gravity Wave Perturbations with Upward and Downward Phase Progression," *J. Geophys. Res.*, vol 99, number 8, pp. 16,959–16,972, 20 August 1994.

136. Liu, A.Z., R. G. Roble, J. H. Hecht, M. F. Larson, and C. S. Gardner, "Unstable layers in the mesopause region observed by Na lidar during the Turbulent Oxygen Mixing Experiment (TOMEX) campaign," J. Geophys. Res., 109(D02S02), doi:10.1029/2002JD003056, 2004.

137. Liu, A., C. S. Gardner and Y. Zhao, "Dynamical Transport of Mesospheric Constituents by Dissipating Gravity Waves: Na Flux Observations at Starfire Optical Range, New Mexico," *J. Atmos. Solar-Terr. Phys.,* in press 2003.

138. Liu, A. Z., R. G. Roble, J. H. Hecht, and M. F. Larsen, Atmospheric tides in the mesopause region during the TOMEX campaign, *J. Geophys. Res.*, in press, 2003.

139. Liu, A. Z., W. K. Hocking, S. J. Franke, and T. Thayaparan, "Comparison of Na lidar and meteor radar wind measurements at Starfire Optical Range, NM, USA," J. Atmos. Solar-Terr. Phys., vol. 64, 31-40, 2002.

140. Liu, Zhi-Shen, Dong Wu, Jin-Tao Liu, Kai-Lin Zhang, Wei-Biao Chen, Xiao-Quan Song, Johnathan W. Hair and Chiao-Yao She, Low-Altitude atmospheric wind measurement from the combined Mie and Rayleigh backscattering by Doppler lidar with iodine filter, Appl. Opt. 41, 7079-7086 (2002).

141. Liu, Z. S., W. B. Chen, T. L. Zhang, J. W. Hair, C. Y. She, An incoherent Doppler lidar for ground-based atmospheric wind profiling, Appl. Phys. B 46, 561- (1996).

142. Manson, A.H., C.E. Meek, J. Qian, and C. S. Gardner, "Spectra of Gravity Wave Density and Wind Perturbations Observed During ANLC-93 Over the Canadian Prairies: Synergistic Airborne Na Lidar and MF Radar Observations,"*J. Geophys. Res.-Atmospheres,* vol. 103, no. 6, pp.6455-6467, 27 March 1998.

143. Mathews, J.D., Q. Zhou, C.R. Philbrick, Y.T. Morton and C.S. Gardner, "Observations of Ion and sodium layer coupled processes during AIDA," *J. Atmos. Terr. Phys.*, vol. 55, no. 3, pp. 487-498, March 1993.

144. McKay, J.A., and T.D. Wilkerson, Direct detection wind speed Doppler lidar systems, in *Application of Lidar to Current Atmospheric Topics II*, edited by A.J. Sedlacek III, K.W. Fischer, pp. 42–52, Proceedings of SPIE, 3127, 1997.

145. McKay, J.A., and T.D. Wilkerson, Diode-pumped alexandrite laser for DIAL and Doppler lidar, in *Applications of Lidar to Current Atmospheric Topics II*, edited by A.J. Sedlacek III, and K.W. Fischer, pp. 124–132, Proceedings of SPIE, 3127, 1997.

146. McKay, J.A., and T.D. Wilkerson, A laser source for spaceflight elastic backscatter, differential absorption, and wind speed Doppler lidar, in *SPIE Annual Meeting*, pp. 19–31, Denver, 1996.

147. Meriwether, J. and C. S. Gardner, "A Review of the Mesosphere Inversion Layer Phenomenon," J. Geophys. Res., vol. 105, D10, pp. 12405, 20 May 2000.

148. Meriwether, J.W., X. Gao, V.B. Wickwar, T.D. Wilkerson, K.C. Beissner, S.C. Collins, and M.E. Hagan, Observed coupling of the mesosphere inversion layer to the thermal tidal structure, *Geophys. Res. Lett.*, *25*, 1479–1482 & 2127, 1998.

149. Mizutani, K., T. Itabe, M. Yasui, T. Aoki, Y. Murayama, R. L. Collins, "Rayleigh and Rayleigh Doppler Lidars for the Observations of the Arctic Middle Atmosphere*," IEICE Transactions on Communications*, vol. E83-B, no. 9, 2004-2009, September, 2000.

150. Moosmüller, H., and T.D. Wilkerson, Combined Raman-elastic backscatter lidar method for the measurement of backscatter ratios, *Appl. Opt.*, *36* (21), 5144–5147, 1997.

151. Omar, A. and C. S. Gardner, " Observations by the Lidar-In-Space Technology Experiment (LITE) of High Altitude Cirrus Clouds Over the Equator in Regions Exhibiting Extremely Cold Temperatures ," J. Geophys. Res.-Atmospheres, Vol. 106, No. D1, 1227-1236, 16 Jan 2001.

152. Pan, W. and C. S. Gardner, "Seasonal Variations of the Atmospheric Temperature Structure at South Pole," *J. Geophys. Res., 108,* doi:10.1029/2002JD003217, 2003.

153. Pan, W., C. S. Gardner, and R. Roble, "The Thermal Structure of the Winter Atmosphere at South Pole," *Geophys. Res. Lett.,* 29(16), doi:10.1029/2002GL015288, 2002.

154. Papen, G.C., C. S. Gardner, and W. M. Pfenninger, "Analysis of a potassium lidar system for upper atmospheric wind/temperature measurements," *Applied Optics,* vol. 34, No. 30, pp. 6950-6958, October 20, 1995.

155. Plane, J.M.C., B. J. Murray, X. Chu, and C. S. Gardner, "Removal of meteoric iron on polar mesospheric clouds," *Science,* in press March 2004.

156. Plane, J. M. C., C. S. Gardner, J. R. Yu, C. Y. She, R. R. Garcia, and H. C. Pumphrey, Mesospheric Na layer at 40oN: Modeling and observations, J. Geophysical Research 104, 3773-3788, 1999.

157. Plane, J.M.C., R. M. Cox, J. Qian, W. M. Pfenninger, G. C. Papen, C. S. Gardner, and P. J. Espy, "Mesospheric Na Layer at Extreme High Latitudes," *J. Geophys. Res.-Atmospheres,* vol. 103, no. 6, pp.6381-6390, 27 March 1998.

158. Qian, J., Y. Gu, and C. S. Gardner, "Characteristics of the Sporadic Na Layers Observed During the ALOHA/ANLC-93 Campaigns," *J. Geophys. Res.-Atmospheres*, vol. 103, no. 6, pp. 6333-6348, 27 March 1998.

159. Qian, J., Y. Y. Gu, G. C. Papen, and C. S. Gardner, "Horizontal wave number spectra of density and temperature perturbations in the mesosphere measured during the 4 August flight of ANLC-93," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section*, vol. 22, no. 20, pp. 2865-2868, October, 15, 1995.

160. Qian, J. and C. S. Gardner, "Simultaneous lidar measurements of mesospheric Ca, Na and temperature profiles at Urbana, IL," *J. Geophys. Res.*, vol. 100, No. D4, pp.7753-7461, 20 April 1995.

161. Raizada, S., and C. A. Tepley, Seasonal variation of mesospheric iron layers at Arecibo: First results from low latitudes, Geophys.Res. Lett., 30(2), 54-1:54-4, 2003.

162. Raizada, S., C. A. Tepley, D. Janches, J. S. Friedman, and Q. Zhou, Lidar observations of Ca and K metallic layers from Arecibo and comparison with micrometeor sporadic activity, In Press, J. Atmos. Solar Terr. Phys, 2003.

163. Raizada, S. and C. A. Tepley, Iron Boltzmann lidar temperature and density observations from Arecibo - A comparison with other techniques, Geophys. Res. Lett., 29(12), 1-1:1-4, 2002.

164. Rees, D., J.A. McKay, T.D. Wilkerson, and V.B. Wickwar, Spaceborne incoherent Doppler wind lidar: reassessment of the UV system, in *Proc. ESA Doppler Wind Workshop, ESTEC*, Noordwijk, Holland, 1995.

165. Schwemmer, G.K., and T.D. Wilkerson, Development of a holographic telescope for optical remote sensing, in *Spin-off technologies from NASA for commercial sensors and scientific applications*, pp. 40–47, Proceedings of SPIE, 2270, 1994.

166. Sears, R.D., and V.B. Wickwar, Lidar observations of stratospheric-mesospheric density structure and its climatology at Logan, Utah, in *Laser Radar: Ranging and Atmospheric Lidar Techniques III*, edited by U. Schreiber, C.H. Werner, G.W. Kammerman, and U.N. Singh, pp. 91–100, Proceedings of SPIE, 4546, 2002.

167. Sears, R.D., T.D. Wilkerson, V.B. Wickwar, J.M. Maloney, and S.C. Collins, Multi-dimensional power spectral analysis of structure in the stratosphere and mesosphere observed by Rayleigh scatter lidar, in *Advances in Atmospheric Remote Sensing with Lidar*, edited by A. Ansmann, R. Neuber, P. Rairoux, and U. Wandinger, pp. 561–564, Springer Verlag, Berlin, 1997.

168. Senft, D.C., G.C. Papen, C.S. Gardner, J.R. Yu, D.A. Krueger and C.Y. She, "Seasonal variations of the thermal structure of the mesopause region at Urbana, IL (40oN, 88oW) and Ft. Collins, CO (41oN, 105oW)," *Geophys. Res. Lett*., 21, 821–824, 1994.

169. Senft, D.C., C. A. Hostetler and C. S. Gardner, "Characteristics of gravity wave activity and spectra in the upper stratosphere and upper mesosphere at Arecibo during early April 1989," *J. Atmos. Terr. Phys*.,.vol. 55, no. 3, pp. 425–439, March 1993.

170. Senft, D.C., and C. S. Gardner, "Seasonal variability of gravity wave activity and spectra in the mesopause

region at Urbana," *J. Geophys. Res.*, vol. 96, no. D9, pp. 17229-17264, September 1991.

171. Senft, D.C., R.L. Collins, and C.S. Gardner, "Mid-latitude lidar observations of large sporadic sodium layers," *Geophys. Res. Lett.,* vol. 16, no 7, pp. 715–718, July 1989.

172. She, C. Y., J. Sherman, T. Yuan, B. P. Williams, K. Arnold, T. D. Kawahara, T. Li, L. Xu, J. D. Vance and D. A. Krueger, The first 80-hour continuous lidar campaign for simultaneous observation of mesopause region temperature and wind, Geophys. Res. Lett.30, 10.1029/2002GL016412, 2003.

173. She, C. Y., and D. A. Krueger, Impact of natural variability in the 11-year mesopause region temperature observation over Fort Collins, CO (41N, 105W), Adv. Space Phys. (Accepted), 2003

174. She, C. -Y., Initial full-diurnal-cycle mesopause region lidar observations: Diurnal-means and tidal perturbations of temperature and winds over Fort Collins, CO (41N, 105W), PSMOS 2002, J. Atmos. Solar-Terr. Phys. (accepted), 2003.

175. She, C. Y., Joe D. Vance, B. P. Williams, D. A. Krueger, H. Moosuller, D. Gibson-Wilde, and D. C. Fritts, Lidar studies of atmospheric dynamics near polar mesopause, EOS, Transactions, American Geophysical Union, 83 (27), P.289 and P.293, 2002.

176. She, C. Y., Songsheng Chen, B. P. Williams, Zhilin Hu, David A. Krueger and M. E. Hagan, Tides in the mesopause region over Fort Collins, CO (41oN, 105oW) based on lidar temperature observations covering full diurnal cycles, Jour. Geophys. Research, 107, N. 0, 10.1029/2001JD001189, 2002.

177. She, C. Y., Jim Sherman, Joe Vance, Titus Yuan, Zhilin Hu, B. P. Williams, Kam Arnold, Phil Acott, and David A. Krueger Evidence of solar cycle effect in the mesopause region: Observed temperatures in 1999 and 2000 at 98.5 km over Fort Collins, CO (41oN, 105oW), J. Atmos. Solar-Terr. Phys. 64, 1651-1657, 2002.

178. She, Chiao-Yao, Spectral structure of laser light scattering revisited: bandwidths of nonresonant scattering lidar, Appl. Opt. 40, 4875-4884, 2001.

179. She, C.Y., S. Chen, Z. Hu, J. Sherman, J.D. Vance, V. Vasoli, M.A. White, J. Yu, and D.W. Krueger, Eight-year climatology of nocturnal temperature and sodium density in the mesopause region (80 to 105 km) over Fort Collins, CO (41oN, 105oW), Geophys. Res. Lett., 27 (20), 3289-3292, 2000.

180. She, C. Y. and U. von Zahn, The concept of two-level mesopause: Support through new lidar observation, J. Geophys. Res., 103, 5855 - 5863, 1998.

181. She, C. Y., S. W. Thiel and D. A. Krueger, Observed episodic warming at 86 and 100 km between 1990 and 1997: Effects of Mount Pinatubo eruption, Geophys. Res. Lett., 25, 497 - 500, 1998.

182. She, C. Y., and R. P. Lowe, Seasonal temperature variations in the mesopause region at mid-latitude: comparison of lidar and hydroxyl rotational temperatures using WINDII/UARD OH height profiles, J. Atmos. Solar-Terr. Physics, 60, 1573-1583, 1998.

183. She, C. Y., J. R. Yu, D. A. Krueger, R. Roble, P. Keckhut, A. Hauchecorne, and M. L. Chanin, Vertical structure of the mid-latitude temperature from stratosphere to mesopause (30 - 105 km), to be published in Geophys. Res. Lett., 22, 377-380, 1995.

184. She, C. Y., and J. R. Yu, Doppler-Free Saturation Fluorescence Spectroscopy of Na Atoms for Atmospheric Applications," Appl. Opt., 34, 1063-1075, 1995.

185. She, C.Y., and J.R. Yu, "Simultaneous three-frequency Na lidar measurements of radial wind and temperature in the mesopause region, *Geophys. Res. Lett.*, 21, 1771–1774, 1994.

186. She, C.Y., "New lidar reveals seasonal temperature variations in a midlatitude mesopause region," *Optics* 1994, p.p.23-24, *Optics & Photonics News*, Dec. 1994.

187. She, C.Y., J.R. Yu, H. Chen, "Observed thermal structure of a midlatitude mesopause," *Geophys. Res. Letts.*, 20, 567–570, 1993.

188. She, C.Y., R.J. Alvarez II, L.M. Caldwell, and D.A. Krueger, "High-spectral-resolution Rayleigh-Mie lidar Measurement of Aerosol and Atmospheric Profiles," *Opt. Lett.* 17, 541–543, 1992.

189. She, C.Y., R.J. Alvarez II, L.M. Caldwell, and D.A. Krueger, "High-spectral-resolution Rayleigh-Mie lidar measurement of vertical aerosol and atmospheric profiles," *J. Appl. Phys.*, B55, 154–158, 1992.

190. She, C.Y., J.R. Yu, H. Latifi, and R.E. Bills, "High-Spectral-Resolution Fluorescence Lidar for Mesopheric Sodium Temperature Measurements," *Appl. Opt.* 31, 2095–2106, 1992.

191. She, C.Y., J.R. Yu, J.W. Huang, and C. Nagasawa, "Na Temperature Lidar Measurements of Gravity Wave Perturbations of Wind, Density and Temperature in the Mesopause Region," *Geophys. Res. Lett.* 18, 1329–1331, 1991.

192. She, C.Y., H. Lafiti, J.R. Yu, R.J. Alvarez II, R.E. Bills, C.S. Gardner, Two-frequency lidar technique for mesospheric Na temperature measurements, *Geophys. Res. Letts.*, 17, 929–932, 1990.

193. She, C.Y., "Remote Measurement of Atmospheric Parameters: New Applications of Physics With Lasers," *Contemp. Phys.* 31, 247–260, 1990.

194. Shepherd, M. G., P. J. Esp, C. Y. She, W. Hocking, P. Keckhut, G. Gavrilyeva, G. G. Shepherd, B. Naujokat, Springtime transition in upper mesospheric temperature in the northern hemisphere, *J. Atmos. Solar-Terr. Physics*, 64, 1183-1199, 2002.

195. Shepherd, M.G., B. Reid, S. Zhang, B.H. Solheim, G.G. Shepherd, V.B. Wickwar, and J.P. Herron, Retrieval and validation of mesospheric temperatures from Wind Imaging Interferometer observations, *J. Geophys. Res.*, *106* (A11), 24813–24829, 2001.

196. Sherman, J, B. P. Williams, T. D. Kawahara, D. A. Krueger and C. Y. She, A dynamical study of the winter mid-latitude mesopause region (80-105km) based on initial simultaneous lidar measurements of temperature, and winds over Fort Collins, CO (41N, 105W), Adv. Space Phys. (Accepted), 2003.

197. Smith, Steven M., M. J. Taylor, G. R. Swenson, C. Y. She, W. Hocking, J. Baumgardner, and M. Mendillo, A multidiagnostic investigation of the mesospheric bore phenomena, Jour. Geophys. Research, 108, 1083, doi:10.1029/2002JA009500, 2003.

198. States, R.J. and C. S. Gardner, "Thermal Structure of the Mesopause Region (80-105 km) at 40º N latitude: 1. Seasonal variations," *J. Atmos. Sci*., vol. 57, No. 1, pp. 66-77, 1 January 2000.

199. States, R.J. and C. S. Gardner, "Thermal Structure of the Mesopause Region (80-105 km) at 40º N latitude: 2. Diurnal variations," *J. Atmos. Sci*., vol. 57, No. 1, pp. 78-92, 1 January 2000.

200. States, R.J. and C. S. Gardner, "Structure of the mesospheric Na layer at 40º N latitude: Seasonal and diurnal variations," *J. Geophys. Res.,* vol. 104, D9, pp. 11783-11798, 20 May 1999.

201. States, R.J. and C. S. Gardner, "Influence of the Diurnal Tide and Thermospheric Heat Sources on the Formation of mesospheric Temperature Inversion Layers," *Geophys. Res. Letts.,* vol. 25, no. 9, pp. 1483-1486, 1 May 1998.

202. Swartz, W. E., S. C. Collins, M. C. Kelley, J. J. Makela, E. Kudeki, S. Franke, J. Urbina, N. Aponte, S. González, M. P. Sulzer, and J. S. Friedman, First observations of an F-region turbulent upwelling coincident with severe E-region plasma and neutral atmosphere perturbations, *J. Atmos. Solar-Terr. Phys*., *64*, 1545-1556, 2002.

203. Swenson, G., R. Haque, W. Yang, and C. S. Gardner, "Momentum and energy fluxes of monochromatic gravity waves observed by an OH imager at Starfire Optical Range, New Mexico," J. Geophys. Res., vol. 104, D6, pp. 6067-6080, 27 March 1999.

204. Swenson, G. R., and C. S. Gardner, "Analytical Models for the Responses of the Mesospheric OH* and Na Layers to Atmospheric Gravity Waves," J. Geophys. Res.-Atmospheres, vol. 103, no. 6, pp.6271-6294, 27 March 1998.

205. Swenson, G.R. and C. S. Gardner, "Preface to the Special Section on the ALOHA/ANLC-93 Campaigns," *J. Geophys. Res.-Atmospheres,* vol. 103, no. 6, pp.6249-6250, 27 March 1998.

206. Swenson, G. R., M. J. Taylor, P. J. Espy, C. S. Gardner, and X. Tao, "ALOHA-93 measurements of intrinsic AGW characteristics using the airborne airglow imager and groundbased Na wind/temperature lidar," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2841-2844, October, 15, 1995.

207. Swenson, G. R., C. S. Gardner, and M. J. Taylor, "Maximum altitude penetration of atmospheric gravity waves observed during ALOHA-93," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2857-2860, October, 15, 1995.

208. Tang, J., F. Kamalabadi, L. G. Rumsey, and G. R. Swenson, "Point-source suppression for atmospheric wave extraction from airglow imaging measurements," *IEEE Trans. Geosci. & Remote Sens*., vol. 41, no. 1, 146-152, 2003.

209. Tang, J., A. Z. Liu, and G. R. Swenson, "High frequency gravity waves observed in OH airglow at Starfire Optical Range, NM: Seasonal variations in momentum flux," *Geophys. Res. Lett*., 29(20), 1966, doi:10.1029/2002GL015794, 2002.

210. Tao, Xin and C. S. Gardner, "Heat flux observations in the mesopause region above Haleakala ," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section,* vol. 22, no. 20, pp. 2829-2832, October, 15, 1995.

211. Taylor, M. J., W. R. Pendleton, Jr., H.-L. Liu, C. Y. She, L. C. Gardner, R. G. Roble and V. Vasoli, Large amplitude perturbations in mesospheric OH Mwinel and 87-km Na Lidar temperatures around the autumnal equinox, Geophys. Res. Lett. 28, 1899-1902, 2001.

212. Taylor, M. J., W. R. Pendleton Jr., C. S. Gardner, and R. J. States, "Comparison of Terdiurnal Tidal Oscillations in Mesospheric OH Rotational Temperature and Na Lidar Temperature at Mid-Latitudes," Earth, Planets Space J.,vol. 51, nos. 7 & 8, pp. 877-885, 1999.

213. Taylor, M. J., Y. Y. Gu, X. Tao, C. S. Gardner, and M. B. Bishop, "An investigation of intrinsic gravity wave signatures using coordinated lidar and nightglow imaging measurements," *Geophys. Res. Lett., ALOHA/ANLC-93 Special Section*, vol. 22, no. 20, pp. 2853-2856, October, 15, 1995.

214. Tepley, C. A., S. Raizada, Q. Zhou, and J. S. Friedman, First simultaneous observations of Ca+, K, and electron density using lidar and incoherent scatter radar at Arecibo, Geophys. Res. Lett., 30(1), 9-1:9-4, 2003.

215. Tepley, C.A., "Neutral winds of the middle atmosphere observed at Arecibo using a Doppler Rayleigh lidar," *J. Geophys. Res.*, 99, 5781-25790, 1994.

216. Tepley, C.A., S.I. Sargoytchev, and R. Rojas, "The Doppler Rayleigh lidar system at Arecibo," *IEEE Trans. Geosci. Remote Sen.*, 31, 36–47, 1993.

217. Tepley, C.A., S.I. Sargoytchev, and C.O. Hines, "Initial Doppler Rayleigh lidar results from Arecibo," *Geophys. Res. Lett.*, 18,167–170, 1991.

218. Thayer, J. P., G. E. Thomas, and F.-J. Lübken, Foreword: Layered phenomena in the mesopause region, J. Geophys. Res., 108(D8), 8434, doi:10.1029/2002JD003295, 2003.

219. Thayer, J. P., M. Rapp, A. J. Gerrard, E. Gudmundsson, and T. J. Kane, Gravity-wave influences on Arctic mesospheric clouds as determined by a Rayleigh lidar at Sondrestrom, Greenland, J. Geophys. Res., 108(D8), 8449, doi:10.1029/2002JD002363, 2003.

220. Thayer, J.P., N.B. Nielsen, R. Warren, C.J. Heinselman, and J. Sohn, "Rayleigh lidar system for middle atmosphere research in the arctic," Opt. Eng., Vol. 36, No. 7, pp. 2045-2061, 1997.

221. Thayer, J.P., N.B. Nielsen, R.B. Kerr, J. Noto, "Rayleigh Lidar Observations During Arctic Summer Conditions," IGARRS Symposium, Lincoln Nebraska, May, 1996.

222. Thayer, J.P., N.B. Nielsen, and J. Jacobsen, "Noctilucent Cloud Observations over Greenland by a Rayleigh Lidar," Geophys. Res. Lett., Vol. 22, No. 21, pp. 2961-2964, 1995.

223. Thompson, L.A., and C.S. Gardner, "Laser guide star experiments at Mauna Kea Observatory for adaptive imaging in astronomy," *Nature*, vol. 328, no. 6127, pp. 229–331, 16 July 1987.

224. Vance, J. D., C. Y. She, and H. Moosmüller, Continuous-wave, all-solid-state, single-frequency 400-mW source at 589 nm based on doubly resonant sum-frequency mixing in a monolithic lithum niobate resonator, Appl. Opt. 37, 4891-4896, 1998.

225. Welsh, B.M., and C.S. Gardner, "Nonlinear resonant absorption effects on the design of resonance fluorescence lidars and laser guide stars," *Applied Optics*, vol. 28, no 19, pp. 4141–4153, 1 October 1989.

226. Wickwar, V. B., M. J. Taylor, J. P. Herron and B. A. Martineau, Visual and lidar observations of a noctilucent cloud above Logan, Utah (41.7°N), *J. Geophys. Res.*, 107, D7-D8, 2002.

227. Wickwar, V.B., T.D. Wilkerson, M.R. Hammond, and J.P. Herron, Mesospheric temperature observations at the USU / CASS Atmospheric Lidar Observatory (ALO), in *Remote Sensing of the Atmosphere, Environment, and Space*, edited by U.N. Singh, T. Itabe, N. Sugimoto, pp. 272–284, Proceedings of SPIE, 4153, 2001.

228. Wickwar, V.B., K.C. Beissner, T.D. Wilkerson, S.C. Collins, J.M. Maloney, J.W. Meriwether, Jr., and X. Gao, Climatology of mesospheric temperature profiles observed with the Consortium Rayleigh-scatter lidar at Logan, Utah, in *Advances in Atmospheric Remote Sensing with Lidar*, edited by A. Ansmann, R. Neuber, P. Rairoux, and U. Wandinger, pp. 557–560, Springer Verlag, Berlin, 1997.

229. Wickwar, V.B., T.D. Wilkerson, J.W. Meriwether, Jr, and D. Rees, The Consortium Lidar: Results and Facilities Present and Planned, in *Optical Remote Sensing of the Atmosphere*, pp. 171-173, Salt Lake City, 1995.

230. Wilkerson, T.D., M.R. Hammond, and V.B. Wickwar, Increased capabilities for conventional lidars using holographic optics, in *Nineteenth International Laser Radar Conference*, edited by U.N. Singh, S. Ismail, and G.K. Schwemmer, pp. 923–924, NASA, Annapolis, MD, 1998.

231. Wilkerson, T.D., and J.A. McKay, Implications of new alexandrite ring laser technology for spaceborne lidar (aerosol backscatter, water vapor, Doppler winds), in *Advances in Atmospheric Remote Sensing with Lidar*, edited by A. Ansmann, R. Neuber, P. Rairoux, and U. Wandinger, pp. 217–220, Springer Verlag, Berlin, 1997.

232. Wilkerson, T.D., and H. Moosmuller, A new lidar method utilizing elastic and Raman scattering for the measurement of backscattering and extinction profiles, in *Tunable Diode Laser spectroscopy, Lidar, and DIAL Technques for Environmental and Industrial Measurements*, edited by A. Fried, D.K. Killinger, and H.I. Schiff, pp. 177–186, Proc. SPIE, 2112, 1994.

233. Williams, B. P., M. A. White, D. A. Krueger and C. Y. She, Observation of a large amplitude wave and inversion layer leading to convective instability in the mesopause region over Fort Collins CO (41N, 105W), Geophys. Res. Lett., 29, 1850-1853, 2002.

234. Williams, B.P., and C. Y. She, "Seasonal climatology of the nighttime tidal perturbation of temperature in the midlatitude mesopause region", Geophys. Res. Letts., 3301-3304, 1998.

235. Wu, D. L., W. G. Read, Z. Shippony, T. Leblanc, T. J. Duck, D. A. Ortland, R. J. Sica, P. S. Argall, J. Oberheide, A. Hauchecorne, P. Keckhut, C. Y. She, D. A. Krueger, Mesospheric temperature from UARS/MLS: retrieval and validation, J. Atmos. Solar-Terr. Phys. 65, 245-267, 2003.

236. Yu, J.R., R. States, S. Franke, C. S. Gardner, and M Hagan, "Observations of Tidal Temperature and Wind Perturbations in the Mesopause Region above

Urbana, IL (40^0 N, 88^0 W)," *Geophys. Res. Lett.,* vol. 24, no. 10, pp. 1207-1210, 15 May 1997.

237. Yu, J.R., and C.Y. She, Climatology of a midlatitude mesopause region observed by a lidar at Fort Collins, Colorado, J. Geophys. Res., 100 (D4), 7441-7452, 1995.

238. Yu, J.R., and C.Y. She, "Lidar observed temperature structures and gravity wave perturbations of the mesopause region in the springs of 1990-1992 over Fort Collins, CO," *Appl. Phys.* B57, 231–238, 1993.

239. Yu, J.R., J.W. Huang, H. Latifi and C.Y. She, "Initial Spring Temperature Profiles of the Mesopause Region Over Fort Collins, CO. measured by the Colorado State Na Temperature Lidar," *Appl. Phys.* B55, 149-153, 1992.

240. Yu, J.R., H. Latifi, C.Y. She, J.H. Yee and R.J. Niciejiewski, "Simultaneous Lidar and Airglow Temperature Measurements in the Mesopause Region," *Geophys. Res.Lett.* 18, 1361–1363, 1991.

241. Zhao, Y., A. Liu, and C. S. Gardner, "Measurements of Atmospheric Stability in the Mesopause Region at Starfire Optical Range, NM," J. Atmos. Solar-Terr. Phys., vol. 65, 219-232, 2003.