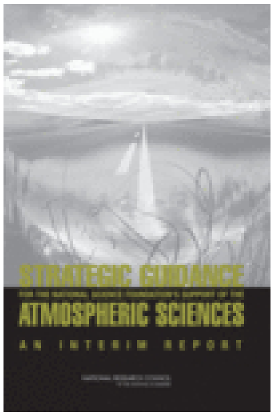

Strategic Guidance for the National Science Foundation's Support of theAtmospheric Sciences: An Interim Report

Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences, National Research Council

ISBN: 0-309-65330-4, 104 pages, 6 x 9, (2005)

STRATEGIC GUIDANCE
FOR THE NATIONAL SCIENCE FOUNDATION'S SUPPORT OF THE
ATMOSPHERIC SCIENCES

AN INTERIM REPORT

Committee on Strategic Guidance for
NSF's Support of the Atmospheric Sciences

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
www.nap.edu

THE NATIONAL ACADEMIES PRESS • 500 Fifth Street, N.W. • Washington, DC 20001

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

Support for this project was provided by the National Science Foundation under Contract No. ATM-0405530. Any opinions, findings, and conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number 0-309-10008-9

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet, http://www.nap.edu.

Printed in the United States of America

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Harvey V. Fineberg is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

COMMITTEE ON STRATEGIC GUIDANCE FOR NSF'S SUPPORT OF THE ATMOSPHERIC SCIENCES

JOHN A. ARMSTRONG (*Chair*), IBM Corporation (retired), Amherst, Massachusetts
SUSAN K. AVERY, University of Colorado, Boulder
HOWARD B. BLUESTEIN, University of Oklahoma, Norman
ELBERT W. FRIDAY, University of Oklahoma, Norman
MARVIN A. GELLER, Stony Brook University, New York
ELISABETH A. HOLLAND, National Center for Atmospheric Research, Boulder, Colorado
CHARLES E. KOLB, Aerodyne Research, Inc., Billerica, Massachusetts
MARGARET A. LEMONE, National Center for Atmospheric Research, Boulder, Colorado
RAMON E. LOPEZ, Florida Institute of Technology, Melbourne
KENNETH OLDEN, National Institutes of Health, Research Triangle Park, North Carolina
SUSAN SOLOMON, National Oceanic and Atmospheric Administration, Boulder, Colorado
JOHN M. WALLACE, University of Washington, Seattle
ROBERT A. WELLER, Woods Hole Oceanographic Institution, Massachusetts
STEPHEN E. ZEBIAK, Columbia University, Palisades, New York

National Research Council Staff

AMANDA STAUDT, Study Director
CLAUDIA MENGELT, Associate Program Officer
ELIZABETH A. GALINIS, Senior Program Assistant

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

ROBERT J. SERAFIN (*Chair*), National Center for Atmospheric Research, Boulder, Colorado
M. JOAN ALEXANDER, Colorado Research Associates, Boulder
FREDERICK R. ANDERSON, McKenna Long & Aldridge LLP, Washington, D.C.
MICHAEL L. BENDER, Princeton University, New Jersey
ROSINA M. BIERBAUM, University of Michigan, Ann Arbor
MARY ANNE CARROLL, University of Michigan, Ann Arbor
CAROL ANNE CLAYSON, Florida State University, Tallahassee
WALTER F. DABBERDT, Vaisala Inc., Boulder, Colorado
KERRY A. EMANUEL, Massachusetts Institute of Technology, Cambridge
DENNIS L. HARTMANN, University of Washington, Seattle
PETER R. LEAVITT, Weather Information Company, Newton, Massachusetts
JENNIFER A. LOGAN, Harvard University, Cambridge, Massachusetts
VERNON R. MORRIS, Howard University, Washington, D.C.
THOMAS H. VONDER HAAR, Colorado State University/CIRA, Fort Collins
ROGER M. WAKIMOTO, National Center for Atmospheric Research, Boulder, Colorado

Ex Officio Members

ANTONIO J. BUSALACCHI, JR., University of Maryland, College Park
ERIC F. WOOD, Princeton University, New Jersey

National Research Council Staff

CHRIS ELFRING, Director
PAUL CUTLER, Senior Program Officer
AMANDA STAUDT, Senior Program Officer
CLAUDIA MENGELT, Associate Program Officer
LEAH PROBST, Research Associate
ELIZABETH A. GALINIS, Senior Program Assistant
ROB GREENWAY, Senior Program Assistant
DIANE GUSTAFSON, Administrative Coordinator
ANDREAS SOHRE, Financial Associate

Preface

In the 1950s, there was growing concern that meteorological research was falling short of its potential for improved understanding and of the recognized needs for meteorological information in scientific, economic, and national security contexts. In response, the National Academy of Sciences formed the Committee on Meteorology "for the purpose of bringing together scientists from meteorology and related physical and geophysical fields to view in broad perspective the present position and future requirements of meteorological research and to recommend the general outline of a program that would accelerate progress in this important field" (NAS/NRC, 1958). That committee produced an interim report, *Research and Education in Meteorology* (NAS/NRC, 1958) that had six major recommendations:

1. Present support for meteorology at the universities and kindred institutions should be increased immediately by 50 to 100 percent, to be directed toward support of basic research.
2. A National Institute of Atmospheric Research should be established.
3. It is recommended that the AMS take the initiative and responsibility for increasing its activities in stimulating interest in meteorology 10-fold or more [….]
4. Representatives of departments of meteorology at the universities should form an interuniversity committee to consider curricula, student recruitment, fellowships, and textbooks.
5. The Chief of the Weather Bureau should be offered the help of a committee of university meteorologists in the educational and personnel development programs of the Bureau.

6. The university meteorological committee and other interested meteorologists should acquaint themselves fully with the availability of fellowships and scholarships in the sciences, and take the responsibility for providing guidance and direction for well-qualified students to obtain such assistance toward their education in meteorology.

Several of these recommendations were acted upon; in particular, there was a significant increase in funding for the field and the National Center for Atmospheric Research (NCAR) and the University Corporation for Atmospheric Research (UCAR) were created (Mazuzan, 1988). Several further reports produced by the National Academies from 1959 to the present have continued to play an important role in shaping the activities of research in meteorology and atmospheric sciences more broadly (e.g., NAS/NRC, 1960; NRC, 1977a, 1998).

The National Academies again have an opportunity to provide input on how atmospheric sciences research in the United States will evolve. The National Science Foundation's (NSF's) Division of Atmospheric Sciences (ATM) has asked the National Academies to perform a study that will provide guidance to ATM on its strategy for achieving its goals in the atmospheric sciences. This request reflects a desire by NSF to get a broad view of the health of the atmospheric sciences and to get some guidance on how best to direct resources in the future.

In response to NSF's request, the National Academies have formed the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences. In essence, the committee is asked to consider how ATM can best accomplish its goals of supporting cutting-edge research, education and workforce development, service to society, computational and observational objectives, data management, and other goals of the atmospheric science community into the future. The committee will provide guidance on the most effective approaches, that is, modes of support and activities, for different goals and on determining the appropriate balance among approaches (see Box P-1 for full statement of task). This interim report of the committee aims to provide some preliminary insight in response to the charge from NSF. The committee will also deliver a final report in fall 2006 in which the study charge will be fully addressed.

Over the past year, the committee has met four times to gather information and conduct deliberations. At several of these meetings, members of the atmospheric sciences community were invited to share their perspectives on study questions, both in sessions devoted to specific issues and in an "open mike" session when any comments were welcome. In addition, the committee made available a Web site through which members of the community could contribute comments (http://dels.nas.edu/basc/strat.shtml), met with the heads and chairs of the UCAR universities, and held town hall sessions at the December 2004 fall meeting of the American Geophysical Union (AGU) and at the January 2005 annual meeting of the American Meteorological Society (AMS). This input has

BOX P-1
Statement of Task for Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences

At the request of ATM, this committee will perform a study that will provide guidance to ATM on its strategy for achieving its goals in the atmospheric sciences (e.g., cutting-edge research, education and workforce development, service to society, computational and observational objectives, data management). In doing so, the committee will seek to engage the broad atmospheric science community to the fullest extent possible. The committee will provide guidance on the most effective approaches for different goals and on determining the appropriate balance among approaches. In essence, the committee is asked to consider how ATM can best accomplish its mission of supporting the atmospheric sciences into the future. Specifically, this study will consider the following questions:

1. What are the most effective activities (e.g., research, facilities, technology development, education and workforce programs) and modes of support (e.g., individual principal investigators, university-based research centers, large centers) for achieving NSF's range of goals in the atmospheric sciences?
2. Is the balance among the types of activities appropriate and should it be adjusted? Is the balance among modes of support for the atmospheric sciences effective and should it be adjusted?
3. Are there any gaps in the activities supported by the Division and are there new mechanisms that should be considered in planning and facilitating these activities?
4. Are interdisciplinary, foundation-wide, interagency, and international activities effectively implemented and are there new mechanisms that should be considered?
5. How can NSF ensure and encourage the broadest participation and involvement of atmospheric researchers at a variety of institutions?

The study will not make budgetary recommendations. The committee will deliver its results in two parts: (1) a short interim report in fall 2005 that provides a preliminary sense of the committee's overarching conclusions; and (2) a final report by fall 2006 that further considers community input and provides the committee's full analysis and recommendations.

been quite helpful in shaping the committee's thinking; we especially acknowledge the comments of the individuals listed in Appendix C. As we develop our final report, we hope to further engage the atmospheric sciences community in discussions of this interim report. In this coming year, we plan to hold town hall sessions at both the AGU and AMS meetings again and to retain options for individuals to submit comments through the Web site.

Several individuals have assisted the committee in gathering information about the current status and evolution of the atmospheric sciences as well as in organizing meetings. We especially appreciate the efforts of Jarvis Moyers and his colleagues at ATM, who graciously accommodated multiple requests for detailed information about the division's activities, budgets, and grants over the past 30 years. Richard Anthes, Susan Friberg, and their colleagues at UCAR and Tim Killeen and his colleagues at NCAR were very helpful in providing information about UCAR/NCAR activities and in planning the committee's meeting in Boulder, Colorado.

Finally, it is a pleasure to recognize the outstanding work of the study director, Senior Program Officer Amanda Staudt, who brought to our task both broad knowledge of atmospheric sciences and great skill in the conduct of National Research Council studies. She was ably assisted by Associate Program Officer Claudia Mengelt and Senior Program Assistant Elizabeth Galinis.

John Armstrong
Committee Chair

Acknowledgments

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

M. Joan Alexander, Colorado Research Associates, Boulder
David Atlas, NASA Goddard Space Flight Center, Silver Spring, Maryland
William H. Brune, Pennsylvania State University, University Park
James B. Edson, Woods Hole Oceanographic Institution, Massachusetts
Cassandra Fesen, Dartmouth College, Hanover, New Hampshire
Jerry Mahlman, National Center for Atmospheric Research, Boulder, Colorado
James C. McWilliams, University of California, Los Angeles
Veerabhadran Ramanathan, Scripps Institution of Oceanography, University of California, San Diego
Gerard Roe, University of Washington, Seattle
Gabor Vali, University of Wyoming, Laramie
Carl Wunsch, Massachusetts Institute of Technology, Cambridge

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or

recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George Hornberger, University of Virginia, and Eugene Rasmusson, University of Maryland, College Park. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Contents

Executive Summary

The National Science Foundation (NSF) is responsible for the overall health of science and engineering across all disciplines and for ensuring the nation's supply of scientists, engineers, and science and engineering educators. NSF's Division of Atmospheric Sciences (ATM) supports research to develop new understanding of Earth's atmosphere and how the Sun impacts it. In addition, ATM supports activities to enhance education at all levels, the diversity of the scientific community, and outreach to the public. ATM scientists conduct research to address NSF-wide priorities and participate in interagency and international research efforts. ATM employs a range of modes of support for these activities: grants to individuals and to teams of researchers; small research centers; a large federally funded research and development center, specifically the National Center for Atmospheric Research (NCAR) located in Boulder, Colorado; and the acquisition, maintenance, and operation of observational and computational facilities operated by NCAR, universities, and other entities.

ATM has asked the National Academies to perform a study that will provide guidance on the division's strategy for achieving its goals in the atmospheric sciences (See Appendix A for full statement of task). This request reflects a desire by ATM to get a broad view on the health of the atmospheric sciences and to get some guidance on how best to direct resources in the future. In response, the National Academies have formed the Committee on Strategic Guidance for NSF's Support of the Atmospheric Sciences. The committee authored this interim report, which aims to provide some preliminary insight in response to the charge from NSF and will also deliver a final report in fall 2006 in which the study charge will be fully addressed.

In considering future directions for the atmospheric sciences, the committee reviewed some aspects of the evolution of the atmospheric sciences over the past several decades. The body of the report also offers some preliminary analysis of the strengths and limitations of the various modes of support employed by ATM. On the basis of these analyses, the committee has identified the findings and recommendations discussed below. The order of the findings and recommendations presented here and in the main body of the report does not strictly reflect priorities, but rather is presented to aid the reader in following the development of the ideas presented. In these findings and recommendations, the committee aims to identify broad areas where additional attention by ATM is warranted; after further deliberation, more specific guidance will be provided in the committee's final report.

EMPLOYING A DIVERSITY OF MODES TO MEET ATM OBJECTIVES

Having diverse modes of support available has benefited the atmospheric sciences.

Finding: The committee finds that the diversity of activities and modes of support is a strength of the program and of our nation's scientific system. The approach and vision outlined in NAS/NRC (1958) and the "Blue Book" ("UCAR," 1959), which together mapped out the complementary roles of a large national center and the individual investigator university grants program, has served the atmospheric science community well and is the envy of many other scientific communities. The newer modes of support (i.e., multi-investigator awards, cooperative agreements, and centers sited at universities) reflect the maturation and increasing interdisciplinary nature of atmospheric sciences. The community input received to date supports this multifaceted approach. The present balance is approximately right and reflects the current needs of the community.

Recommendation: ATM should continue to utilize the current mix of modes of support for a diverse portfolio of activities (i.e., research, observations and facilities, technology development, education, outreach, and applications).

It is essential to preserve opportunities for high-risk, potentially transformative research.

Finding: Among federal science agencies, NSF is a leader in its commitment to support high-risk, potentially transformative research (excluding satellite instrument development). This type of research is instrumental in making major advances in the field, as well as in sustaining the nation's economic development and global competitiveness. Currently, program directors have discretion to use 5 percent of their budgets for Small Grants for Exploratory Research projects, though typically about 1 to 2 percent of each program's funds are applied this way. In addition, program directors can choose to support other high-risk work through regular grant mechanisms as they see fit. However, it is unknown to what extent this flexibility to support exploratory research is utilized. Furthermore, there may be some research questions of this type that require a bigger investment than what typically can be made by a program director. One option to be more effective is to pool some of the funding for exploratory research from all ATM programs and run an internal competition to which program directors can submit promising, high-risk ideas for consideration.

Recommendation: ATM should support high-risk, potentially transformative research at the current rate or a greater one, seeking new mechanisms to enhance opportunities for investigators, such as pooling some of the existing funding. The success of this effort should be evaluated every five years.

ENHANCING CROSS-DISCIPLINARY, INTERAGENCY, AND INTERNATIONAL COORDINATION

Effective identification of cross-disciplinary opportunities and related funding mechanisms are critical to the health of the atmospheric sciences.

Finding: Research questions in the subdisciplines of atmospheric science are interrelated. Further, many are connected to those in other scientific disciplines, such as oceanography, ecology, terrestrial science, solar physics, and social science. In some cases, the science questions extend beyond the boundaries of ATM or NSF's Geosciences directorate. ATM does make efforts to foster cross-disciplinary research, for example, by partnering with other divisions to support individual proposals or jointly soliciting proposals on a topic that falls at their interface. Yet, some research questions that fall at the interface between two or more disciplines can challenge NSF's funding structures even when evaluations show these to be prime opportunities for scientific advancement. Examples of the challenges faced in cross-disciplinary science include the need to address the water cycle, biogeochemical cycles, paleoclimate, air-sea fluxes, and health impacts of atmospheric oxidants and fine particles. Improving opportunities for cross-disciplinary research will require commitments from ATM and other NSF divisions that support related research.

Recommendation: ATM should work to reduce institutional barriers within NSF to appropriate cross-disciplinary research.

A more strategic approach is needed to facilitate interagency coordination.

Finding: Despite compelling motivations for interagency coordination, ATM does not always have clear mechanisms for effectively facilitating such interactions. Some interagency coordination takes place through formalized interagency programs (e.g., Climate Change Science Program, National Space and Weather Program), interagency working groups, community-driven initiatives (e.g., Climate Variability and Change, [CLIVAR]), and ad hoc interactions between program directors. A strategic plan would both increase the transparency and decrease the ad hoc nature of NSF's approach to these interagency collaborations. Another way to address this problem would be to facilitate the establishment of an interagency Federal Coordinator for Atmospheric Research. This individual would be supported by all relevant agencies, with duties and responsibilities similar to the role of the Office of the Federal Coordinator for Meteorology, but with a focus on sustaining the overall health of basic research in atmospheric science by maintaining liaisons with all relevant agencies and identifying their contributions to atmospheric research. Other options for fostering interagency coordination could also be effective.

Recommendation: ATM should be even more proactive in developing clear mechanisms for interagency collaborations.

A more strategic approach is needed to facilitate international coordination.

Finding: The atmosphere knows no national boundaries; thus, international collaboration is critical to the study of the atmosphere. The research capabilities of other nations are becoming more sophisticated and their investments in the atmospheric sciences are growing. There is a breadth of atmospheric research coordinated internationally through organizations such as the World Climate Research Programme (WCRP), the International Geophysical-Biophysical Programme, the World Meteorological Organization (WMO), and the Scientific Committee on Solar Terrestrial Physics. Often these international efforts address broad cross-disciplinary research agendas. ATM has been extensively involved in international efforts, but U.S. participation has been largely on an ad hoc basis. It is not clear that this ad hoc approach is desired in the future when pressure on ATM funding will likely increase. A proactive and judicious mechanism, including the ability to commit with long lead time the participation of U.S. facilities and investigators, is needed for coordinated, efficient, and effective participation in international programs. Such a mechanism would help U.S. investigators and international bodies more fully understand the basis for ATM funding decisions and hence plan accordingly. In particular, this mechanism would be useful for evaluating potential ATM involvement in international field campaigns; in this case, existing international bodies (such as WCRP, the World Weather Research Program, and WMO) could help determine the merits of potential field campaigns

Recommendation: ATM should develop systematic and clearly communicated procedures for tracking international program development, identifying potential ATM contributions, committing resources where appropriate, and reevaluating participation in international activities at regular intervals.

SUPPORTING FIELD PROGRAMS, DATA ARCHIVES, AND DATA ANALYSIS

Longer-term field programs have not received sufficient support.

Finding: ATM has well-established mechanisms for supporting short-duration field programs. However, ATM has not yet clearly articulated mechanisms for supporting field programs that require continuous, longer-term (i.e., up to multi-year) deployment and observations not available from operational monitoring networks. This type of observation protocol is generally ill-suited to the existing funding opportunities, in part because they were prohibitively expensive until recently. Three factors motivate the need and appropriateness of this approach today: (1) these types of observations are especially critical to understanding the interaction between the atmosphere and Earth's surface, which are growing areas of research and concern; (2) many instruments that would be used are less expensive, making it reasonable to deploy them in the field for longer durations; and (3) there are existing observational programs developed by other NSF divisions and agencies (e.g., Long Term Ecological Research, the Ocean Research Interactive Observatory Networks Ocean Observing Initiative, the proposed hydrological observatories of the Consortium of Universities for the Advancement of Hydrologic Science, Inc.), which can be leveraged with additional investments to conduct atmospheric research.

Recommendation: ATM, in coordination with other NSF divisions and federal agencies, should develop the explicit capability to support longer-term (i.e., up to multiyear) lower-atmosphere field programs to study atmospheric processes that are important on these timescales.

Support for field data archives, visualization tool development, and analysis is not commensurate with the investment in obtaining the measurements.

Finding: A longstanding challenge in the atmospheric sciences is providing sufficient support for scientists to analyze data obtained during field programs and from observational networks. Because analysis comes at the end of a field program and competes against the start of other new field programs, it is at times subject to reduction in support. Thus, the full benefit from the investment in a field program often is not realized. Maximum benefit from many NSF-supported studies also would be facilitated by easy access to data from operational observational and monitoring networks (including surface, upper air, radar, and satellite) in addition to easy access to field-program data, historical data, and numerical model data. All these datasets should be archived and provided to the community in a manner consistent with common standards, along with the necessary analysis and visualization tools. In enhancing these capabilities, there are opportunities for NSF to work with other federal agencies who have faced similar challenges, particularly in terms of data archiving.

Recommendation: ATM should maximize the benefit of field data by ensuring that archiving, visualization, and analysis activities are well supported and continue for many years after the completion of field campaigns. ATM is encouraged to work with the community by sponsoring a series of workshops on development of standards for metadata, data archival, and software tools and by providing support for the implementation of the recommendations of the workshops.

PARTNERING WITH NATIONAL CENTERS

Partnerships between university or private-sector scientists and existing and emerging national centers need to be strengthened.

Finding: NCAR has a rich history of collaboration with university and private-sector scientists, particularly to make progress on large scientific problems that are beyond the reach of a single university department or private-sector laboratory. Whereas there are many opportunities for collaboration between NCAR and university or private-sector scientists, decisions about NCAR strategic initiatives (e.g., recent new efforts in biogeosciences and water) could benefit from broader community input. Indeed, because both NCAR and the broader atmospheric sciences community have grown in size and complexity, there are new challenges for the center in terms of maintaining a balance between inward- and outward-looking efforts. New challenges also exist in engaging a larger, more fragmented university and private-sector research community. This suggests that there may need to be additional new mechanisms to leverage the investment in a large center in a way that provides synergism with the needs of the university and private-sector research community.

Collaborations between large national centers (both existing and emerging) and university or private-sector scientists could be enhanced by new mechanisms to stimulate joint research initiatives at a larger scale than existing ad hoc collaborations. For example, ATM could conduct a regular competition for collaborations between NCAR and the outside community, focusing on research efforts that address important atmospheric science problems that are beyond the capability of single university departments or individual private-sector laboratories. The award should be significant, in excess of $1 million a year for five years. For initiatives that have large interdisciplinary scope, ATM could seek mechanisms for shared funding with other NSF divisions.

Recommendation: ATM should encourage new modes of partnership between the university and private-sector research community and the large national center.

DEVELOPING A STRATEGIC PLAN FOR ATM

ATM has not published a strategic plan to guide its activities in the coming years. A community-based strategic planning effort could provide a means by which ATM can advance the preceding recommendations. For example, the strategic plan should address the objectives of improved interdisciplinary collaboration (Recommendation 2); opportunities for high-risk, potentially transformative research (Recommendation 3); enhanced interagency and international coordination (Recommendations 4 and 5, respectively); and the planning of field programs (Recommendation 6).

Strategic plans can take many different forms, ranging from describing a mission and fairly high-level goals for a program to providing more details about implementation. At a minimum the strategic plan recommended here should clearly articulate ATM's mission and goals in the context of the multidisciplinary, multiagency, and multinational environment of atmospheric research. However, the committee envisions ATM's strategic plan going beyond providing a set of goals to include actions on how to attain the goals, although not prescribing in great detail the specifics of implementation. Rather, it should address practical implementation challenges, such as interagency relations, international relations, and university relations with NCAR. Further, the plan should put flexible structures in place that will give ATM a means for making decisions about prioritization, for example, in response to pressures resulting from an evolving budgetary environment, competing international initiatives, and multiple demands for facilities. Having a strategic plan in place may call for a reorganization of ATM to direct staff and resources in a way that may better address emerging challenges. Furthermore, the balance of modes should evolve in the future in a manner that is consistent with strategic planning efforts.

The committee believes that the strategic plan itself will be useful to ATM, but the process of producing it may prove even more valuable, particularly if it is conducted with ample and transparent community engagement. The committee envisions the strategic planning process as providing a mechanism for the community as a whole to participate in an active conversation about the direction of the field and where best to use resources, while remaining sensitive to the societal expectations of that research. Thus, the strategic plan must be flexible and responsive and developed by the science community in collaboration with ATM management. Ideally, the process of developing the strategic plan would be simple, revisited at regular intervals, and eventually ingrained in the ATM culture.

A strategic plan will be essential to maintain a balanced, effective portfolio in an evolving programmatic environment.

Finding: We are now in a phase of rapid change in graduate education demographics, the role of the United States in the global atmospheric science community, potentially the role of NSF in national atmospheric science funding, and the maturation and interdisciplinary growth of atmospheric science, as well as a likely period of constrained budgets. GEO (2000) represents a broad strategic plan for the NSF Geosciences Directorate and reflects the considerable evolution of the geophysical scientific enterprise. Yet, ATM has not developed its own strategic plan. Given the changing programmatic environment, ATM should take a more proactive approach to strategic planning. A flexible strategic plan developed with ample community input will enable determination of the appropriate balance of activities and modes of support in the ATM portfolio; help plan for large or long-term investments; facilitate appropriate allocation of resources to interdisciplinary, interagency, and international research efforts; and ensure that the United States will continue to be a leader in atmospheric research. In addition, a strategic planning effort that effectively engages the community will enhance the transparency of the rationale behind ATM's decisions.

Recommendation: ATM should engage the community in the development of a strategic plan, to be revisited at regular intervals, and should rethink its programmatic organization in light of this plan.

1

Introduction

The scientific method is applied in a fundamentally different fashion in atmospheric and geophysical sciences than in the laboratory-based physical sciences (i.e., physics, chemistry, etc.). This is a consequence of these laboratory-based sciences being able to perform experiments in a laboratory setting where individual parameters can be varied in a controlled manner to test experimental evidence against predictions from theory. In contrast, nature provides only single realizations that are, by and large, beyond our control. Therefore, the scientific method is applied by continually testing theoretical predictions or simulations of system parameters against observations of these same parameters. By iteratively comparing model results with observations and improving understanding of individual processes, representations of natural physical processes in mathematical models of physical systems, such as the atmosphere, the ocean, or the climate system, are continually improved, thereby yielding improved agreement between models and observations. An ultimate test occurs when these models are used to predict future behavior of natural systems and are tested against observations. Better predictions imply better understanding and representation of the natural system, but success should be measured against the inherent mathematical predictability of the system.

Thus, in the laboratory-based sciences, application of the scientific method implies the interplay between laboratory experiments and theory, whereas in the atmospheric sciences, the interplay is between iterative models (conceptual or mathematical) and observations. There are a few examples of atmospheric research that can be done with the more traditional scientific method. They include laboratory measurements of reaction rates of atmospheric species and scaleddown models of air flow, but these do not form the bulk of today's atmospheric research. Atmospheric observations can come from routine weather observations, special field programs of relatively short duration, long-term research observations, and climate observing systems. The strategies for conducting atmospheric research are determined by such considerations of how the scientific method is applied.

ATMOSPHERIC SCIENCES AT THE NATIONAL SCIENCE FOUNDATION

NSF is responsible for the overall health of science and engineering across all disciplines and for ensuring the nation's supply of scientists, engineers, and science and engineering educators. The Division of Atmospheric Sciences (ATM) supports research to develop new understanding of Earth's atmosphere and how the Sun impacts it, as illustrated in the organizational chart for the division (Figure 1-1). Over the past six years, ATM has devoted about 30 percent of its budget to supporting the Lower Atmospheric Research Section, 16 percent to the Upper Atmospheric Research Section, 42 percent to the University Corporation for Atmospheric Research and Lower Atmospheric Facilities Oversight Section,

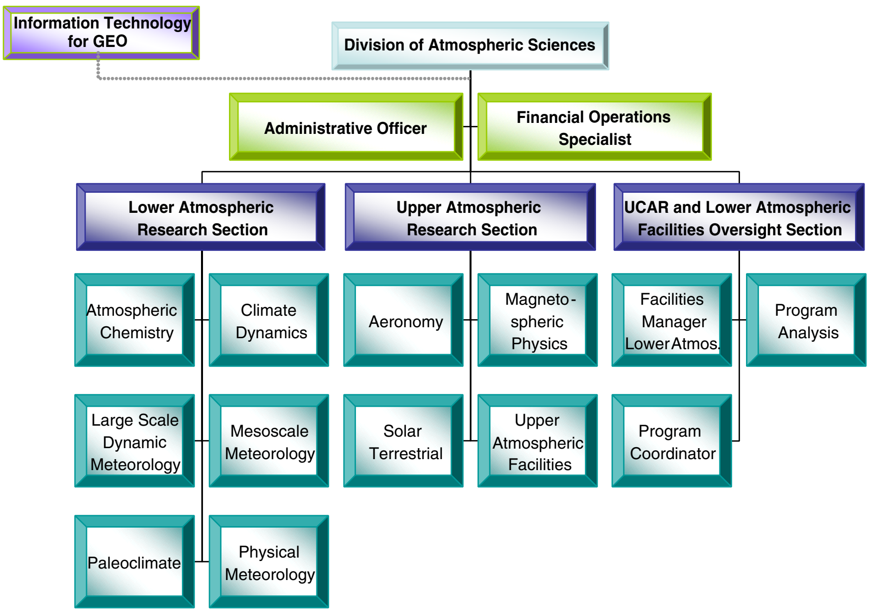

FIGURE 1-1 Organizational chart for ATM.

and the remaining 12 percent to other activities (including Science and Technology Centers, cross-directorate funding, special activities within the Geosciences Directorate, and the division-wide account for midsize infrastructure). ATM's total budget for these activities in 2004 was $238.8 million.

ATM supports activities to enhance education at all levels, the diversity of the scientific community, and outreach to the public. ATM scientists conduct research to address NSF-wide priorities and participate in interagency and international research efforts. ATM employs a range of modes of support for these activities: grants to individuals and to teams of researchers; small research centers; a large federally funded research and development center, specifically the National Center for Atmospheric Research (NCAR) located in Boulder, Colorado; and the acquisition, maintenance, and operation of observational and computational facilities operated by NCAR, universities, and other entities (see also Box 1-1). About 65 percent of the ATM's budget is for science research projects and 35 percent for facility support (Figure 1-2).

BOX 1-1
Clarification of Terminology

The committee is asked to evaluate the "activities" and "modes of support" ATM uses to achieve its goals for supporting the atmospheric sciences. For the purposes of this report, the committee defines these terms as follows:

Goals:	The overarching objectives of NSF in supporting the atmospheric sciences, including cutting-edge research, education and workforce development, service to society, computational and observational objectives, and data management.
Activities:	The pursuits taken to achieve the goals, including theoretical and laboratory research, field measurement programs, technology development, education and workforce programs, product development, and outreach.
Modes of support:	The programmatic tools NSF employs to support the activities, including support for individual or multiple principal investigators (PIs), small centers, large national centers, cooperative agreements to support facilities, and interagency programs.

Occasionally in this report, "approaches" is used to refer to the collection of activities and modes of support. There are ambiguities in classifying some efforts as activities versus modes of support. For example, field programs are discussed both as an activity that is typically supported by a collection of grants to individual or multiple PIs and as a mode of support because NSF has developed some mechanisms specifically for facilitating field programs.

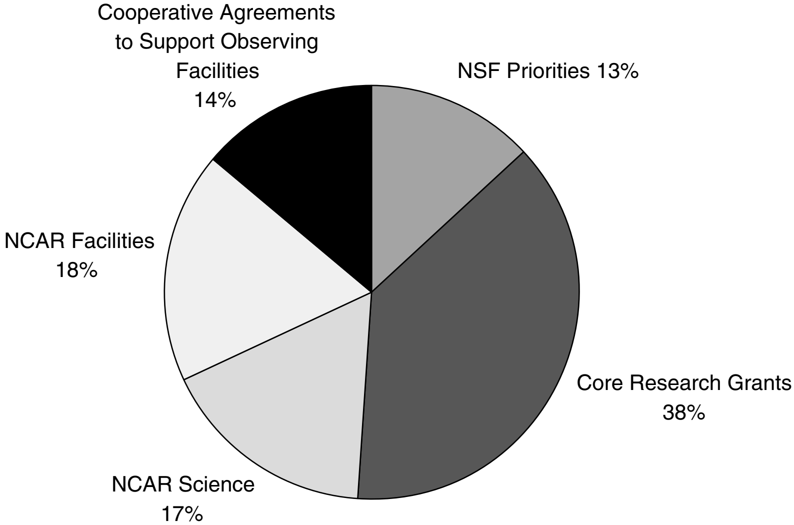

FIGURE 1-2 Expenditure balance for ATM in FY 2004; total is $238.8 million.

PRINCIPLES FOR SUCCESSFUL SUPPORT OF THE ATMOSPHERIC SCIENCES

The committee's preliminary evaluation of ATM's evolution over the past 45 years and current activities, as discussed in Chapters 2 and 3, has revealed that the division has done a good job in meeting its mission to support the atmospheric sciences. In particular, there have been significant advances in answering fundamental scientific questions about the atmosphere, in utilizing new knowledge of the atmosphere to address societally relevant applications, and in educating a workforce to advance the science and its application. This conclusion was also the clear consensus of the many members of the broad atmospheric sciences community who have provided input to the committee's deliberations thus far.

The committee has identified a set of 10 principles that have enabled ATM to be successful over the past 45 years. Continuing to strive to meet these principles should ensure that the division remains strong in the coming decades. A robust set of principles can be used as a framework for making funding decisions in an understandable and describable way. Such clarity is of benefit in times of expanding or declining budgets. The committee notes that all principles are not equal and that they should be applied differently depending upon the context.

1. High Quality. The division has maintained a high level of quality in the research it funds. This has been achieved through rigorous competition, strong peer review, and close working relationships between ATM program officers and members of the research community. In the case of STCs, the enforcement of a "sunset date" for the centers is generally viewed as positive, and has led to evolution that allows the centers to address cutting-edge research questions. This high level of quality is essential to the continued success of ATM.

2. Flexibility. ATM will be better able to meet its objectives of supporting the atmospheric science research community if it has the flexibility to apply different modes and create new modes to address evolving needs. This flexibility is essential, given the evolving roles of other federal agencies, the private sector, and the international research efforts.

3. Responsiveness. ATM's success over the past decades reflects in part a commitment to being responsive to the needs of the research community. Indeed, NSF's support of the atmospheric sciences is particularly important in this regard because it is the main federal agency that supports high-risk, potentially transformative research, except, of course, the National Aeronautics and Space Administration's (NASA's) satellite-based research.

4. Balance. Atmospheric science comprises many subdisciplines—ranging from dynamic meteorology to climate change and from atmospheric chemistry to upper atmospheric dynamics and solar physics—and is inherently interdisciplinary in that the atmosphere interacts with the oceans, land surface, and near-space environment. Furthermore, the research efforts span the spectrum from fundamental research to efforts with direct applications. A portfolio that addresses the range of these research objectives and utilizes the range of modes of support in a balanced way is essential.

5. Interagency Partnerships. Research in the atmospheric sciences benefits from the relevance of weather, climate, and air quality to multiple federal agencies that support some extramural research. These agencies include NASA, the National Oceanic and Atmospheric Administration, Department of Energy, Environmental Protection Agency, Federal Aviation Administration, and Department of Defense. Building effective partnerships with other agencies that have shared priorities is critical to the long-term health of the field.

6. Connections to International Communities. Other nations support significant research in the atmospheric sciences, offering excellent opportunities for collaboration. ATM should maintain connections to international efforts both through engagement directly with other nations and through international programs to coordinate research (e.g., WCRP, World Weather Research Program).

7. Robust Research Community. The atmospheric sciences research community includes professors and other permanent university research staff, postdoctoral fellows, graduate and undergraduate students, staff at centers (i.e., large national centers, STCs, engineering research centers), and private-sector researchers.

Some stability in the support for this research community and for the training of new scientists is critical for the continuing strength of the atmospheric sciences.

8. Community Input. Opportunities for the broad atmospheric science community to provide input in defining strategic directions for NSF's programs helps strengthen the scientific foundation of the research endeavor and builds community support.

9. Access to Necessary Resources. The atmospheric research community needs access to appropriate observing and computational facilities. In many cases, these facilities can be shared by multiple researchers. Furthermore, resources are needed to ensure adequate time for analysis and synthesis of field campaign results.

10. High-Quality Staff. The atmospheric sciences research community has benefited from the consistent professionalism and dedication of ATM staff over the past decades. Maintaining and renewing high-quality ATM staff with keen understanding of current scientific frontiers is essential to continued success of the field.

LOOKING FORWARD TO THE COMMITTEE'S FINAL REPORT

In fall 2006, the committee will issue its final report that responds to its charge in full. To prepare the final report, the committee will continue to gather information and to deliberate on the questions in its charge. In addition, the committee hopes that this interim report sparks community input on the findings and recommendations presented as well as on the questions it leaves unanswered. Input from the community is especially important in considering how ATM's activities may need to evolve to meet future challenges. Some major questions that the committee intends to address in the final report include the following:

- Should the balance among the modes of support evolve in response to the changing research environment and, if so, in what way?
- Should the balance of support among different disciplines evolve to reflect changing research priorities?
- Should there be an evolution in the balance of support between research that is curiosity-driven and that which is motivated by broader societal objectives?
- What are the implications of the shift in recent decades toward a larger fraction of grants being awarded to multi-investigator projects?
- What are the implications of a shift in recent decades toward a larger fraction of the ATM budget being used to support facilities?
- How can ATM best support supercomputing, particularly in terms of balancing centralized and distributed facilities?
- Are there new approaches that ATM could employ to better facilitate interdisciplinary, interagency, and international coordination?

- How can ATM best support research on phenomena that operate on timescales much longer than normal NSF grants?
- Are there new approaches that ATM could employ to better meet its goals for education and workforce development?
- How can ATM ensure and encourage the broadest participation and involvement of atmospheric researchers (including underrepresented populations) at a variety of institutions?
- How should ATM engage the atmospheric research community in the development, execution, and evolution of its strategic plan?

As is discussed in the next chapters, the committee has conducted preliminary evaluations of the various modes of support ATM employs to enable a range of research and related activities in the atmospheric sciences. On the basis of this analysis, the committee believes that the balance is about right to address current needs. However, given ongoing and anticipated changes in the atmospheric research environment—including demographics, globalization, and the growth of interagency and interdisciplinary research—it is possible, and even likely, that this balance will need to shift. The evolving balance among the modes will be a focus of the committee's final report.

Finally, the committee notes that several findings and recommendations are offered in this interim report. This guidance is intended to point to broad areas where attention by NSF is warranted to improve support for the atmospheric sciences. In most cases, specific recommendations about how to tackle these challenges are not provided, largely because the committee feels that further deliberation is needed to develop carefully considered courses of action. As appropriate, the final report will provide more detailed recommendations.

2

The Changing Context for Atmospheric Science

In considering future directions for the atmospheric sciences, the committee reviewed some aspects of the evolution of the atmospheric sciences from 1958, when the National Academy of Sciences first considered the status of research and education activities in the field, to the present. While illustrative rather than comprehensive, this consideration of a number of key defining characteristics of the field—including demographics, advances in science, interdisciplinarity, technology developments, and societal expectations—has helped inform the committee's thinking about what factors are important in shaping future directions for the atmospheric sciences.

The committee is aware that the context for the present study is much different from that in 1958. The field of atmospheric sciences has evolved significantly. The expansion of university, private-sector, and National Center for Atmospheric Research (NCAR) research and the development of new communications and computational infrastructure, coupled with greatly expanded research and operational efforts at other agencies and in other countries, has transformed understanding of the atmosphere, created new operational observational and modeling capabilities, and changed the way in which atmospheric research is conducted. New subdisciplines of atmospheric science have emerged, such as climate change and atmospheric chemistry, which grew out of an increased awareness of air pollution. The number and size of university atmospheric science programs has increased by nearly a factor of 5, indicating a more comprehensive and richer research endeavor. NCAR has grown to an institution that houses about 935 scientists and support personnel, builds and maintains observational and modeling facilities, and serves as a leader in organizing field campaigns, educational and outreach activities, and other community service efforts. Federal agencies besides the National Science Foundation (NSF), including the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Department of Energy (DOE), Department of Defense, and Environmental Protection Agency, have added to the support for atmospheric research, both internally and extramurally. These other agencies have focused efforts on their own missions and supporting research objectives (e.g., air quality) and have pioneered new approaches to research, most notably the introduction by NASA of space-based platforms for observing the atmosphere and near-space environment. International collaborations, including large multi-investigator and multinational field campaigns, now play a major role and require a significant fraction of the research budget.

The committee believes that this evolution of atmospheric science research since 1958 introduces not only new opportunities but also new challenges. For example, five years of steady growth in NSF budgets have given way to a new period of limited budget growth, while support of atmospheric science research by other federal agencies exhibits considerable volatility. The constrained budget environment combined with the expanded scope of scientific questions have increased the need for interagency and international coordination. In developing findings and recommendations in this interim report, the committee first reviews how atmospheric science research has evolved. With that foundation the committee goes on to conduct a preliminary examination of the opportunities, challenges, successes, and shortcomings of the various modes of support for the atmospheric sciences. The final report will include a more complete analysis in order to address issues of balance among, and future evolution of, the modes.

RESEARCH SUPPORT AND DEMOGRAPHICS

The atmospheric sciences have enjoyed a slow but steady increase in funding by NSF since the late 1950s. NSF funding for atmospheric sciences was $16.3 million (in constant 1996 dollars) in 1958, increasing to $53.9 million in 1959. The Division of Atmospheric Sciences (ATM) budget had increased to $122 million by 1972, reaching $196 million in 2004 (Figure 2-1). Much of the budget increase that ATM has experienced since the 1980s can be traced to new funds for facilities operated by entities other than NCAR ($27 million increase since 1982) and for NSF-wide priorities, such as "Biocomplexity in the Environment" and "Information Technology Research" ($25 million increase since 1989). The core grants program and NCAR have experienced modest increases in support over the past 30 years.

The funding is currently directed to the modes of support of core grants, university facilities, NCAR facilities and science, and NSF priorities, as shown in Figure 1-1. These modes overlap in many ways, for example, because facilities are integral to the research process. Over these 30 years, core research has

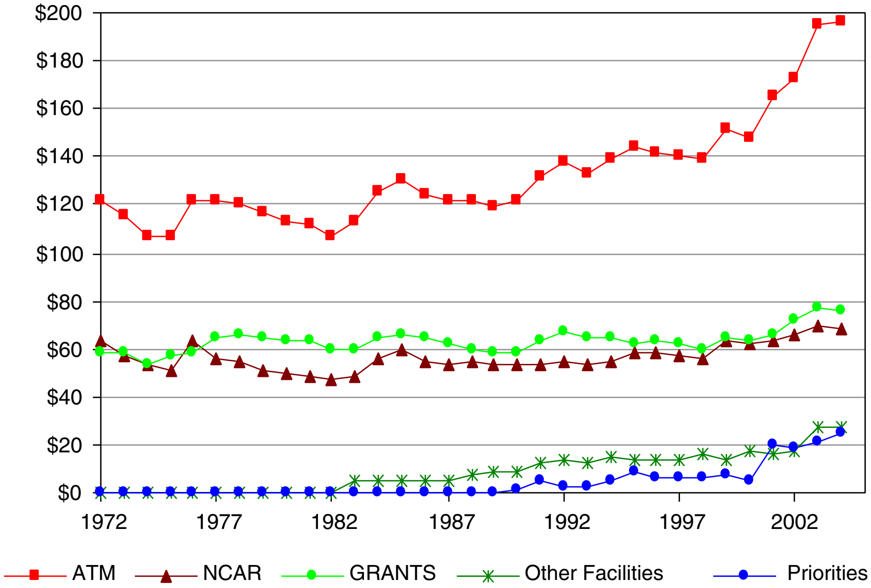

FIGURE 2-1 ATM funding for the atmospheric sciences since FY 1972 in millions of constant 1996 dollars. The NCAR numbers include support for both science and facilities housed at the center. "Other facilities" refers to support for facilities operated by institutions other than NCAR. "Priorities" refers to NSF-wide initiatives, such as "Biocomplexity in the Environment" and "Information Technology Research."

decreased from 50 percent to 38 percent of the overall ATM budget, and support for science at NCAR has decreased from 23 percent to 18 percent of the ATM budget. However, given the overall increase in the ATM budget, NSF core grant support has remained about constant in total dollars. At the same time, support for facilities at NCAR and at universities has increased from 23 percent to 33 percent of the ATM budget. Thus, facilities support has increased faster than core grant support, most likely due to the increasing sophistication of computing and observing capabilities. The committee notes that the availability of facilities creates research opportunities for individual investigators.

Other agencies have experienced much larger fluctuations in their extramural funding for atmospheric science. It is not easy to track down exactly how much each agency spends on atmospheric research; Figure 2-2 shows efforts by the Office of the Federal Coordinator for Meteorology (OFCM) and the U.S. Climate Change Science Program (CCSP) to sum up the contributions of different agencies to research relevant to their individual mandates. Note that the agencies also

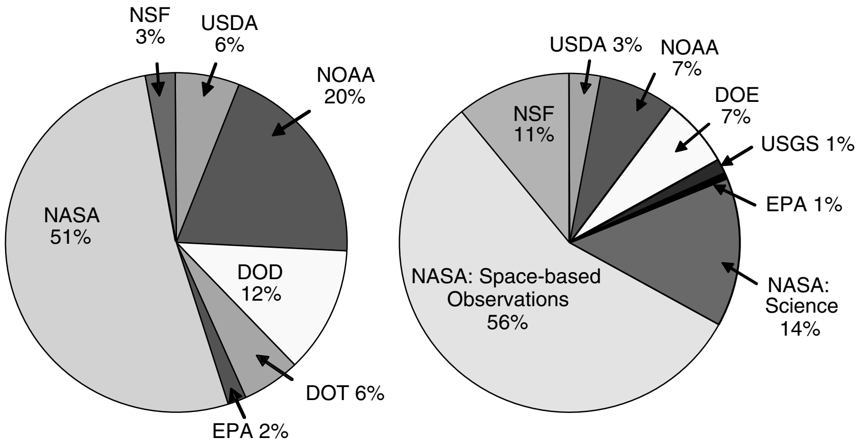

FIGURE 2-2 *(Left)* FY 2004 funding for atmospheric sciences research by the 10 agencies surveyed by the OFCM. The overall funding by these agencies for this year totals about $503 million. Note that the NSF funding only includes the foundation's contributions to space weather research and the U.S. Weather Research Program, which together total about $14 million. The NASA proportion of the OFCM funding is composed of the estimated meteorology share of the supporting research and analysis programs as well as Earth Observing System (EOS) and Earth Probe instruments, EOS science, and the EOS Data Information System elements of the NASA Office of Earth Science budget (OFCM, 2004). *(Right)* Estimated FY 2003 budget for atmospheric-related climate change research (i.e., the atmospheric composition, climate variability and change, carbon cycle, and water cycle program areas) by the 13 agencies of the CCSP (CCSP and SGCR, 2004). Total funding for these program areas is approximately $1.4 billion.

support research on air quality and solar sciences, which neither of the charts in Figure 2-2 includes. These budgets include both intramural and extramural support for research. ATM is a relatively small player overall, but plays a significant role in supporting university and other extramural research.

The National Academy of Sciences (NAS/NRC, 1958) concluded that there was a strong need for more professionals in the atmospheric sciences. At the time, only about 10 to 15 doctorates were awarded each year. By the late 1970s, an average of 84 doctorates a year were awarded by a greatly expanded number of university atmospheric sciences departments in the United States, meeting the needs for professionals in the field at that time (http://www.ametsoc.org/EXEC/TenYear/figs.html). Table 2-1 provides a number of indices for the growth in the atmospheric sciences research community. It is difficult to pin down the exact size of the community because of its diversity, but the table illustrates the signifi-

TABLE 2-1 Overview of Trends in Demographics and Research Support in the Atmospheric Sciences

Year	Number of UCAR Member Institutions[a]	Number of Atmospheric Science Ph.D.'s Granted[b]	Number of AGU Meteorology Section Members[c]	Number of AGU Atmospheric Science Section Members[c]	Number of AGU Space Physics & Aeronomy Section Members[c]	Number of AMS Members[d]	Total Annual for NSF Support Atmospheric Science (millions of 1996 dollars)
Late 1950s	14	10	1,700 (in 1958)	—	—	7,000	16.3 (in 1958) 53.9 (in 1959)
1976-1980	46	84	—	1,600[e]	1,610[e]	9,000	119
1996-2000	68	133	—	5,300	3,430	12,000	144

[a] Data from NAS-NRC (1958), University Corporation for Atmospheric Research (UCAR) archives for 1976-1980, and UCAR Web site for 1996-2000
[b] Data from the NSF Science Resource statistics.
[c] Data provided by American Geophysical Union (AGU). In the late 1950s, atmospheric science, space physics, and aeronomy were all grouped into a meteorology section. Note that approximately 30 percent of AGU membership in recent years is from outside the United States.
[d] Data from http://www.ametsoc.org/EXEC/TenYear/figs.html; the membership of the American Meteorological Society is distributed almost equally among the private, public, and academic sectors.
[e] Averages are for 1978-1981.

cant expansion of educational efforts, professionals, and research funding over the past four decades.

The size of the research workforce in atmospheric and related sciences seems to have been leveling off since the 1990s because of lower interest in the physical sciences, the growth of research programs overseas, and movement of some of the Ph.D. population to the private sector (Hoffer et al., 2001; Vali et al., 2002). On average, 133 atmospheric science doctorates were awarded annually in the late 1990s.The number of applicants to atmospheric science graduate programs declined between 1995-1996 and 1999-2000 (Vali et al., 2002), but increased slightly as of the 2002-2003 academic year, the most recent year with available data (Vali and Anthes, 2003). In the coming years, there is a projected shrinkage of the science and engineering research labor pool through retirements (NSB, 2002) coupled with a projected growth in science and engineering career opportunities. It is not clear exactly how these trends for physical sciences and engineering might broadly impact the atmospheric sciences.

Note that not all atmospheric scientists are trained in atmospheric science, meteorology, astronomy, or Earth science departments. In particular, atmospheric chemists and cloud/aerosol microphysicists may be enrolled in chemistry, physics, applied science, chemical engineering, aerospace/mechanical engineering, civil/environmental engineering, or public health programs. Aeronomers and other near-space scientists may be trained in physics, chemistry, or electrical engineering departments. Those who study marine meteorology or interactions between the atmosphere and the ocean may enroll in marine science departments. ATM supports research in all of these academic enclaves.

Along with efforts to increase the size of the atmospheric sciences workforce, the meteorological community worked to make the production and communication of weather information more professional (NRC, 2003). Private-sector meteorology began in earnest in this country shortly after the end of World War II, when several thousand meteorologists trained to support the massive aviation activities of the U.S. armed forces left government service eager to apply their newly acquired skills (Mazuzan, 1988). The Weather Bureau made the decision to permit its weather data to be used by the emerging private sector, and the first group of private meteorological companies began operating in 1946. The emerging television industry was a natural outlet for weather information and forecasts, and the decision by the Weather Bureau that government employees would not provide television weathercasts prompted the development of an influential component of the private sector—broadcast meteorology—as well as competition among weather information providers to develop better visualizations and other products for the weathercasters. The American Meteorological Society (AMS) started its Board on Broadcast Meteorology in 1957 to encourage more science-based programming, with the first AMS Seal awarded in 1960 (*www.ametsoc.org*). Today, there are over 250 private meteorological companies in this country providing operational forecasts, consulting services, data services, and research and development.

The community of atmospheric scientists in the United States has long included significant participation by individuals from other nations. In recent decades, students have come to the United States to train; the number of foreign-born graduate students in physical sciences and engineering has increased both in absolute numbers and as a percentage. Growth continued into the mid-1990s, when it reversed (Hoffer et al., 2001). The downturn is related to the increase in opportunities for university training abroad (NSB, 2003) and, since 2001, there have been modest impacts on graduate school enrollments from increased restrictions for foreign students traveling to the United States (NRC, 2005).

SCOPE AND CROSS-DISCIPLINARY APPROACH

NAS/NRC (1958) anticipated the necessity for atmospheric research to involve other disciplines, recognizing that specialists in physics, mathematics, chemistry, and engineering should join meteorologists in the new NCAR. Indeed, around 1960, NSF agreed to include the High Altitude Observatory in the new NCAR, as a condition of Walt Roberts' becoming the first NCAR director, creating a partnership between NSF's Division of Astronomical Sciences and ATM in funding solar physics that continues today. The definition of cross-disciplinary research for atmospheric sciences has expanded substantially over the past 45 years to include biology, oceanography, economics, and societal impacts in current research. Some of the highest impact and most transformative atmospheric research has taken place at disciplinary boundaries, including the discovery of and research on chaos theory, stratospheric ozone depletion, and climate change. Major efforts in climate modeling have depended upon cross-disciplinary connections.

Many challenges remain. Physical science is not a solved problem, and there is a growing need for a better understanding of, for example, the linkages between chemistry, cloud microphysics, and climate; the linkages between oceans and the atmosphere; and the relationship between climate and ice dynamics, including the key challenge of changes in the crysophere. In addition, cross-disciplinary aspects of the coupling between the atmosphere and the land surface, including the biosphere and the carbon cycle, remain areas of focus. Studying the climate also presents challenges to standard NSF funding mechanisms because of the long timescales of many of the phenomena. Emerging science linking economics and societal impacts is of great interest, but it also represents the greatest challenge insofar as its maturity and readiness must be balanced with its potential. Finally, aggressively pursuing cross-disciplinary research runs the risk of diverting funding from or diluting discipline-specific research.

Several members of the committee, as well as many members of the broader atmospheric research community who provided input to the study, recounted anecdotal information suggesting that some cross-disciplinary research is falling between NSF's programmatic boundaries. These programmatic boundaries exist both within ATM (e.g., support for projects that straddle climate and weather research questions) and between ATM and other NSF divisions. The difficulties that exist are with finding the right program to support cross-disciplinary research projects and in harmonizing the reviews from experts in different fields. ATM leadership stressed that they collaborate with their colleagues in other divisions to support cross-disciplinary proposals and work with principal investigators (PIs) to identify funding opportunities. The committee believes, however, that more needs to be done to foster cross-disciplinary research. This problem cannot be solved by ATM alone, but requires also a commitment from the rest of NSF. Indeed, a recent report by the National Academy of Public Administration recommended that NSF ensure that information about interdisciplinary research opportunities and criteria for reviewing interdisciplinary proposals are clearly communicated to investigators (NAPA, 2004).

Effective identification of cross-disciplinary opportunities and related funding mechanisms are critical to the health of the atmospheric sciences.

Finding: Research questions in the subdisciplines of atmospheric science are interrelated. Further, many are connected to those in other scientific disciplines, such as oceanography, ecology, terrestrial science, solar physics, and social science. In some cases, the science questions extend beyond the boundaries of ATM or NSF's Geosciences directorate. ATM does make efforts to foster cross-disciplinary research, for example, by partnering with other divisions to support individual proposals or jointly soliciting proposals on a topic that falls at their interface. Yet, some research questions that fall at the interface between two or more disciplines can challenge NSF's funding structures even when evaluations show these to be prime opportunities for scientific advancement. Examples of the challenges faced in cross-disciplinary science include the need to address the water cycle, biogeochemical cycles, paleoclimate, air-sea fluxes, and health impacts of atmospheric oxidants and fine particles. Improving opportunities for cross-disciplinary research will require commitments from ATM and other NSF divisions that support related research.

Recommendation: ATM should work to reduce institutional barriers within NSF to appropriate cross-disciplinary research.

INFORMATION TECHNOLOGY AND COMPUTATIONAL MODELING

The extraordinary evolution in information technology over the past 50 years has had a huge impact on the atmospheric sciences. Roughly speaking, computational capability has advanced at nearly a 100-fold per decade throughout the entire time period. Associated with this are increases nearly as great in internal memory, data storage, and data transfer. The advent of the Internet has served to connect the community in unprecedented ways, and presently allows practical exchange of vast amounts of information. These changes have allowed an entirely new dimension of research—that of simulation and prediction—to join theory, observation, and analysis, in underpinning the science. Numerical weather and climate "experiments" may now be conducted in an environment that can be controlled in ways not available naturally, and in great numbers compared with what can be observed in nature. Computational models allow a new means to learn, as well as a new means to harness existing knowledge, toward the development of the best possible operational and research products.

Meteorological analysis itself has undergone a dramatic advancement due to technology development. Today, it is a trivial matter to apply sophisticated multivariate statistical techniques to huge datasets consisting of millions of elements, in order to identify relationships and recurrent patterns to be studied and understood physically.

The field of data assimilation has emerged, and has become a critical part of both research and operational prediction. Data assimilation lies at the intersection of analysis and simulation. It is one of the most demanding and resource-intensive aspects of modern weather prediction. Today's methodologies provide optimized analyses of observations in the context of a prediction model. Such analyses were not possible even a decade ago and have led to significant improvement in prediction skill. The concept of climate "reanalyses," that is, analyses of past observations using current models and assimilation methodologies, is relatively recent but has provided extremely important products for research (despite known difficulties).

The use of computer simulations as a tool to understand the space environment has grown markedly in the past two decades. Models have been developed to study aspects of the solar interior and to reproduce aspects of the sunspot cycle. Simulations of Earth's magnetosphere and the interaction with the solar wind are now able to reproduce real events and, in the future, will be able to provide predictions of space environmental conditions. The NSF has funded a Science and Technology Center, the Center for Integrated Space Weather Modeling (CISM) that is developing a set of coupled codes extending from the surface of the Sun to the upper atmosphere of Earth. Techniques developed in tropospheric weather modeling, particularly data assimilation, are increasingly being used in space physics. For example, the Space Environment Center (SEC) specifies the total electron content over the United States in near real time using such a data-assimilation-driven model. ATM has also supported community access to space physics models by providing partial support to the interagency Community Coordinated Modeling Center, where users can request specific model runs and visualize the results.

OBSERVATIONS: TECHNOLOGY DEVELOPMENT AND EMERGENCE OF FIELD PROGRAMS

Atmospheric research, operations, and products rely heavily on observations of the state and composition of the atmosphere, oceans, and land surfaces. Evolution of our understanding and forecast capabilities have been associated in part with new measurement capabilities resulting from new sensors, new observing platforms, and systems of instruments within networks. Automation for remote observations, reduction in size of instrumentation, computational processing, easy access to data and information, new signal processing capabilities for analysis and visualization have provided us with the tools to produce science products for research, operations, and user information services.

Major advances in technology since 1950s include satellite observing platforms and instrumentation; new Doppler radars for the lower and upper atmosphere; and the ability to measure processes, not just state variables. Satellites have led to great improvements in the study of evolving weather patterns and the distribution of atmospheric pollutants, especially in data-sparse regions. The development and implementation of satellite-based observing platforms has largely been the purview of NASA and NOAA, while ATM has been the primary funding source for non-space-based platform instrumentation development. A major portion of the NSF-supported instrument development has taken place at NCAR, where a major, centralized national facility was formed. This facility consists of unique observing systems and platforms otherwise not readily accessible to NSF-sponsored PIs because they would be difficult for any single university person or group to develop. The observing systems are supported for field programs by the NSF deployment pool.

Major technical achievements in incoherent scatter radars along with the siting of these radars in a longitudinal network have enhanced process understanding of geomagnetic storms, Sun-Earth connections, and ionospheric disturbances. Combined with models, these technical advances have provided the framework for space weather forecasting. A variety of smaller upper-atmosphere radars have emerged, providing sometimes the only observational information on the dynamics of the neutral mesosphere-lower thermosphere, leading to major revolutionary thinking about the theory of circulations in the upper atmosphere. Associated optical instrumentation development, especially resonance and Rayleigh-scatter lidars, has led to new measurements of chemical constituents in the upper atmosphere.

The development of compact, robust, highly sensitive real-time trace-species and fine-particle sensors, many based on spectroscopic or mass spectrometric measurements, has allowed the deployment of multisensor suites on mobile platforms (aircraft, balloons, ships, vans) capable of mapping ambient atmospheric pollutant concentrations and characterizing surface sources and sinks (Kolb, 2003). The development of fast trace-gas and fine-particle sensors has also enabled the direct measurement of surface emission and deposition fluxes, using micrometeorological techniques from flux towers and low-altitude aircraft.

Typical atmospheric observational studies have involved a mix of routinely available measurements and those collected as part of a field program. Since the 1950s, the level and sophistication of routinely available observations has expanded. The U.S. Weather Service modernization provided improved radar coverage starting in the 1990s. Longer-term field campaigns, such as the DOE Atmospheric Radiation Testbeds, have provided continuous streams of measurements in the central United States, the Pacific, and Alaska. The Tropical Ocean and Global Atmosphere-Tethered Atmospheric Observing Systems (TOGA-TAOS) array provides surface atmospheric and oceanic data from the tropical Pacific. Starting in the 1990s, the U.S. commercial aircraft fleet started sampling temperature and wind, and humidity measurements are now being taken. Satellite data supply a rich mix of data that characterize the surface, ocean currents, atmosphere, thermal stratification of the atmosphere, cloud cover, tropical precipitation, aerosol distribution, and trace gas concentrations. Assimilated into numerical models, these data can provide a reasonably good picture of the systems that provide our day-to-day weather and motions of longer time and spatial scales, particularly over land, especially over the developed nations. Providing a framework for analyzing historical data are up to four decades worth of dynamically consistent data produced by reanalysis efforts.

In recent years, the importance of climate change in the atmospheric sciences has created new observational demands for monitoring of the atmosphere, in particular, for sustained observations with global coverage. Satellite-based observations have provided major advances, but suffer from lack of continuity and related problems of calibration among instruments, necessitating continued investment in, and use of, *in situ* platforms. The need for enhanced monitoring overall requires continued attention to the development of instruments that are more robust, numerous, lightweight, easily deployable and maintained, and less expensive. NASA and NOAA are major players in the monitoring arena, but further work in this area is needed to ensure an adequate future climate observing system (NRC, 1998, 1999).

Although operational and monitoring data are often sufficient to study larger-scale motions, field programs are needed for coordinated additional measurements to address specific questions regarding atmospheric processes not resolved by models, and requiring measurements not routinely made. Making instruments and platforms available to the community to make these measurements was a major reason for the establishment of NCAR. Many important field campaigns over the past 45 years have been relatively small, involving fewer than a dozen investigators and focusing on short-term atmospheric processes over a relatively limited geographical area.

In 1974, ATM and NCAR were major players in the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE)—the first

TABLE 2-2 Recent Large ATM Field Projects (Over $1 million in facility deployment costs)

Description of Field Program	Estimated Support from NSF Grants
The **first Aerosol Characterization Experiment (ACE-1)** in FY 1995 was the first of several experiments to characterize the chemical and physical processes controlling the evolution and properties of atmospheric aerosols and radiative climate forcing. NOAA and Australia also provided facilities.	$5.0 million
The **Surface Heat Budget of the Arctic Ocean (SHEBA)** in FY 1998 was a multiagency program supported by NSF's Arctic System Science Program. Its goal was to acquire data on pack ice that covers the surface of the Arctic Ocean. The study involved many research facilities, including ones from DOE, the Office of Naval Research, and Japan.	$15.0 million
In FY 1999 the **Indian Ocean Experiment (INDOEX)** addressed natural and anthropogenic climate forcing by aerosols and feedbacks on regional and global climate. Participants contributed research facilities from U.S. agencies, Europe, India, and island countries in the Indian Ocean.	$5.0 million
The **Mesoscale Alpine Experiment (MAP)** was an FY 1999 coordinated international effort to explore the three-dimensional effects of complex topography. The goal was to combine advances in numerical modeling with those in remote observing technology. Researchers and facilities from 12 countries were active participants. NOAA and several countries also provided research facilities.	$7.5 million
Tropospheric Ozone Production About the Spring Equinox (TOPSE) was an FY 2000 study that investigated the chemical and dynamical evolution of tropospheric chemical composition over continental North America during the winter-to-spring transition. Ozone budget, distribution of radical species, sources and portioning of nitrogen compounds, and composition of volatile organic carbon species were determined. NASA, Canada, and numerous universities provided research facilities.	$2.8 million
Eastern Pacific Investigation of Climate (EPIC) was conducted in FY 2001 to address processes that determine the nature of deep convection in and near the East Pacific Intertropical Convergence Zone; the evolution of the vertical structure of the atmospheric boundary layer; and how sea-air coupling affects ocean mixed-layer dynamics and sea surface temperature in the East Pacific warm pool. NOAA and Mexico also provided research facilities.	$5.5 million
ACE-Asia, conducted in FY 2001, focused on climate forcing caused by aerosols over eastern Asia and developed a quantitative understanding of the gas/aerosol particle/cloud system. NASA, NOAA, DOE, the U.S. Navy, Australia, Japan, China, France, the United Kingdom, and Korea also provided research facilities.	$8.0 million

continues

TABLE 2-2 Continued

Description of Field Program	**Estimated Support from NSF Grants**
The **Maui Mesosphere and Lower Thermosphere (MALT)** campaign started in FY 2001 and continues today. It is using nested instrumentation with the 3.7-meter-diameter telescope at the Maui Space Surveillance Complex to study dynamical coupling between the mesosphere and the lower thermosphere. The Air Force Office of Scientific Research also supports this field campaign.	In FY 2005, 5 awards and 1 supplement totaling ~$1 million
The **International H_2O Project (IHOP_2002)** in FY 2002 examined the moisture tracks that fuel large convective storms in the Midwest, to better understand when and where these massive storms form and how intense they will be. NOAA, NASA, France, and Germany provided research facilities.	$6.4 million
Bow Echo and MCV Experiment (BAMEX) in FY 2003 studied the life cycles of mesoscale convective storm systems. The study combined two related programs to investigate bow echoes, especially those that produce damaging winds, and larger convective systems that produce long-lived mesoscale convective vortices. NOAA and Germany also contributed research facilities.	$3.6 million
The **North American Monsoon Experiment (NAME)**, an FY 2004 joint Climate Variability and Change (CLIVAR) and Global Energy and Water Cycle Experiment (GEWEX) project, was aimed at determining the sources and limits of predictability of warm-season precipitation over North America. The project focused on the key components of the North American monsoon system and its variability within the context of the evolving land surface-atmosphere-ocean annual cycle. NOAA and Mexico also contributed research facilities.	$3.6 million
The **Rain in Cumulus over the Oceans (RICO)** project was completed in January 2005. Its objective was to characterize and understand the properties of trade-wind cumulus clouds at all spatial scales, with special emphasis on determining the importance of precipitation. University of Wyoming provided research facilities.	$3.8 million

large, international field program—by providing three aircraft and significant support in planning and logistics. Since GATE, the number of large and multinational field programs addressing tropospheric research questions has multiplied (e.g., see Table 2-2). Many current lower-atmosphere field programs address a broader spectrum of disciplines (e.g., oceanography, soils, ecology, hydrology, and chemistry), and there is pressure to extend to longer timescales, largely in response to increased focus on climate issues and biogeochemical cycles. More frequent field campaigns and more large field programs now compete for resources. Also, leadership in large international field campaigns is shifting toward countries outside the United States, such as the African Monsoon Multiscale Analysis Experiment, which is sponsored by the European Union (EU) and led by scientists in France, and the Atmospheric Brown Clouds project sponsored by NOAA and the United Nations Environment Programme (UNEP) and led by German and U.S. scientists.

The upper-atmospheric research community also conducts field campaigns, often planned around fixed observing facilities, such as is the case for the Maui Mesosphere and Lower Thermosphere (Maui MALT) campaign. There have also been a series of field campaigns over the past two decades that have been supported by both monthly World Day observations and longer periods of continuous observations by the network of incoherent scatter radars.

Numerical modeling has played an increasingly important role in developing observational strategies and subsequent data analysis. Starting in the 1970s, numerical modelers influenced the location, type, and frequency of observations; the design of field programs to test parameterization schemes for moist convection; and the forecasts used for measurement strategy. Now, the roles of models and observations are intimately entwined, with much more specific and useful guidance in more challenging forecast scenarios. Aircrafts may be deployed to fill in a data void that a set of numerical simulations shows is a source of forecast uncertainty, or direct a group of platforms to where convective storms are likely to originate. Finally, detailed datasets are assimilated into models to provide a more complete picture of the phenomenon being studied.

INTERNATIONAL RESEARCH ENVIRONMENT

It has long been realized that, because the atmosphere is global in extent, the meteorological discipline should span national boundaries. An International Meteorological Organization was founded in 1873 and was succeeded in 1950 by the World Meteorological Organization (WMO) organized under the umbrella of the United Nations. The WMO has fostered international cooperation on operational weather observations, for example, to ensure global coverage from satellite-based observations of the atmosphere, and has advocated free and open exchange of weather data. This cooperative international perspective has resulted in the recent establishment of international agreements for the development of a Global Earth Observing System of Systems (GEOSS; http://earthobservation.org/) and through international collaboration on the development of new research programs such as the World Climate Research Programme's (WCRP's) Coordinated Observation and Prediction of the Earth System (COPES; http://copes.ipsl.jussieu.fr/index.html), which recognizes that "there is a seamless prediction problem from weather through to climate timescales, the necessity to address the broader climate/Earth system and the increasing ability to do this, [and] new technology for observations and computing."

Many of the major field programs over the past 50 years have involved international coordination (e.g., see Table 2-2), and several international organizations have been established to facilitate coordination of observational and other research efforts. WMO coordinated international atmospheric research programs in the past, participating in the International Geophysical Year (1957-1958), establishing a Tropical Cyclone Project in 1971, carrying out GATE in 1974, and coordinating the GARP Global Weather and Monsoon Experiments in 1978-1979. GATE provides a good illustration of the potential complexity of international atmospheric research: it involved 40 research ships, 12 research aircraft, many moorings, and 72 countries. The WCRP was established as a successor to GARP by WMO, the International Council for Science (ICSU), and the Intergovernmental Oceanographic Commission. The WCRP has organized a succession of large projects, including the TOGA program running from 1984 to 1995; the GEWEX, which continues today; the international CLIVAR program; the study of Stratospheric Processes and Their Role in Climate (SPARC); the World Ocean Circulation Experiment (WOCE); and the Arctic Climate System Study (ACSYS).

The International Geosphere-Biosphere Programme (IGBP) was established by ICSU to coordinate research activities on "the interactive physical, chemical and biological processes that regulate the total Earth System, the unique environment that it provides for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions" (http://www.igbp.kva.se/). Of particular relevance to atmospheric science, IGBP activities include the International Global Atmospheric Chemistry (IGAC) project, the Integrated Land Ecosystem-Atmosphere Processes Study (iLEAPS), and the Surface Ocean-Lower Atmosphere Study (SOLAS). In addition, IGBP has initiated two studies to examine the Earth system as a whole: (1) Analysis, Integration and Modeling of the Earth System (AIMES), which focuses on improving our understanding of the role of human perturbations to the Earth's biogeochemical cycles and their interactions with the coupled physical climate system; and (2) PAGES, which is focused on understanding past climate changes.

Several activities act to coordinate modeling internationally. In part, these collaborations are directed at the assessment of climate change under the Intergovernmental Panel on Climate Change (IPCC). However, it also fosters a joint effort on improving numerical models of the atmosphere and parameterizations in these models of atmospheric processes both under the aegis of international research programs such as GEWEX (e.g., the GEWEX Cloud System Study effort) and CLIVAR and by bringing operational weather and climate modeling centers together. U.S. scientists work closely with scientists from other countries for the model computation, data analysis, and model/data synthesis used to characterize the science included in assessments (e.g., IPCC, 2001) and WMO/UNEP ozone assessment reports (e.g., WMO, 2003). Models, satellite observations, and computing resources are shared across national boundaries. Atmospheric sciences has led the development of Earth system models which couple climate, oceans, land, and atmospheric chemistry, geology, and biogeochemistry. Earth system model development is now going on around the world with France, Germany, Japan, the United Kingdom, and the United States playing important roles. Many model runs are now done using ensembles of models and initial conditions to characterize uncertainties in our understanding. Model and data comparisons rely on data collected around the globe and on observational programs that are coordinated and shared internationally. Groups organized under the WCRP and WMO focus on the development and evaluation of models, for example, numerical techniques and intercomparisons of models is the focus of the Working Group on Coupled Modeling (WGCM). Expanding coordination of modeling activities, forecasting, archiving of model output, and exchange of data is crucial for atmospheric sciences.

The space environment affects the entire globe, so it is not surprising that ATM research initiatives in solar-terrestrial science have a significant international dimension. The National Space Weather Program, in addition to the interagency cooperation, maintains links and collaboration to similar programs in other countries. The National Space Weather Program Implementation Plan (July 2000) specifically calls for collaboration with entities such as the International Space Environment Service and the European Space Agency. This has led participation in workshops on space weather, such as the December 2004 European Space Weather Week, which was modeled on the highly successful annual NOAA SEC conference. The SuperDARN network of incoherent scatter radars in both the northern and southern polar regions is another example of international collaboration on the part of ATM in the area of solar-terrestrial science. Likewise, ATM is one of 22 institutions supporting the Advanced Technology Solar Telescope under the leadership of the National Solar Observatory. ATM has also provided financial support for the International Coordination Office for the Scientific Committee On Solar-Terrestrial Physics-Climate and Weather of the Sun-Earth System (SCOSTEP-CAWSES) Program.

The U.S. atmospheric research community works within this international, intergovernmental fabric. Large research programs are discussed, planned, and approved years in advance of their going into the field. Data collected in these programs are coordinated and shared internationally. Analysis and modeling activities are also often coordinated by the U.S. and international steering and oversight groups of these large programs, such as CLIVAR, that work under the supervision of the WCRP. This advanced and increasing level of coordination across the nations has many benefits to all participants. However, it also creates the need for the U.S. funding agencies to make, or to the extent possible, commitments of facilities, research funding, and researchers on timetables constrained by the multiple, interlocking activities of U.S. and international atmospheric scientists.

Many large international field programs are developed by international bodies, the projects of the WCRP and IGBP being especially notable in this regard, and U.S. participation is often vital to the success of these field programs. This presents a challenge to ATM because they receive proposals from U.S. investigators to participate in these field programs and, in many cases, significant budgets are involved, but at the same time the ATM budget remains relatively flat. ATM has tried to cope with this situation by knowing when such large international field programs will occur and to anticipate that some of their overall budget will be used to support the participation of U.S. investigators in these programs. There are also demands on ATM investigators to produce large numbers of IPCC climate model runs, and the NSF participation in this mainly involves NCAR staff. ATM has approached this situation in a largely ad hoc, but reasonably successful, manner so far. It is not clear that this ad hoc approach will be desired in the future when pressures on ATM funding will likely increase. There are also benefits to ATM having a more transparent procedure for deciding these international coordination issues in that U.S. investigators and international bodies will more fully understand the basis for ATM funding decisions that affect them and can plan accordingly.

The United States has been a leader in supporting atmospheric research over the past decades, but recent years have seen increasing investments, sophistication, and leadership from other nations as well. The European Union and other countries are more frequently initiating and leading major field programs. Many U.S. capabilities for observing and modeling the atmosphere and climate are matched or exceeded by Europe, the United Kingdom, and Japan. Some key examples of advances include the EU Framework programs such as ENSEMBLES, Japan's Frontier Research System for Global Change, and the European Space Agency satellite SCIAMACHY. This shift provides opportunities to leverage investments by ATM with those of other nations and also creates challenges in terms of coordinating facilities and other resources for joint studies. Indeed, the role for ATM will vary depending on the international program, ranging from taking on a leadership role or supporting international program offices to contributing to programs led by other countries.

A more strategic approach is needed to facilitate international coordination.

Finding: The atmosphere knows no national boundaries; thus, international collaboration is critical to the study of the atmosphere. The research capabilities of other nations are becoming more sophisticated and their investments in the atmospheric sciences are growing. There is a breadth of atmospheric research coordinated internationally through organizations such as WCRP, IGBP, WMO, and SCOSTEP. Often, these international efforts address broad cross-disciplinary research agendas. ATM has been extensively involved in international efforts, but U.S. participation has been largely on an ad hoc basis. It is not clear that this ad hoc approach is desired in the future when pressure on ATM funding will likely increase. A proactive and judicious mechanism, including the ability to commit with long lead time the participation of U.S. facilities and investigators, is needed for a coordinated, efficient, and effective participation in international programs. Such a mechanism would help U.S. investigators and international bodies more fully understand the basis for ATM funding decisions and hence plan accordingly. In particular, this mechanism would be useful for evaluating potential ATM involvement in international field campaigns; in this case, existing international bodies (such as WCRP, the World Weather Research Program, and WMO) could help determine the merits of potential field campaigns.

Recommendation: ATM should develop systematic and clearly communicated procedures for tracking international program development, identifying potential ATM contributions, committing resources where appropriate, and reevaluating participation in international activities at regular intervals.

EDUCATIONAL ACTIVITIES

Each mode of support employed by ATM provides some resources for educational activities (see Table 2-3). Most of ATM's support of science education is accomplished through traditional research grants, which allow undergraduate and graduate students and postdoctoral scientists to participate in research efforts directly. NSF-wide and ATM-led initiatives also support a wide range of other educational activities. At the NSF-wide level, the Research Experiences for Undergraduates (REU) program provides support for undergraduates in individual projects as well as special REU summer-site programs. NSF supports graduate students through the NSF Graduate Research Fellowship Program. ATM also provides scholarships through the American Meteorological Society and postdoctoral fellowships through UCAR.

A number of educational efforts are organized through UCAR and NCAR. A prime example is the effort to bring underrepresented minorities into the atmospheric sciences through the Scientific Opportunities in Atmospheric and Related Sciences (SOARS®) program. SOARS® is dedicated to increasing the participation of African American, American Indian, and Hispanic/Latino students enrolled in master's and doctoral degree programs in the atmospheric and related sciences. ATM also supports a postdoctoral program through the Advanced Studies Program at NCAR. Additional educational and outreach activities, such as efforts to build digital libraries, are conducted by UCAR through partnerships with educational institutions to enhance formal and informal learning about the geosciences.

Many educational activities are undertaken as part of an individual grantee's project or as part of larger grants for small centers or university facilities. The former include involvement with K-12 students, special research and training opportunities for K-12 teachers or scientists who are involved in primarily under-

TABLE 2-3 Examples of Educational Activities Conducted Using Each Mode of Support

Mode of Support	Educational Activities
Single and multiple PIs	• Undergraduate and graduate student research through research grants • Postdoctoral research through research grants • REUs as separate PI-funded activity
Small centers	• Undergraduate and graduate student research • Postdoctoral research • Community education resources (e.g., CISM summer school) • Graduate student communities and mentoring • K-12 science education • Informal science education • Undergraduate education and course development
Large center (NCAR/UCAR)	• Advanced Study Program for postdoctoral researchers • Young Faculty Forum • Community-wide summer workshops • Meeting for heads and chairs of UCAR member departments • Visiting Scientist program • Sabbaticals from teaching • Cooperative Meteorological Education and Training (COMET) • SOARS® • Resources for graduate students
Cooperative agreements for university and other facilities	• Provide facility for graduate and undergraduate research • Provide venue for REU programs (MIT Haystack, Arecibo, CHILL Radar) • Make data available via the Web (e.g., radar data)
NSF-wide initiatives	• Provide resources for graduate research • Provide geoscience diversity initiative funded programs at a professional society (AMS) and a facility (Arecibo)
Interagency programs	• Provide resources for graduate research
International collaboration	• Provide resources for graduate research

graduate institutions, and public outreach activities. Examples of the latter include a two-week summer school in space weather phenomena, consequences, and modeling offered by CISM, and related summer programs are also held at the Arecibo Observatory and at the Millstone Hill Radar. Likewise, efforts associated with the CHILL Radar operated by Colorado State University give faculty and students the opportunity to explore technical and scientific topics in radar meteorology.

SOCIETAL RELEVANCE AND EXPECTATIONS

Atmospheric science has been deeply rooted in practical applications since its inception, so that the need for research to meet societal expectations and to lead to progress in operations has long been an organizing principle. Indeed, it is striking that many of the topics highlighted in the 1959 NAS/NRC report *Proceedings of the Scientific Information Meeting on Atmospheric Sciences* remain among the major focus areas for research and development, such as improvement of understanding and methods related to weather forecasting, pollution and its health effects, fire risk, droughts, agriculture, erosion, and water management, to name a few. Although a few topics identified in the 1959 report have so matured through technical advances that continued research is not as prominent a feature of the scientific landscape as it was in the past, these are the exceptions. Further, a number of topics have been added to the menu of societal concerns, particularly seasonal-to-interannual climate forecasting, global change, space weather, and atmospheric dispersion of chemical, nuclear, and biological contaminants.

The range of products that are needed and expected by an ever more engaged and broader public continues to expand and deepen, building upon the successes and development since the 1950s. It seems apparent that the public's interest in gaining access to the information relating to these topics has increased rapidly. Today's citizen makes greater demands on research to deliver a far larger number of user-oriented products. Examples include urban air quality forecasts, agricultural forecasts tailored to specific farming areas or crop types, as well as lightning detection systems to assist in fire risk evaluation. New warning systems, such as online access to hurricane and tornado forecasts, are also among the products that now enjoy large constituencies due to the availability of the Internet as well as the greatly improved capacity of scientists to provide increasingly accurate and ever faster response information, enhancing public safety. These are only a few examples of the many types of products that reflect the ever increasing pace of application of research to operations and products (NRC, 1998).

Society also expects more finely tailored and more types of information, provided in terms understandable to a broad audience. As scientific information and understanding has deepened on topics such as atmospheric pollution and climate change, there has been a far deeper appreciation of the policy relevance of atmospheric science for societal decision making. Indeed, the findings of atmospheric science have provided the cornerstones for policy measures such as the Clean Air Act, the Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments, and the Kyoto Protocol. Public interest in understanding how such policies work, the basis for their application and the impact they will have has led to an increasing demand for research organizations to provide summaries aimed not just at the policymaker and other scientists, but to a far broader range of audiences, including the public, local and state governments, industry, and the education sector.

Addressing broader impacts of research beyond advancement of knowledge has been an important thrust of NSF in recent years. All NSF grant proposals are evaluated in terms of their broader impacts, which include educational objectives, broadening the participation of underrepresented groups, enhancing the infrastructure for research, wide dissemination of research results, and benefits to society. The NSF-wide small-center programs (i.e., Science and Technology Centers and Engineering Research Centers have placed even more emphasis on education and outreach, as discussed in Chapter 3.

3

Modes of Support and Issues of Balance

In this chapter, each of the major modes of support employed by the National Science Foundation (NSF) that now contributes specifically to the atmospheric sciences—that is, grants to individual and multiple principal investigators (PIs), small centers, large national centers, cooperative agreements to support facilities at universities and other locations, NSF-wide initiatives, interagency programs, and field programs—is described and some preliminary analysis of their strengths and limitations are offered. The committee intends to provide a more detailed evaluation of the modes in its final report, in which the questions of which modes are best suited for meeting NSF's Division of Atmospheric Sciences' (ATM's) goals and how to determine an effective balance among the modes will be addressed. In addition, the final report will explore the applicability of modes that are not currently employed by ATM.

GRANTS

ATM supports academic atmospheric research principally through the proposal and peer review process for individual or multiple investigator grants. Table 3-1 shows proposal statistics for ATM as compared to the Geosciences Directorate (GEO) as a whole and to the NSF averages. The bulk of the approximately 300 NSF-funded ATM grants each year are to individual PIs (in many cases with co-investigators), mostly at universities. The number of grants awarded each year has increased slowly over the past two decades (Figure 3-1), but there has been little trend over this time period in the success rate for grant proposals, which has fluctuated around 40 to 50 percent for the division (Jarvis Moyers,

TABLE 3-1 ATM Research Proposal Statistics for FY 2003

	ATM	GEO	NSF
Submitted proposals	~800	~4,000	~40,000
Competitive awards	~300	~1,500	~11,000
Average annual award	$127,000	$147,000	$136,000
(in 1996 dollars)	($108,300)	($125,350)	($116,000)
Average duration	3 years	3 years	3 years

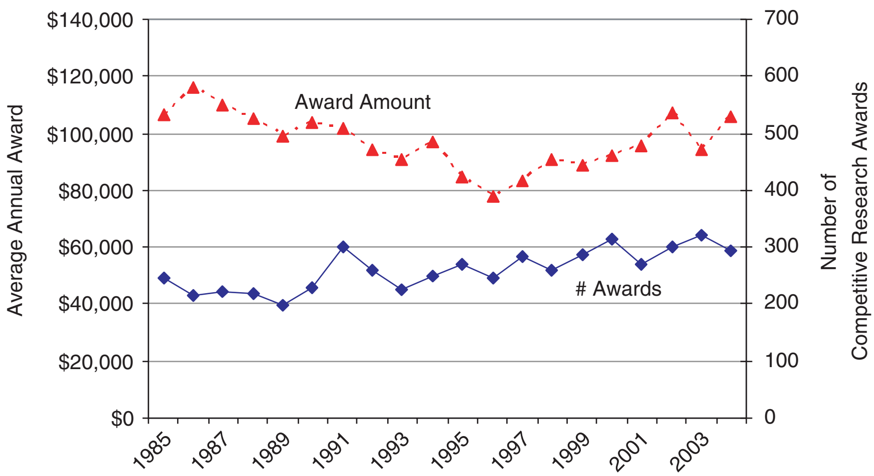

FIGURE 3-1 Trends in average annual awards (in millions of FY 1996 dollars) and number of grants awarded by ATM since 1985.

ATM, personal communication, July 22, 2005). Until recently, most grants were of three-year duration, but this has been changing slowly toward a larger number of four- and five-year grants.

The average annual amount of ATM awards to PIs is about $127,000 per year, although actual support to an individual PI may be less if the grant is awarded to multiple investigators or more if allocations of computing or observing facilities are included in the award. For university faculty members, this amount normally includes up to two months of summer salary; support for graduate students, undergraduate students, or both; miscellaneous expenses such as travel, computing, and page charges; and institutionally determined fringe benefits and indirect costs. Over the past 10 years, 570 graduate students, on average, have been supported by ATM research grants each year, constituting a large percentage of graduate students in atmospheric science departments. The funding is committed for the duration of the grant, contingent on adequate progress being demonstrated though annual reports. Funding of investigators in nonacademic institutions proceeds similarly.

Most grants are unsolicited; scientists with an idea for a research project send in a proposal which is then judged on the basis of scientific excellence and potential broader impacts, such as educational and other societal benefits. A small number of grants of limited scale and duration are awarded as part of the Small Grants for Exploratory Research (SGER) program, which is intended to promote investigation of more radical ideas. NSF and ATM also solicit proposals that address priority research areas or other specific objectives (e.g., Box 3-1). Often, these directed research programs respond to needs identified by the community, thereby alleviating the concern that investigators must shoehorn their proposals to meet research priorities that do not necessarily reflect community goals. This mechanism is used more prominently by the upper atmospheric section.

There are several grant programs directed at young faculty and underrepresented groups. For example, the NSF-wide Faculty Early Career Development (CAREER) and the Presidential Early Career Awards for Scientists and Engineers (PECASE) grants target young, tenure-track faculty investigators who have not yet been awarded tenure. The number of these early career grant proposals is relatively small in ATM because of the relatively small number of tenure-track faculty in the field. GEO has grant programs that seek to enhance demographic diversity, including targeted programs for historically black colleges and universities, for tribal colleges and universities, and for improving female and minority representation.

While NSF grants from ATM are important for private-sector research companies, they are crucial to the career of university faculty members. The more mission-oriented agencies (e.g., National Aeronautics and Space Administration [NASA], National Oceanic and Atmospheric Administration [NOAA], Department of Energy [DOE], Environmental Protection Agency [EPA], Department of Defense [DoD], and the Federal Aviation Administration [FAA]) support extramural research, but these funds are granted on the basis of mission relevance and scientific merit. Because NSF funding decisions are made primarily on the grounds of scientific excellence, there is a perception that success in obtaining NSF grants is considered more important to academic advancement.

Small science and technology oriented businesses can also apply for Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants through an NSF-wide solicitation each year (NRC, 2004). STTR projects must involve at least one small business and one not-for-profit research group, usually from an academic institution. SBIR and STTR grants, which receive about 2.7 percent of the NSF's extramural research budget, have funded the development and demonstration of a number of innovative instruments currently used in atmospheric research.

An increasing fraction of NSF grants are for multiple PIs collaborating on a larger-scale project (see Figure 3-2). In particular, multi-PI grants support model-

BOX 3-1
Focused Programs That Are Community-Driven

Ongoing Programs with an Annual Competition for Funding:
Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR) is a broad-based upper-atmospheric research program with the goal of understanding the behavior of atmospheric regions from the middle atmosphere upward through the thermosphere and ionosphere into the exosphere in terms of coupling, energetics, chemistry, and dynamics on regional and global scales.

The **Geospace Environment Modeling (GEM)** program supports basic research into the dynamical and structural properties of the magnetosphere. One of the objectives is the construction of a global geospace general circulation model with predictive capability.

Solar and Heliospheric Interaction (SHINE) research focuses on the connections between eruptive events and magnetic phenomena on the Sun and the corresponding solar wind structures in the inner heliosphere. The goal of SHINE research is to enhance both our physical understanding and predictive capabilities for solar-driven geoeffective events.

Earth System History (ESH) is a cross-divisional research program, which is managed by ATM's Paleoclimate Program Director. The program seeks to provide better understanding of Earth's paleoenvironmental system and its evolution over geologic time by (a) documenting the past temporal and spatial variability of the Earth system, (b) assessing the rates of change associated with this variability, and (c) determining the sensitivity of the Earth system to variations in climate-forcing factors.

The **Geoscience Education** program aims at initiating or encouraging innovative geoscience education activities. It specifically seeks projects that are informed by results of current education-related research or that conduct educational research with a geoscience education venue.

The **Opportunities for Enhancing Diversity in the Geosciences** program supports activities that will increase the number of members of underrepresented groups that (a) are involved in formal precollege geoscience education programs; (b) pursue bachelor, master, and doctoral degrees in the geosciences; (c) enter geoscience careers; and (d) participate in informal geoscience education programs.

Recent Solicitations for Proposals on Targeted Topics:
The **Pilot Climate Process and Modeling Teams (CPT)** program was cosponsored by NOAA and NSF. The goal was to further the development of global coupled climate models by enhancing collaborations between theoreticians, field observationalists, process modelers, and the large modeling centers.

The **Water Cycle Research** initiative was intended to enhance innovative basic research contributing to the understanding of the water cycle and its function as a transport agent for energy and mass (water and biologically/geochemically reactive substances).

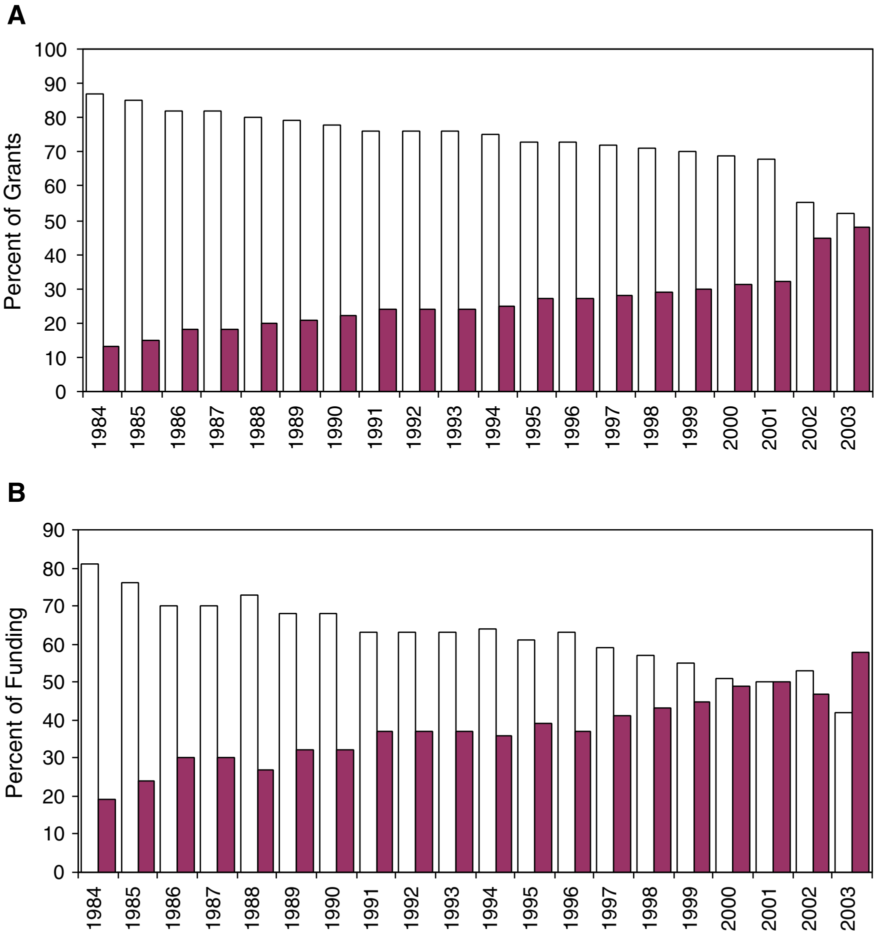

FIGURE 3-2 Percent of grants (top panel) and funding (bottom panel) awarded to single PIs (white) and multiple PIs (grey).

ing and measurement efforts. Atmospheric scientists have long recognized the value of collaboration (NAS/NRC, 1958) and are increasingly seeing the need to form teams that can access the multiple skills, tools, and facilities that are frequently required to plow new scientific ground. The demand on ATM for multi-investigator project funding is likely to continue to grow. An issue that arises as the scale grows is the ability for agencies to work together, and for agencies to coordinate with international partners, in the fostering and support of such programs.

Increasingly, advances in modeling capabilities rest on critical collaborations and shared infrastructure. Likewise, the increasing complexity and frequent multidisciplinary nature of atmospheric science measurements—including laboratory experiments, ground-based and airborne field measurements, and advanced research instrument development and testing—often require collaboration of two or more research groups to be addressed effectively. Atmospheric field measurements often need to be performed at one or more remote sites, may require complex logistics involving site access or mobile measurement platforms, usually require the simultaneous measurement of multiple physical and/or chemical parameters, and normally require significant modeling capabilities for proper analysis. All of these factors push the requirement for multiple-PI projects.

There is a synergy between ATM PI grants and National Center for Atmospheric Research (NCAR) programs for both individual and multiple PIs. Many NSF grantees use research tools developed and maintained at NCAR. These include numerical models, equipment, and computing. Also, there is a great deal of science collaboration between NCAR scientists, who are frequently unfunded co-PIs on grants, and PIs from universities or the private sector in the conduct of their research, including field programs.

This mode of core grant support has benefited the atmospheric sciences in several ways. First, it has enabled lots of good science. For example, grants to individual and multiple PIs have enabled the development of theory, analysis of observation and model results, process studies, provision of data to a broad suite of users, and development and acquisition of instruments by universities. Second, it has provided multiple options and flexibility in the ways ATM supports PIs, including unsolicited proposals, solicitation for new money that came in via various NSF-wide initiatives, ATM-initiated solicitations, and solicitations for field programs. This flexibility allows ATM to both encourage submission of proposals around specific themes and to encourage good ideas for proposals to be submitted at any time.

The NSF approach to reviewing and selecting research activities to support generally ensures that good science is funded and poor or mediocre science is not. A challenge to this approach is making sure to fund some science that is particularly innovative, high risk, and may have large potential payoffs. Such research efforts are more likely to fail, but also may lead to transformative discoveries. Whereas other federal agencies typically fund research directly related to their mission, NSF is the primary place where scientists turn for support of research that has no obvious applications or even a guarantee of success. Identifying proposals that fall into this category and ensuring adequate support for them has presented challenges for NSF as a whole, despite encouragement from NSF leadership to pursue innovation and risk taking (NAPA, 2004). Aside from those grants awarded through the SGER program, most proposals that might be considered high risk undergo the regular merit review process; thus it is unknown how much research of this sort is supported. Furthermore, because peer reviewers tend to be risk averse, particularly innovative proposals may not fare well when competing against regular proposals. NAPA (2004) found that NSF's support for high-risk research could be enhanced by better communicating opportunities for such support to the scientific community, perhaps through specialized calls for proposals; by modifying the review criteria used to evaluate proposals to place more weight on innovation; or by subjecting high-risk proposals to a specially designated review process.

Currently, ATM does not set aside any funds specifically for high-risk research, but program officers are encouraged to be receptive to such proposals that come in through the regular grant process. In some cases, awards are made despite the lack of reviewer endorsement, shorter-duration proof-of-concept awards are made, or ATM or GEO reserves are used to fund such activities. One example of such an action by an ATM program director took place in the early 1980s when Dr. Ronald Taylor put funding into the newly emerging area of the MST (Mesosphere-Stratosphere-Troposphere) radar. This action accelerated progress in this field so that we now have many such radars around the world collecting valuable data. ATM does not track how many grants are awarded for high-risk proposals, either through the regular grant process or through the discretion of the program directors, or the outcomes of the high-risk research that is funded. Some high-risk projects that are of limited duration and of modest cost are supported through the SGER program. No more than 5 percent of any NSF program can be used for SGER awards; in ATM, typically 1 to 2 percent of each program's funds are applied to SGER. It is not entirely clear to investigators what funding mechanisms are available for support of high-risk projects that are larger in scope than that which an individual program director could fund.

It is essential to preserve opportunities for high-risk, potentially transformative research.

Finding: Among federal science agencies, NSF is a leader in its commitment to support high-risk, potentially transformative research (excluding satellite instrument development). This type of research is instrumental in making major advances in the field, as well as in sustaining the nation's economic development and global competitiveness. Currently, program directors have discretion to use 5 percent of their budgets for SGER projects, though typically about 1 to 2 percent of each program's funds are applied this way. In addition, program directors can choose to support other high-risk work through regular grant mechanisms as they see fit. However, it is unknown to what extent this flexibility to support exploratory research is utilized. Furthermore, there may be some research questions of this type that require a bigger investment than what typically can be made by a program director. One option to be more effective is to pool some of the funding for exploratory research from all ATM programs and run an internal competition to which program directors can submit promising, high-risk ideas for consideration.

Recommendation: ATM should support high-risk, potentially transformative research at the current rate or a greater one, seeking new mechanisms to enhance opportunities for investigators, such as pooling some of the existing funding. The success of this effort should be evaluated every five years.

SMALL CENTERS

Over the past two decades, NSF has begun to employ a small-center mode of funding. This mode was initiated by the Engineering Directorate, which introduced Engineering Research Centers (ERCs) in the early 1980s. Subsequently, the Office of Integrated Activities created Science and Technology Centers (STCs), which are designed to enable innovative research and education projects of national importance that require a center to achieve significant research, education, and knowledge-transfer goals shared by the partners. ERCs and STCs are funded at the level of $2 million to $5 million per year. In addition, there are centers supported under the NSF-wide Information Technology Research (ITR) program and ATM supports some centers from core funds. Box 3-2 lists atmospheric science centers established over the past 15 years along with the science problems they are addressing. Because these centers are supported primarily by other parts of NSF, they provide an opportunity to expand the overall NSF level of support for atmospheric sciences.

The NSF Office of Integrative Activities supports 11 STCs. Competition for the class of 2005 is underway, with six to eight proposals to be selected. Two atmospheric-sciences-related STCs were awarded in the early years: the Center for the Analysis and Prediction of Storms (CAPS) housed at the University of Oklahoma and the Center for Clouds, Chemistry and Climate (C4) at Scripps Institution of Oceanography. Although CAPS and C4 have been sunsetted as STCs, support for the research initiated at these centers has continued because of successful competition for ATM core funding. The Division of Engineering Education and Centers supports 23 current ERCs, with 4 new centers expected to be funded in 2006. There have been a total of 41 centers since the program started in 1985, and the last competition for new centers was in 2003, with 3 funded. Currently, ATM is represented by one STC, the Center for Integrated Space Weather Modeling (CISM), and one ERC, the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA).

The STC and ERC programs provide participating investigators with long-term, relatively stable funding of sufficient size to tackle large problems. They involve the creation of large, interdisciplinary research efforts with targeted goals. Such a goal-oriented research focus, with milestones and metrics, is a different environment than the work of the individual PI. Stable funding benefits graduate students and postdoctoral fellows, and allows researchers to focus on key science issues that extend beyond the regular grant cycle for single and multiple PIs. With a recent trend of three to five years for grants to individual investigators, this advantage of centers may become less important.

BOX 3-2
Small Atmospheric Centers Supported by NSF

Center for Analysis and Prediction of Storms (CAPS) was an STC at the University of Oklahoma from 1989 to 2000, funded at a rate of $0.9 million to $1.5 million per year. The CAPS mission was the development of techniques for the computer-based prediction of high-impact local weather with operational Doppler radars serving as key data sources.

Center for Clouds, Chemistry and Climate (C4) was an STC spearheaded by Scripps Institution of Oceanography from 1991 to 2001, funded at a rate of $1.5 million per year. The goal of C4 was to develop theoretical, observational, and modeling bases required to understand and predict Earth's changing climate as affected by clouds, radiation, and atmospheric chemistry and their interactions.

Center for Integrated Space Weather Modeling (CISM) is an STC coordinated by Boston University, starting in 2002, funded at a rate of $4 million per year for up to 10 years. CISM consists of research groups at eight universities and several government and private nonprofit research organizations and commercial firms. The center's mandate is to construct a comprehensive physics-based numerical simulation model that describes the space environment from the Sun to the Earth, thus enabling reliable prediction of space weather events at least two days in advance.

Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) is an ERC led by the University of Massachusetts-Amherst, funded at a rate of $1.5 million to $2 million per year for up to 10 years. Established in late 2003, the center brings together a multidisciplinary group of engineers, computer scientists, meteorologists, sociologists, and industry and government representatives to conduct fundamental research, develop enabling technology, and deploy prototype engineering systems based on a new paradigm: distributed collaborative adaptive sensing. These networks are deployed to overcome fundamental limitations of current tropospheric observational approaches by using large numbers of appropriately spaced sensors capable of high spatial and temporal resolution.

Linked Environments for Atmospheric Discovery (LEAD) is an ITR program led by the University of Oklahoma and established in 2003. It is funded at a rate of $11.25 million for five years. The transforming element of LEAD is dynamic workflow orchestration and data management, which will allow use of analysis tools, forecast models, and data repositories as dynamically adaptive, on-demand systems.

Global Multi-Scale Kinetic Simulations of the Earth's Magnetosphere Using Parallel Discrete Event Simulation is an ITR project at the Georgia Institute of Technology to develop scalable, parallel, numerical models for the simulation of space plasmas and the dynamics of the Earth's magnetosphere, based on discrete event simulation (DES). The investigators will develop DES methods with situation-dependent physics, suitable for space physics problems, and then develop the algorithms required to execute these efficiently on massively parallel computer systems.

Tree Ring Reconstruction of Asian Monsoon Climate Dynamics is a new five-year collaborative project at Columbia University. The project will use the science of dendrochronology to examine the relationship between the Asian monsoon and the large-scale coupled processes that drive much of its variability.

In addition to their research objectives, STCs and ERCs have mandates to conduct education activities and to develop applications and knowledge transfer. The STCs and ERCs are required to spend approximately 20 percent of their resources on education and diversity programs, well beyond the requirements of other grants and agency requirements. Thus, the centers significantly broaden education resources. For example, CISM holds a two-week summer school that provides a broad-based exposure to space weather in the entire Sun-Earth system, which has proved to be very successful (Simpson, 2004). ERCs are specifically mandated to include minority-serving institutions in the team. STCs and ERCs also have to devote considerable resources to knowledge transfer—making the products of the research useful to users in the real world. For ATM, this has meant moving atmospheric or space weather predictive capability from research into operations (NRC, 2000).

LARGE NATIONAL CENTER

One of the mechanisms used by NSF for support of research is a large national center. Typically designated as federally funded research and development centers (FFRDCs), they provide for a larger aggregation of research capability than that which could ordinarily be expected to occur at an individual university department. The largest of NSF's FFRDC is NCAR, located in Boulder, Colorado. The University Corporation for Atmospheric Research (UCAR), a nonprofit consortium of 68 North American universities with graduate programs in atmospheric sciences, has managed NCAR since its founding in 1960 through a cooperative agreement with ATM. This structure was designed to foster interactions and joint management between NCAR and the university community.

The specific objectives for NCAR were laid out in the 1959 "Blue Book" authored by the University Committee on Atmospheric Research ("UCAR"; see Box 3-3). The critical mass of resources that NCAR brings to bear on the atmospheric sciences includes computational resources, aircraft resources, observational capabilities, laboratories, and machine shops. An additional objective was to provide a personnel base that could support large-scale research, including interdisciplinary research. The center would have sufficient support personnel to enhance the research environment. The initial planning for NCAR called for half the staff to be from the atmospheric sciences with the remainder being from disciplines such as physics, mathematics, chemistry, and engineering. This disciplinary composition has evolved since 1959 as demanded by new research avenues in the atmospheric sciences.

Today, NCAR has about 220 scientists, 100 associate scientists, and 620 support personnel (which encompasses everything from software engineers to administrative assistants) who conduct research in the atmospheric and ocean sciences and in solar and space physics, and participate in a suite of activities that support the broad community. As shown in Box 3-4, NCAR and its scientists

BOX 3-3
Four Compelling Reasons for Establishing a National Institute for Atmospheric Research Identified in the "Blue Book" ("UCAR," 1959):

1. The need to mount an attack on the fundamental atmospheric problems on a scale commensurate with their global nature and importance.
2. The fact that the extent of such an attack requires facilities and technological assistance beyond those that can properly be made available at individual universities.
3. The fact that the difficulties of the problems are such that they require the best talents from various disciplines to be applied to them in a coordinated fashion, on a scale not feasible in a university department.
4. The fact that such an Institute offers the possibility of preserving the natural alliance of research and education without unbalancing the university programs.

BOX 3-4
Overview of NCAR Organization, Activities, and Facilities

NCAR Organization:
Computational Information and Systems Laboratory*,* which houses the Institute for Mathematical Applications in the Geosciences and the Scientific Computing Division.

Earth Observing Laboratory (EOL), which includes the Atmospheric Technology Division (ATD) and the High-performance Instrumented Airborne Platform for Environmental Research (HIAPER). EOL maintains and deploys observational facilities for the lower-atmosphere research community.

Earth and Sun Systems Laboratory (ESSL), which houses much of NCAR's scientific research as well as its community models. ESSL includes:
- Atmospheric Chemistry Division
- Climate and Global Dynamics Division
- High Altitude Observatory (HAO)
- Mesoscale and Microscale Meteorology Division
- The Institute for Multidisciplinary Earth Studies
- The NCAR library

Research Applications Laboratory, which includes the Research Applications Programs, is involved in a spectrum of activities relating to technology transfer and application of new knowledge to practical use.

Societal and Environmental Research and Education Laboratory, including the Advanced Study Program, which offers postdoctoral positions that enable

continues

BOX 3-4 Continued

participants to explore the research areas of their choice, and the Institute for the Study of Society and Environment.

Strategic Initiatives are intended to bridge disciplines to advance Earth system science. Current initiatives include:

- Biogeosciences
- Community Spectro-Polarimetric Analysis Center
- Coronal Magnetic Fields
- Cyber Infrastructure
- Data Assimilation
- Education and Outreach
- Measurement of Winds and Temperatures in the Upper Atmosphere
- Geographic Information Sciences
- Megacity Impacts on Regional and Global Environments: Mexico City Pollution Outflow Field Campaign (MIRAGE-MEX)
- Software Framework Development
- Upper Troposphere-Lower Stratosphere
- Water Cycle Across Scales
- Weather and Climate Impact Assessment Science
- Wildland Fire Research and Developement Collaboratory

NCAR Activities:

- Community model development, maintenance, support, analysis, and dissemination (e.g., Community Climate System Model [CCSM], Whole Atmosphere Chemistry Climate Model [WACCM], MM5, Weather Research and Forecast [WRF] Model)
- Expensive large facility acquisition, maintenance, and support (e.g., aircraft, computers, Mauna Loa Solar Observatory [MLSO])
- Data storage and access
- Large field program logistical support in coordination with UCAR's Joint Office for Scientific Support (JOSS), part of which will move to NCAR in October 2005
- Long-term technology development, (e.g., Cross Chain LORAN Atmospheric Sounding System, Global Positioning System [GPS] Lower Atmospheric Sounding System balloon soundings, Solo radar editing and analysis software, flux towers, eye-safe lidars, instruments to observe the Sun, and community instruments)
- Virtual small centers to address larger interdisciplinary research questions, (i.e., Strategic Initiatives listed above)
- Major partner in support of small centers housed at universities, (e.g., C4, CISM)
- Intergovernmental Panel on Climate Change model runs

Lower-Atmosphere Facilities (EOL):

Aircraft

- HIAPER, high-altitude, long-range, high-performance Gulfstream V aircraft, starting January 1, 2006
- C-130, long-range, tropospheric, heavy-payload aircraft

Aircraft remote-sensing instrumentation

- ELDORA (ELectra DOpplar RAdar), 3-cm high resolution airborne Doppler radar, flown on a Naval Research Laboratory P-3 aircraft.
- Airborne imaging microwave radiometer
- Multichannel cloud radiometer
- Scanning aerosol backscatter lidar

Ground-based remote sensing

- Raman-shifted eye-safe aerosol lidar
- S-Pol

Surface and sounding systems

- Global Atmospheric Observing System (GAOS): Rawinsonde, housed in small trailer; employs GPS or LORAN-C navigation for winds
- Tethered Atmospheric Observing System: measurements on balloon tether
- Integrated Sounding System: GAOS, surface station, 915-MHz radar wind profiler, Radio Acoustic Sounding System (RASS) virtual-temperature profiler
- Multiple Antenna Profiler: enhanced 915-MHz radar wind profiler
- Integrated Surface Flux Facility: flux of sensible and latent heat, trace gases, and radiation; standard atmospheric and surface variables

Solar Facilities (HAO):

The **Mauna Loa Solar Observatory (MLSO)** takes long-term synoptic observations of the Sun and makes the data available to a worldwide community. The instruments at MLSO include:

- Advanced Coronal Observing System, which consists of three instruments that monitor the flow of plasma and energy from the Sun's chromosphere through its corona and into interplanetary space
- Precision Solar Photometric Telescope, which measures brightness on the solar disc
- Coordinated Helioseismic Observations (ECHO), in coordination with a second telescope operated by the Astronomical Institute of the Canaries at Tenerife, observes pulsations in the photosphere and low chromosphere, to monitor the Sun's energy budget in several important wavelength ranges

Advanced Stokes Polarimeter at the Dunn Solar Telescope at National Solar Observatory's Sacramento Peak site collects precise polarization measurements to infer the three-dimensional magnetic field and thermodynamic structure of the solar photosphere

Fabry-Perot Interferometer at the Early Polar Cap Observatory at Resolute Bay measures wind speeds in the mesosphere, and will be used to support the Advanced Modular Incoherent Scatter Radar (AMISR), which will be deployed at Resolute in 2006 support the broad community in many ways, ranging from model development to maintenance of observing facilities and data archives. These scientists collaborate in large research programs involving many institutions as well as with scientists who visit NCAR through various fellowship programs. In the initial conception, NCAR was to be involved in only basic research in "recognition that there is a need in atmospheric research for work to progress on a broader basis than that which is possible under the constraints imposed on applied research and development responsive to operational requirements" ("UCAR," 1959, p. 21). The programs at NCAR now include more applied research and transfer of the information, expertise, and technology developed to the public and private sectors; these efforts are often supported by other federal agencies. Indeed, about a third of NCAR funding comes from sources other than NSF (Figure 3-3). Furthermore, the recent undertaking of Strategic Initiatives, listed in Box 3-4, has aimed to enhance interdisciplinary approaches to major research questions in the Earth system sciences.

UCAR is a not-for-profit consortium of 68 universities that grant doctorates in fields related to atmospheric science. At its inception, UCAR consisted of a president who oversaw NCAR with the help of a small staff and the advice of a Board of Trustees, who were elected from among the two member representatives from each of the UCAR universities. UCAR's primary activity is managing NCAR, but in the past few decades, UCAR has grown considerably, providing its

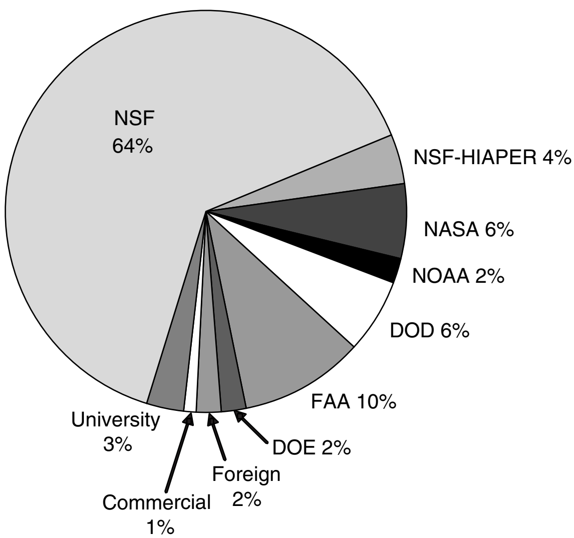

FIGURE 3-3 Sources of NCAR FY 2004 funding. Total funding was $138 million. Data provided by UCAR (Richard Anthes, UCAR, personal communication, July 22, 2005).

own "national center" services, often in coordination with NCAR (see Box 3-5). In particular, UCAR supports its university members through the UCAR Office of Programs (UOP), which provides real-time weather data, digital library services, training to forecasters, field research support, and other activities. The yearly budget (December 31, 2004 figures) was $210 million for UCAR; 27 percent of which went to UOP and 71 percent to NCAR. UCAR currently employs 1,472 staff, of which 36 percent work directly for UCAR and 64 percent are at NCAR. NSF provides 65 percent of the funding for NCAR/UCAR.

BOX 3-5
UCAR Activities Besides NCAR

The **UCAR Office of Programs**, whose portfolio includes:

- Unidata, whose function is "providing data, tools, and community leadership for enhanced earth-system education and research"
- The Joint Office for Science Support (JOSS), which arranges logistics for international conferences and complex field programs, helps conduct the field program, and archives the field catalog and data (note that on October 1, 2005, part of JOSS will move from UCAR to NCAR)
- The Cooperative Meteorological Education and Training (COMET) program, which trains forecasters from the National Weather Service, the military, and foreign weather services in the application of new research results and technology through face-to-face and distance-learning classes, in collaboration with University faculty and NCAR staff
- The Digital Laboratory for Earth Systems Education, which supplies datasets, imagery, and other educational resources to K-16 educators
- The National Science Digital Library, which is NSF's digital library for science, technology, engineering, and mathematics education
- The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) program supports collection of meteorological data using the Global Positioning System (GPS) network of satellites
- The Global Learning Through Observations for the Benefit of the Environment program, an international inquiry-based education and science program to provide K-12 students with authentic science experiences through taking and analyzing environmental science measurements
- Visiting Scientist Program, which provides opportunities for scientists to visit other institutions

Education and Outreach, which supports:

- Windows to the Universe Web site (http://www.windows.ucar.edu), which includes development of K-12 educational materials and professional development of K-12 educators
- SOARS®, a multiyear program to entrain promising minority students into the atmospheric sciences, using NCAR scientists as mentors

To some extent, it is difficult to differentiate between the roles of NCAR and UCAR. The two organizations work together to provide a range of activities, with staff and resources shared between them. For example, Unidata and JOSS provide significant university support, sometimes with the help of NCAR and university scientists, while the Cooperative Meteorological Education and Training (COMET) program provides a venue for the NCAR and university communities to transfer new technology to operational forecasters. About 50 NCAR staff participate in UCAR's Scientific Opportunities in Atmospheric and Related Sciences (SOARS®) program each year, acting as scientific, writing, or community mentors.

In the opinion of the committee, NCAR/UCAR has been a highly successful center in terms of advancing knowledge of atmospheric science and providing community-based resources. NCAR/UCAR has met many of the objectives laid out in the Blue Book. However, it is prudent to mention several potential challenges to such institutions. A key challenge is the establishment and communication of clear mechanisms for setting priorities in new directions as the center evolves to meet new research needs while continuing to ensure that it is meeting the needs of the nation in the purpose for which it was intended. A related challenge is the tendency for institutes such as NCAR to grow over time. Some have questioned whether NCAR/UCAR has become too large, perhaps at the expense of NSF-supported university research. The committee notes that NSF's level of support for NCAR over the past 30 years closely tracks that for PIs (see Figure 2-1). In fact, the percentage of the ATM budget spent on both NCAR and PIs has decreased as more resources have been devoted to observing and other facilities. In its final report the committee will return to the question of how the balance among the various modes of support should evolve in response to a changing research environment.

Maintaining an effective and balanced relationship with the university community may be the most significant challenge for NCAR. The center has a long track record of successful collaboration with university scientists to make progress on large scientific problems. This is consistent with the vision expressed in the Blue Book ("UCAR," 1959). These collaborations have originated in several ways, including through (a) scientist-to-scientist interactions, (b) large national or international programs (e.g., Global Atmospheric Research Program [GARP] Atlantic Tropical Experiment [GATE]), (c) NCAR initiatives (e.g., International H_2O Project [IHOP_2002]), (d) STC proposals, and (e) the development of large numerical models (e.g., Community Climate System Model). Through these collaborations, U.S. atmospheric research and operations have benefited greatly from the existence and productivity of NCAR.

Yet scientific collaborations among widely dispersed investigators with different sets of priorities at other organizations are difficult to implement. It can be easier to assemble most of the experts that are needed into one organization and to include only a few investigators from other organizations when necessary for specific research projects. In the current NCAR, there are elements that are truly collaborative with the university community, but there are also elements that are competitive with the university community. NCAR, the university, and the private-sector research communities have become so large and complex that new ways to stimulate NCAR partnerships with the university and private-sector research community may be necessary. In particular, new interactions could be instrumental in developing an agenda for the center that meets the needs and interests of both the large, and highly competent, in-house scientific staff and the broader atmospheric research community.

Partnerships between university or private-sector scientists and existing and emerging national centers need to be strengthened.

Finding: NCAR has a rich history of collaboration with university and private-sector scientists, particularly to make progress on large scientific problems that are beyond the reach of a single university department or private-sector laboratory. Whereas there are many opportunities for collaboration between NCAR and university or private-sector scientists, decisions about NCAR strategic initiatives (e.g., recent new efforts in biogeosciences and water) could benefit from broader community input. Indeed, because both NCAR and the broader atmospheric sciences community have grown in size and complexity, there are new challenges for the center in terms of maintaining a balance between inward- and outward-looking efforts. New challenges also exist in engaging a larger, more fragmented university and private-sector research community. This suggests that there may be additional new mechanisms to leverage the investment in a large center in a way that provides synergism with the needs of the university and private-sector research community.

Collaborations between large national centers (both existing and emerging) and university or private-sector scientists could be enhanced by new mechanisms to stimulate joint research initiatives at a larger scale than existing ad hoc collaborations. For example, ATM could conduct a regular competition for collaborations between NCAR and the outside community, focusing on research efforts that address important atmospheric science problems that are beyond the capability of single university departments or individual private-sector laboratories. The award should be significant, in excess of $1 million a year for 5 years. For initiatives that have large interdisciplinary scope, ATM could seek mechanisms for shared funding with other NSF divisions.

Recommendation: ATM should encourage new modes of partnership between the university and private-sector research community and the large national center.

COOPERATIVE AGREEMENTS TO SUPPORT OBSERVING FACILITIES

In addition to the facilities at NCAR, ATM uses cooperative agreements to support several facilities, often operated by universities and used by the broader atmospheric sciences research community (Table 3-2). These facilities provide scientists with instrumentation necessary to conduct cutting-edge science, are frequently utilized in field programs, and serve to meet educational objectives. Facility funding is provided through cooperative agreements with NCAR and a number of universities, to acquire, maintain, and operate specific observational and cyber infrastructure facilities or services that support the research and educational activities of NSF-sponsored projects, scientists, and students.

New emerging modes are under consideration for supporting facilities. In FY 2002, ATM created a "midsize facility" account to enable construction of new infrastructure that did not meet the minimum cost consideration for the NSF-wide Major Research Equipment and Facilities Construction account line (about $75 million for GEO), but costs in excess of the resources of any individual ATM program or section. The first two projects to be supported by this account are the AMISR and the Constellation Observing System for Meteorology, Ionosphere

TABLE 3-2 Facilities Supported by ATM and Operated by Universities or Other Entities

Operational	Under Development
Lower Atmospheric Facilities:	*Lower and Upper Atmospheric Facility:*
The **CHILL Radar**, operated by Colorado State University, is a deployable dual Doppler radar. It provides remote sensing data of the lower atmosphere in support of collaborative radar research with federal, state, and academic research entities, and the meteorological community.	The **Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)** is being built through a partnership between NSF, NASA, NOAA, the U.S. Air Force and U.S. Navy, and Taiwan. COSMIC will include a fleet of six low-Earth-orbiting satellites to measure the refraction, retardation, and bending by Earth's atmosphere of radio waves transmitted by the fleet of 28 DoD-supported high-Earth-orbit GPS satellites. The refraction of the radio waves yields a measure of electron density in the ionosphere and density variations in the stratosphere and troposphere, which in turn yield vertical profiles of temperature, water vapor, and pressure. Launch is scheduled for late 2005.
The **T-28 Storm Penetration Aircraft**, operated by the South Dakota School of Mines and Technology, is specially modified to penetrate and survive active convective storms. It is employed for studies of precipitation and hail development, and various thunderstorm processes.	
The **King Air Aircraft**, operated by the University of Wyoming, has been highly modified to support atmospheric and remote sensing instrumentation and is used to obtain in-situ and remotely sensed atmospheric measurements of the lower atmosphere.	

TABLE 3-2 Continued

Operational	Under Development
Upper Atmospheric Facilities:	*Upper Atmospheric Facility:*
SuperDARN Radar Network, operated by Johns Hopkins University Applied Physics Laboratory and the University of Alaska, is located in Canada and Alaska, and is part of a larger international network of sites. Its observations contribute to the global specification of the ionospheric electric potential pattern.	**Advanced Modular Incoherent Scatter Radar (AMISR)** is a modular, mobile radar facility for studying the upper atmosphere and observing space weather events. SRI International is leading the development and construction of AMISR along with several other partners.
Four large incoherent-scatter radar facilities located along a longitudinal chain from Greenland to Peru:	
Sondrestrom Radar Facility operated by SRI International is the northernmost radar in the chain, located in Kangerlussuaq, Greenland. It is used to further the understanding of the high-latitude upper atmosphere and space environment, in particular by investigating polar magnetosphere-ionosphere coupling under varying solar forcing conditions.	
Millstone Hill Radar, operated by the Massachusetts Institute of Technology, is located outside of Boston, Massachusetts, and is used to investigate mid-latitude magnetosphere, magnetospheric-ionospheric coupling, and thermospheric-ionospheric processes.	
Arecibo Observatory, operated by Cornell University, is located in the Karst region of Puerto Rico and explores the mesosphere, thermosphere, and the F region energetics and dynamics, as well as ionospheric-thermospheric coupling. It is particularly well suited for studies of the topside ionosphere.	
Jicamarca Radio Observatory, operated by Cornell University, is located on the magnetic equator near Lima, Peru. This instrument examines topside light ion distribution, latitudinal variability, and storm time response, F region thermal balance, and E region composition profiles of the equatorial region.	

and Climate (COSMIC). AMISR has just been initiated; the grant for building it was awarded to SRI International. COSMIC is being operated by UCAR.

A number of issues arise in making choices about which observing facilities to support and how to implement them. One must consider the balance in needs for observational platforms across the disciplines (i.e., climate, mesoscale convection, space weather, etc.) and in needs for different types of platforms (i.e., aircraft, radars, etc.). It is not clear whether the appropriate distribution should be determined by the number of researchers, the cost, or other priorities. Another dimension of balance to consider is the extent to which small or large centers, universities, or private-sector entities should support development and maintenance of observational platforms. Similarly, NSF must determine an appropriate balance for maintaining and keeping existing facilities up to date, retiring facilities as appropriate, and developing new facilities. Since some facilities are very expensive to operate and maintain, it is important that NSF frequently and carefully continue to determine which facilities are essential for research and which facilities might best not be supported any more. How best to utilize partnerships of NSF with other agencies that support observational facilities is another area of consideration. NSF has collaborated with other agencies to develop observing facilities, as it is currently doing in the case of COSMIC, and to deploy observing facilities for large field programs, such as the Indian Ocean Experiment (INDOEX) campaign. There may be further opportunities to build such collaborations. How ATM's support for facilities should evolve will be considered in more detail in the committee's final report.

NSF-WIDE INITIATIVES

ATM participates in a number of NSF-wide, interagency, and international programs, which in some cases require different approaches to providing support. The NSF-wide emphasis areas result from national initiatives spearheaded by Congress or the President, or else are activities such as the STCs that NSF leadership chooses as a priority. They can bring new funds into the Foundation, which are then distributed to relevant divisions. Since 2000, ATM has received additional funds toward five NSF priority areas, as well as from the STC and ERC programs described previously (Table 3-3). Typically, these funds are distributed as grants to individual and multiple PIs who respond to specialized calls for proposals.

INTERAGENCY PROGRAMS

Several government agencies support extramural research in the atmospheric sciences—including NASA, NOAA, EPA, DOE, DoD, and FAA—in part because atmospheric science is directly relevant to the missions of these agencies. Effective coordination of ATM with other agencies is important for meeting ATM's

TABLE 3-3 Investments in ATM Research from NSF-wide Priority Areas (millions of dollars for each fiscal year)

Priority Area	2000	2001	2002	2003	2004
Biocomplexity in the Environment: improve environmental forecasting capabilities; enhance decision-making tools; and integrate human, social, and ecological factors into investigations of the physical environment and environmental engineering.	0.00	7.50	7.40	7.40	12.00
Information Technology Research: deepen fundamental research on large-scale networks and create new integrative software and advanced architectures for high-end computing.	0.00	3.40	3.40	4.60	5.00
Nanoscale Science and Engineering: develop and strengthen promising fields (including nanobiotechnology, manufacturing at the nanoscale) and establish the science and engineering infrastructure and workforce needed to exploit new capabilities in systematic organization, manipulation, and control of matter at atomic, molecular, and supramolecular levels. NSF activities are part of the larger, cross-agency National Nanotechnology Initiative.	0.00	0.00	0.50	0.50	0.60
Mathematical Sciences: deepen support for fundamental research in the mathematical sciences and statistics and integrate mathematical and statistical research and education across the full range of science and engineering disciplines.	0.00	0.00	0.00	1.50	2.40
Human and Social Dynamics: draw on recent convergence of research in biology, engineering, information technology, and cognitive science to investigate the causes and ramifications of change and its complex consequences—cultural, economic, individual, political, and social.	0.00	0.00	0.00	0.00	0.50

goals for several reasons. First, many essential resources for atmospheric sciences research are created and supported by other agencies. These include space-based observational platforms, long-term monitoring efforts, and data archiving. Pooling resources supported by multiple agencies is an important component of many field programs. Second, whereas NSF's funding has remained fairly stable in recent decades, these other agencies have had more volatility. Thus, scientists supported by the other agencies turn to NSF for support when those agencies have downswings in funding, placing a larger demand on the NSF support for the atmospheric sciences. Third, because ATM is the one source for federal funding that aspires to address research needs spanning all of atmospheric science, the division has additional responsibility to consider supporting critical areas of the science not addressed by other agencies for programmatic reasons.

ATM participates in three major interagency programs that include atmospheric components (see Box 3-6): the U.S. Climate Change Science Program (CCSP), the U.S. Weather Research Program (USWRP), and the National Space Weather Program (NSWP). In addition, ATM supports the Center for Ocean, Land, and Atmosphere (COLA), a not-for-profit research institution in Calverton, Maryland, with interagency support that has some of the characteristics of the small centers discussed earlier (see Box 3-6). The division contributes to these efforts by supporting scientists who are doing research on related topics and in some cases providing funds for central coordination of the programs. ATM's involvement in the CCSP, USWRP, NSWP, and COLA commits the division to ongoing support of research that addresses the goals of these programs. A possible concern has been that these targeted initiatives would constrain the community to follow certain lines of inquiry, possibly channeling emphasis away from other important research areas. However, this has not proved to be the case in the initiatives listed in Box 3-6. In fact, these initiatives have all brought new funds into ATM, thus supporting more investigators and resulting in excellent science. Many of these funds have been distributed through PI grants, and significant funds within CCSP have gone to NCAR, helping to support climate system modeling.

Interagency activities in operational meteorology and supporting research have been coordinated by the federally mandated Office of the Federal Coordinator for Meteorology (OFCM) since 1964. Fifteen federal departments and agencies currently participate in OFCM's coordination infrastructure, which includes program councils, committees, working groups, and joint action groups staffed and populated by representatives from the federal agencies. OFCM focuses on coordinating operational weather observing and forecasting requirements. In addition, it produces annual reports on federal investments in weather-related activities and research and, as needed, holds workshops and produces reports on specific issues. Like the other interagency coordination efforts, OFCM has had varied effectiveness over its tenure.

Interagency coordination is a longstanding challenge for federally funded research in the atmospheric sciences, as recognized in many previous reports (e.g., NRC, 1997b, 1998, 2003), and requires the commitment of other agencies along with NSF. Yet it is essential to ensure that the critical science issues identified by the programs in Box 3-6, as well as other issues that require interagency coordination, are adequately addressed. Over the past decades, there have been mixed levels of success in these programs and in other efforts at interagency coordination, such as the Committee on Environment and Natural Resources, Subcommittee on Air Quality Research. The success depends in part on the leadership of each program, the willingness of the participating agencies to work

BOX 3-6
Major Interagency Programs

The **U.S. Climate Change Science Program (CCSP)** is an interagency effort to better understand how climate, climate variability, and potential human-induced changes in climate, affect the environment, natural resources, infrastructure, and the economy in our nation and the world. The guiding vision for CCSP is "a nation and the global community empowered with the science-based knowledge to manage the risks and opportunities of change in the climate and related environmental systems."

The **U.S. Weather Research Program (USWRP)** has the goal of improving the delivery and use of weather information. NSF's role is to provide leadership and support for all aspects of the fundamental science components—experimental, theoretical, and numerical. The current three priority thrust areas are quantitative precipitation forecasting and estimation, hurricane landfall, optimal mix of observing systems.

The overarching goal of the **National Space Weather Program (NSWP)** is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts. The program includes contributions from the user community, operational forecasters, researchers, modelers, and experts in instruments, communications, and data processing and analysis. It is a partnership between NSF, NASA, DoD, NOAA, DOE, the Department of the Interior, academia, and industry. NSF provides support to advance state-of-the-art instruments and data gathering techniques, to understand the physical processes, to develop predictive models, and to perform detailed analysis of data associated with past events that have caused significant impacts to space systems.

The **Center for Ocean, Land, and Atmosphere (COLA)** is devoted to understanding the predictability of Earth's current climate fluctuations on seasonal to decadal timescales using state-of-the-art, comprehensive models of the global atmosphere, world oceans, and land surface. COLA activities include (a) independently evaluating the climate variability characteristics of the nation's climate change models, (b) providing leadership on prediction of climate variability on seasonal-to-interannual timescales, (c) characterizing the impact of long-term climate change on climate variability, and (d) providing information technology infrastructure for efficient exchange of climate model and observational data. COLA is supported by NSF, NOAA, and NASA.

toward mutual objectives, and the extent to which opportunities for coordination are clearly communicated to the research community. Typically, these interagency programs have not asserted control over the budgets of individual agencies, but instead facilitate coordination by defining shared research agendas to which each agency contributes.

ATM is to be commended for its participation in the large interagency efforts described in Box 3-6. Furthermore, ATM program directors have been proactive about working with their colleagues from other agencies to support cross-agency research efforts, in particular, field programs (see Table 2-2). The committee is concerned, however, that ATM does not appear to have a strategic approach to its interagency activities. Thus, it is not clear to the research community exactly how ATM intends to contribute to large interagency programs, and interactions between program directors from NSF and other agencies appear to have an ad hoc nature. A more strategic approach is especially important for addressing large research problems that span the research investments of multiple agencies, such as climate or air quality, and for research avenues that have significant potential applications for operational capabilities, such as weather, for which coordination with mission-oriented agencies such as the National Weather Service is critical.

A more strategic approach is needed to facilitate interagency coordination.

Finding: Despite compelling motivations for interagency coordination, ATM does not always have clear mechanisms for effectively facilitating such interactions. Some interagency coordination takes place through formalized interagency programs (e.g., CCSP, NSWP), interagency working groups, community-driven initiatives (e.g., Climate Variability and Change [CLIVAR]), and ad hoc interactions between program directors. A strategic plan would both increase the transparency and decrease the ad hoc nature of NSF's approach to these interagency collaborations. Another way to address this problem would be to facilitate the establishment of an interagency Federal Coordinator for Atmospheric Research. This individual would be supported by all relevant agencies, with duties and responsibilities similar to the role of OFCM, but with a focus on sustaining the overall health of basic research in atmospheric science by maintaining liaisons with all relevant agencies and identifying their contributions to atmospheric research. Other options for fostering interagency coordination could also be effective.

Recommendation: ATM should be even more proactive in developing clear mechanisms for interagency collaborations.

FIELD PROGRAMS

Taking observations of the atmosphere in organized field programs to study specific processes continues to be integral to atmospheric research. Major field programs supported by ATM during the past decade are described in Table 2-2. Field programs are supported through a combination of modes, usually including grants to individuals or groups, NCAR, or university facilities, and often involve other agencies or countries. ATM supports smaller field programs through individual investigator grants and the facilities deployment pool. However, ATM supports large field programs in a variety of ways: as the lead agency (e.g., Bow Echo and MCV Experiment [BAMEX], IHOP_2002), as a major partner in an international effort (e.g., Tropical Ocean and Global Atmosphere Coupled Ocean Atmosphere Response Experiment [TOGA COARE]), as a supporting agency for field programs sponsored by other agencies (e.g., Boreal Ecosystem-Atmosphere Study [BOREAS], led by NASA), and, on occasion, supplying NSF facilities for which other agencies pay. Individual NSF-funded PIs can also participate in field campaigns sponsored by other agencies through individual grants. ATM indirectly supports field programs by supporting investigators to develop research capabilities that are then employed in campaigns funded by other agencies. In the case of INDOEX, the C4 STC was instrumental in initiating and carrying out the field program. To facilitate the planning of field programs, ATM requires those interested in using facilities from the NSF deployment pool to submit requests as much as two years in advance. The procedures for reviewing field programs were updated in February 2005 (NSF, 2005).

As the atmospheric sciences have become more complex, conducting field programs has presented new challenges for ATM in determining how to support these efforts, including:

1. *Increased demand for facilities*. Particularly for the large and diverse lower-atmosphere community, there is significant demand for facilities that often leads to conflicts in scheduling. Carefully developed protocols for requesting facilities years in advance, negotiation with NSF program officers and facility providers, and input from the Observing Facility Advisory Panel have often, but not always, resolved conflicts. The problem is exacerbated by the fact that scheduling is often driven by probable weather and the scheduling of other facilities belonging to other agencies and countries (e.g., University-National Oceanographic Laboratory System) or the schedules of cooperating institutions.

2. *Data archiving and development of data analysis tools*. Currently, there are varied destinations for data archival, including NCAR, Web sites set up by universities, and data archives established by other government agencies (e.g., National Climatic Data Center). For lower-atmospheric field campaigns back to the early 1990s, UCAR/JOSS has served as a center for data archiving for observational data and model simulations, or as a clearinghouse for PI-supported datasets archived elsewhere. Likewise, HAO maintains data archives from its solar instruments. Other government agencies, such as NASA, NOAA, and DOE, also have made efforts to establish data archives for data from field programs, satellite instruments, and monitoring networks. However, it is becoming increasingly difficult to access older observational or model datasets: changing technology and analysis packages make these datasets more difficult to analyze, and supporting metadata are often absent for the historical datasets. There is not always a clear responsibility for providing archived data for researchers for both large, multi-investigator field experiments and small field experiments. Thus,

data archival formats, quality control, and metadata are not necessarily standardized.

3. *Supporting data analysis*. Inadequate time and resources for analysis of data collected in the field has been a problem for decades. LeMone (1983) reported that it took six years to reach the peak in publications from GATE data. There was a time lag of five to six years between Cooperative Convective Precipitation Experiment (1981) and the peak in resulting publications, and the peak in Free Atmosphere Carbon Experiment publications was four years after the experiment. Some scientists analyzing TOGA COARE data ran out of funding before they completed analysis and publication; some even ran out of funding before they obtained all their data. A 2- to 10-year post-analysis phase is recognized in the lifetime of a generic large NSF field program, discussed in the recently released document, "Field Program Support at UCAR" (available at http://www.ucar.edu/fps/fps.pdf). NSF's new procedures for reviewing field programs (NSF, 2005) emphasize advance notice more than the post-field phase. Providing adequate time for careful analysis and synthesis of field data, which today typically involves complementary numerical simulations, increases the probability of significant payoff. Although the recent trend toward five-year grants allows more time for data analysis, the closer spacing of field programs exacerbates this problem.

4. *Spacing of field programs*. In addition to increased demand for facilities and the need for additional time and money for data analysis and synthesis, there are other factors that must be considered. The large infrastructure maintained to operate the facilities requires a certain level of use, not only to justify its existence, but to test instruments and maintain proficiency of the personnel, a requirement for airplane pilots. Furthermore, field programs are effective ways to inspire and recruit new students and to stimulate new questions.

5. *A need for longer-term sustained intensive measurements*. While ATM has a distinguished record in supporting long-term measurements of the upper atmosphere (Table 3-2) and the Sun (Box 3-4), current ATM policies and procedures for lower-atmosphere field programs are consistent with instrument deployments on the order of a few months. However, many problems related to weather and climate—for example, the interaction between the atmosphere and Earth's surface in the context of heat, moisture, or biogeochemical cycles—require sustained, specially designed, and focused measurements for a complete annual cycle or even several years. There are examples where ATM supported longer-term measurement goals by supporting field programs on an episodic basis (e.g., First ISLSCP [International Satellite Land Surface Climatology Project] Field Experiment in the 1980s), but sustained measurements are often needed. There are also efforts within other divisions of NSF to develop capabilities for long-term observations over the ocean (e.g., Ocean Research Interactive Observatory Networks Ocean Observing Initiative [ORION OOI]) and the land surface (e.g., Consortium of Universities for the Advancement of Hydrologic Science, Inc.

[CUASHI] Hydrological Observatories). Operational weather- and climate-monitoring networks provide observations over the longer term, but often not at the intensive level needed for process studies.

6. *Adapting to a changing international scene*. Historically, the United States usually has been the leader or at least a major partner in international field efforts. In the past few years, however, the major leadership in field programs has started to come from other nations. For example, the African Monsoon Multiscale Analysis (AMMA) field program is a large international field program supported by the European Union and led by France.

7. *Development of innovative observing techniques and methods.* For the U.S. atmospheric science community to remain at the cutting edge of field research, innovative techniques and methods need to be developed in order to obtain the observations needed to test hypotheses, better resolve the variability and structure of the atmosphere, and understand the coupling of the atmosphere to the land, ocean, and space. Once developed and proven, these new methods need to be transferred to facilities that can make them available to the broader community.

Longer-term field programs have not received sufficient support.

Finding: ATM has well-established mechanisms for supporting short-duration field programs. However, ATM has not yet clearly articulated mechanisms for supporting field programs that require continuous, longer-term (i.e., up to multi-year) deployment and observations not available from operational monitoring networks. This type of observation protocol is generally ill-suited to the existing funding opportunities, in part because they were prohibitively expensive until recently. Three factors motivate the need and appropriateness of this approach today: (1) these types of observations are especially critical to understanding the interaction between the atmosphere and Earth's surface, which are growing areas of research and concern; (2) many instruments that would be used are less expensive, making it reasonable to deploy them in the field for longer durations; and (3) there are existing observational programs developed by other NSF divisions and agencies (e.g., Long Term Ecological Research, ORION OOI, the proposed CUASHI Hydrological Observatories), which can be leveraged with additional investments to conduct atmospheric research.

Recommendation: ATM, in coordination with other NSF divisions and federal agencies, should develop the explicit capability to support longer-term (i.e., up to multiyear) lower-atmosphere field programs to study atmospheric processes that are important on these timescales.

Support for field data archives, visualization tool development, and analysis is not commensurate with the investment in obtaining the measurements.

Finding: A longstanding challenge in the atmospheric sciences is providing sufficient support for scientists to analyze data obtained during field programs and from observational networks. Because analysis comes at the end of a field program and competes against the start of other new field programs, it is at times subject to reduction in support. Thus, the full benefit from the investment in a field program often is not realized. Maximum benefit from many NSF-supported studies also would be facilitated by easy access to data from operational observational and monitoring networks (including surface, upper air, radar, and satellite) in addition to easy access to field-program data, historical data, and numerical model data. All these datasets should be archived and provided to the community in a manner consistent with common standards, along with the necessary analysis and visualization tools. In enhancing these capabilities, there are opportunities for NSF to work with other federal agencies who have faced similar challenges, particularly in terms of data archiving.

Recommendation: ATM should maximize the benefit of field data by ensuring that archiving, visualization, and analysis activities are well supported and continue for many years after the completion of field campaigns. ATM is encouraged to work with the community by sponsoring a series of workshops on development of standards for metadata, data archival, and software tools and by providing support for the implementation of the recommendations of the workshops.

ENSURING A BALANCED PROGRAM

The committee's preliminary analysis of the modes of support employed by ATM leads to the conclusion that each of the modes is serving an important function. In particular, the complementary roles of a large national center and grants to PIs have been a constructive component of the atmospheric science enterprise. The diversity of available modes has facilitated several different ways to tackle the scientific questions in the atmospheric sciences. Indeed, it appears that many of the newer modes arose out of emerging needs of the research community. The current balance among the modes is serving the community well, but may need to shift in coming years to respond to a changing research environment. For example, domestic budget constraints at NSF and other federal agencies that support atmospheric research, increasing sophistication and investments in the international research community, and changing societal expectations of research may make it necessary to rely more on some modes of support or to introduce new modes to the ATM portfolio. In its final report, the committee will consider the extent to which the balance should be modified.

Having diverse modes of support available has benefited the atmospheric sciences.

Finding: The committee finds that the diversity of activities and modes of support is a strength of the program and of our nation's scientific system. The approach and vision outlined in NAS/NRC (1958) and the Blue Book ("UCAR," 1959), which together mapped out the complementary roles of a large national center and the individual investigator university grants program, has served the atmospheric science community well and is the envy of many other scientific communities. The newer modes of support (i.e., multi-investigator awards, cooperative agreements, and centers sited at universities) reflect the maturation and increasing interdisciplinary nature of atmospheric sciences. The community input received to date supports this multifaceted approach. The present balance is approximately right and reflects the current needs of the community.

Recommendation: ATM should continue to utilize the current mix of modes of support for a diverse portfolio of activities (i.e., research, observations and facilities, technology development, education, outreach, and applications).

ATM has not published a strategic plan to guide its activities in the coming years. Some indication of strategic directions for the division can be found in a major, long-term planning effort undertaken by GEO and culminating in a report titled *NSF Geosciences Beyond 2000: Understanding and Predicting Earth's Environment and Habitability* (GEO, 2000). A community-based strategic planning effort could provide a *means* by which ATM can advance on many of the issues identified in this report, thereby bringing the division's activities even closer to the guiding principles laid out in Chapter 1. A clear strategic vision would help guide choices among different priorities and help facilitate interdisciplinary, interagency, and international collaborations. Likewise, a strategic plan would help schedule multiyear commitments of facilities, especially to ensure an approach to field programs that would balance many competing demands. Although there is some concern that a strategic plan could impose constraints on funding opportunities, the committee feels that the benefits of transparency in making difficult choices among competing demands outweigh this concern.

Strategic plans can take many different forms, ranging from describing a mission and fairly high-level goals for a program to providing more details about implementation. At a minimum the strategic plan recommended below should clearly articulate ATM's mission and goals in the context of the multidisciplinary, multiagency, and multinational environment of atmospheric research. However, the committee envisions ATM's strategic plan going beyond providing a set of goals to include actions on how to attain the goals, although not prescribing in great detail the specifics of implementation. Rather, it should address practical implementation challenges, such as interagency relations, international relations, and university relations with NCAR. Further, the plan should put flexible structures in place that will give ATM a means for making decisions about prioritization, for example, in response to pressures resulting from an evolving budgetary environment, competing international initiatives, and multiple demands for facilities. Strategic planning should provide a broad framework to address key long-term scientific needs such as those related to climate change. Having a strategic plan in place may call for a reorganization of ATM to direct staff and resources in a way that may better address emerging challenges. Furthermore, the balance of modes should evolve in the future in a manner that is consistent with strategic planning efforts.

The committee believes that the strategic plan itself will be useful to ATM, but the process of producing it may prove even more valuable, particularly if it is conducted with ample and transparent community engagement. The committee envisions the strategic planning process as providing a mechanism for the community as a whole to participate in an active conversation about the direction of the field and where best to use resources, while remaining sensitive to the societal expectations of that research. Thus, the strategic plan must be flexible and responsive, and developed by the science community in collaboration with ATM management. Ideally, the process of developing the strategic plan would be simple, revisited at regular intervals, and eventually ingrained in the ATM culture.

A strategic plan will be essential to maintain a balanced, effective portfolio in an evolving programmatic environment.

Finding: We are now in a phase of rapid change in graduate education demographics, the role of the United States in the global atmospheric science community, potentially the role of NSF in national atmospheric science funding, and the maturation and interdisciplinary growth of atmospheric science, as well as a likely period of constrained budgets. GEO (2000) represents a broad strategic plan for NSF GEO and reflects the considerable evolution of the geophysical scientific enterprise. Yet, ATM has not developed its own strategic plan. Given the changing programmatic environment, ATM should take a more proactive approach to strategic planning. A flexible strategic plan developed with ample community input will enable determination of the appropriate balance of activities and modes of support in the ATM portfolio; help plan for large or long-term investments; facilitate appropriate allocation of resources to interdisciplinary, interagency, and international research efforts; and ensure that the United States will continue to be a leader in atmospheric research. In addition, a strategic planning effort that effectively engages the community will enhance the transparency of the rationale behind ATM's decisions.

Recommendation: ATM should engage the community in the development of a strategic plan, to be revisited at regular intervals, and should rethink its programmatic organization in light of this plan.

References

CCSP and SGCR (Climate Change Science Program and Subcommittee on Global Change Research). 2004. Our Changing Planet: The U.S. Climate Change Science Program for Fiscal Years 2004 and 2005. Washington, DC: CCSP.

GEO (National Science Foundation Geosciences Directorate). 2000. NSF Geosciences Beyond 2000: Understanding and Predicting Earth's Environment and Habitability. NSF 00-27. Arlington, VA: NSF.

Hoffer, T., B. Dugoni, A. Sanderson, S. Sederstrom, R. Ghadialy, and P. Rocque. 2001. Doctorate Recipients from United States Universities: Summary Report 2000. Chicago: National Opinion Research Center.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, eds. Cambridge, UK: Cambridge University Press.

Kolb, C. E. 2003. Measurement challenges and strategies in atmospheric and environmental chemistry. Pp. 127-136 in Challenges for the Chemical Sciences in the 21st Century—The Environment. Washington, DC: National Academy Press,.

LeMone, M. A., 1983: The time between a field experiment and its published results. Bull. Am. Meteorol. Soc. 64: 614-615.

Mazuzan, G. T. 1988. Up, up, and away: The reinvigoration of meteorology in the United States: 1958-1962. Bull. Am. Meteorol. Soc. 69: 1152-1163.

NAPA (National Academy of Public Administration). 2004. National Science Foundation: Governance and Management for the Future. Washington, DC: NAPA.

NAS/NRC (National Academy of Sciences/National Research Council). 1958. Research and Education in Meteorology: Interim Report of the Committee on Meteorology. Washington, DC: NAS/NRC.

NAS/NRC. 1959. Proceedings of the Scientific Information Meeting on Atmospheric Sciences. Washington, DC: NAS/NRC.

NAS/NRC. 1960. Meteorology on the Move: A Progress Report of the Committee on Atmospheric Sciences. Washington, DC: NAS/NRC.

NRC (National Research Council). 1977a. The Atmospheric Sciences: Problems and Applications. Washington, DC: National Academy of Sciences.

NRC. 1977b. Planning and Management of Major Atmospheric Research Programs. Washington, DC: National Academy of Sciences.

NRC. 1998. The Atmospheric Sciences Entering the Twenty-First Century. Washington, DC: National Academy Press.

NRC. 1999. Adequacy of Climate Observing Systems. Washington, DC: National Academy Press.

NRC. 2000. From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death. Washington, DC: National Academy Press.

NRC. 2003. Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan. Washington, DC: The National Academies Press.

NRC. 2004. SBIR Program Diversity and Assessment Challenges: Report of a Symposium. Washington, DC: The National Academies Press.

NRC. 2005. Policy Implications of International Graduate Students and Postdoctoral Scholars in the United States. Washington, DC: The National Academies Press.

NSB (National Science Board). 2002. Science and Engineering Indicators—2002. NSB-02-1. Arlington, VA: National Science Foundation.

NSB. 2003. The Science and Engineering Work Force: Realizing America's Potential. NSB 03-69. Arlington, VA: National Science Foundation.

NSF (National Science Foundation). 2005. Policy, Procedures, and Guidelines for Science Programs That Require Field Facilities. Arlington, VA: NSF

OFCM (Office of the Federal Coordinator for Meteorology). 2004. The Federal Plan for Meteorological Services and Supporting Research: Fiscal Year 2005. Washington, DC: OFCM.

Simpson, S. 2004. A sun-to-mud education in two weeks. Space Weather, 2, July 10.

"UCAR" (University Committee on Atmospheric Research). 1959. Preliminary Plans for a National Institute for Atmospheric Research (the "Blue Book"). Prepared for the National Science Foundation under Grant G 5807. Available http://www.ucar.edu/news/images/PDFs/BlueBook.PDF. Accessed July 29, 2005.

Vali, G. R. and R. Anthes. 2003. UCAR 2003 Graduate Student Enrollment Survey. Available http://www-das.uwyo.edu/~vali/grad_stud/surv03.html. Accessed August 30, 2005.

Vali, G., R. Anthes, D. Thomson, D. Houghton, J. Fellows, and S. Friberg. 2002. Wanted: More Ph. D.s graduate enrollment in the atmospheric sciences. Bull. Am. Meteorol. Soc. 83: 63-71.

WMO (World Meteorological Organization). 2003. Scientific Assessment of Ozone Depletion: 2002 Global Ozone Research and Monitoring Project—Report No. 47. Geneva, Switzerland: WMO.

Appendixes

A

Statement of Task

At the request of ATM, this committee will perform a study that will provide guidance to ATM on its strategy for achieving its goals in the atmospheric sciences (e.g., cutting-edge research, education and workforce development, service to society, computational and observational objectives, data management). In doing so, the committee will seek to engage the broad atmospheric science community to the fullest extent possible. The committee will provide guidance on the most effective approaches for different goals and on determining the appropriate balance among approaches. In essence, the committee is asked to consider how ATM can best accomplish its mission of supporting the atmospheric sciences into the future. Specifically, this study will consider the following questions:

1. What are the most effective activities (e.g., research, facilities, technology development, education and workforce programs) and modes of support (e.g., individual principal investigators, university-based research centers, large centers) for achieving NSF's range of goals in the atmospheric sciences?
2. Is the balance among the types of activities appropriate and should it be adjusted? Is the balance among modes of support for the atmospheric sciences effective and should it be adjusted?
3. Are there any gaps in the activities supported by the Division and are there new mechanisms that should be considered in planning and facilitating these activities?
4. Are interdisciplinary, foundation-wide, interagency, and international activities effectively implemented and are there new mechanisms that should be considered?

5. How can NSF ensure and encourage the broadest participation and involvement of atmospheric researchers at a variety of institutions?

The study will not make budgetary recommendations. The committee will deliver its results in two parts: (1) a short interim report in fall 2005 that provides a preliminary sense of the committee's overarching conclusions; and (2) a final report by fall 2006 that further considers community input and provides the committee's full analysis and recommendations.

B

Biographical Sketches of Committee Members and Staff

COMMITTEE MEMBERS

Dr. John A. Armstrong, *Chair,* received his Ph.D. in the field of nuclear magnetic resonance from Harvard University in 1961. Dr. Armstrong spent most of his career at IBM, until he retired as vice president of science and technology. He is the author or coauthor of some 60 papers on nuclear resonance, nonlinear optics, the photon statistics of lasers, picosecond pulse measurements, the multiphoton spectroscopy of atoms, the management of research in industry, and issues of science and technology policy. As a result of his contributions in nonlinear optics, quantum physics, and technical leadership in advanced very-large-scale integration technology, Dr. Armstrong was elected a member of the National Academy of Engineering (NAE) in 1987. In addition, he received the George E. Pake Prize of the American Physical Society (APS) in 1989. Dr. Armstrong was a member of the presidentially appointed National Advisory Committee on Semiconductors. He was also a member of the National Science Board from 1996 to 2002 and served on its Special Commission on the Future of the National Science Foundation (NSF). Dr. Armstrong has served on numerous National Research Council (NRC) bodies, including the Commission on Physical Sciences, Mathematics, and Applications, where he was liaison to the Computer Science and Technology Board; he chaired the Committee on Partnerships in Weather and Climate Services and the Committee on Future Needs in Deep Submergence Science. Dr. Armstrong serves as chair of the Industrial Advisory Board for the NSF Engineering Research Center "Collaborative Adaptive Sensing of the Atmosphere" located at the University of Massachusetts at Amherst.

Dr. Susan K. Avery is vice chancellor and dean at the University of Colorado, Boulder. Dr. Avery received her Ph.D. in atmospheric science from the University of Illinois. She served as assistant professor in the Department of Electrical Engineering, University of Illinois, Urbana; professor in the Department of Electrical and Computer Engineering, University of Colorado; and associate dean of research and graduate education, College of Engineering, University of Colorado, Boulder, and Director of the Cooperative Institute for Research in Environmental Sciences. Dr. Avery has broad interests in upper-atmosphere dynamics, Doppler-radar techniques for observing the atmosphere, and the application of weather and climate information for decision support. From 2002 to 2003, she assisted the U.S. Climate Change Science Program in drafting its strategic plan; she was particularly instrumental in shaping the chapter on decision support, a new emphasis for the program. Dr. Avery is the current president of the American Meteorological Society (AMS), a member of the American Geophysical Union (AGU), and a Fellow of the Institute of Electrical and Electronics Engineers. She is a past officer of the University Corporation of Atmospheric Research (UCAR). Dr. Avery receives research support from NSF and the National Oceanic and Atmospheric Administration (NOAA).

Dr. Howard B. Bluestein is George Lynn Cross Research Professor of Meteorology at the University of Oklahoma, where he has served since 1976. He received his Ph.D. in meteorology from the Massachusetts Institute of Technology. His research interests are the observation and physical understanding of weather phenomena on convective, mesoscale, and synoptic scales. Dr. Bluestein is a fellow of the AMS and of the Cooperative Institute for Mesoscale Meteorological Studies. He is past chair of the NSF Observing Facilities Advisory Panel, the AMS Committee on Severe Local Storms, and UCAR's Scientific Program Evaluation Committee, a past member of the AMS Board of Meteorological and Oceanographic Education in Universities, and a former member of the NRC Board on Atmospheric Sciences and Climate (BASC). He is also the author of a textbook on synoptic-dynamic meteorology and of *Tornado Alley*, a book for the scientific layperson on severe thunderstorms and tornadoes.

Dr. Elbert W. (Joe) Friday is currently the WeatherNews Chair of Applied Meteorology and Director of Sasaki Applied Meteorology Research Institute at the University of Oklahoma. Most recently, he was director of the NRC BASC from 1998 to 2002, and senior scholar from 2002 to 2003. In the previous year, he served as the assistant administrator for research for NOAA. From 1988 to 1997, he was director of the National Weather Service, serving during its extensive modernization. During this same period, he served as the U.S. Permanent Representative to the World Meteorological Organization. Dr. Friday completed a 20-year career in the U.S. Air Force, retiring in 1981 as a colonel. He is a fellow of the AMS and a member of the American Association for the Advancement of

Sciences, the National Weather Association, and, the research society Sigma Xi. He has been awarded the Presidential Rank Award of Meritorious Executive, the Distinguished Graduate Award from the University of Oklahoma, where he received a Ph.D. in Meteorology in 1969, and the 1993 Federal Executive of the Year Award from the Federal Executive Institute Alumni Association. He received the 1997 Cleveland Abbe Award for Outstanding Service from AMS.

Dr. Marvin A. Geller is a professor of atmospheric sciences at the State University of New York at Stony Brook. His research deals with atmospheric dynamics, middle and upper atmosphere, climate variability, and aeronomy. Dr. Geller has served on many national and international advisory committees on atmospheric science, the upper atmosphere, and the near-space environment, and is currently president of the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP); the NSF's Division of Atmospheric Sciences (ATM) pays dues to SCOSTEP through BASC. His past NRC service includes a 2003 Review of the National Aeronautics and Space Administration (NASA) Earth Sciences Enterprise Strategic Plan; membership on BASC, the Committee on Metrics for Global Change Research, and the Committee on Solar and Space Physics; and chair of the Committee on Solar-Terrestrial Research. He is a Fellow of AMS, a Fellow of AGU and past president of AGU's Atmospheric Sciences Section. Dr. Geller receives research funding from NSF and NASA.

Dr. Elisabeth A. Holland obtained her Ph.D. from Colorado State University in 1988, followed by a postdoctoral fellowship at Stanford University. She has worked in the Atmospheric Chemistry Division at the National Center for Atmospheric Research (NCAR) since 1989, focusing on linkages between atmospheric chemistry and terrestrial ecosystems. She has combined modeling and measurements to examine interactions between the terrestrial carbon and nitrogen cycles, ranging from initial endeavors in microbiology to her current focus on global and regional biogeochemistry. Dr. Holland directed the NATO Advanced Study Institute on Soils and Global Change, was an associate editor for the *Journal of Geophysical Research*, a fellow with both the Natural Resources Ecology Laboratory (Colorado State University) and the Institute for Arctic and Alpine Ecology (University of Colorado), and serves on a number of steering committees including the International Committee on Atmospheric Chemistry and Global Pollution and NCAR's Significant Opportunities in Atmospheric and Related Sciences program, which provides research opportunities to minority students. Dr. Holland is a member of the graduate faculty at Colorado State University and the University of Colorado, and has also worked with students from Stanford University, the University of California at Berkeley, State University of New York Stony Brook, and the University of New Hampshire. From 1999 to 2001, she was C3 Professor and Atmospheric Chemistry Group Leader for the Max Planck Institute of Biogeochemistry in Jena, Germany.

Dr. Charles E. Kolb received his Ph.D. from Princeton University in physical chemistry. Dr. Kolb is president and chief executive officer of Aerodyne Research, Inc. in Billerica, Massachusetts. Aerodyne is a private company that receives research support from many government agencies, including NSF. Dr. Kolb's principle research interests have included atmospheric and environmental chemistry, combustion chemistry, materials chemistry, and the chemical physics of rocket and aircraft exhaust plumes. He has served on several NASA panels dealing with environmental issues, as well as on several previous NRC committees and boards dealing with atmospheric and environmental chemistry. These include the NRC's BASC, the Committee to Review NARSTO's Scientific Assessment of Airborne Particulate Matter, and the Committee on Atmospheric Chemistry. He is a fellow of the APS, AGU, the American Association for the Advancement of Science, and the Optical Society of America.

Dr. Margaret A. LeMone is a senior scientist at NCAR. She has two primary scientific interests: the structure and dynamics of the atmosphere's planetary boundary layer and its interaction with the underlying surface and clouds overhead, and the interaction of mesoscale convection with the boundary layer and surface underneath, and with the surrounding atmosphere. Dr. LeMone is also the chief scientist for Global Learning through Observations for the Benefit of the Environment (GLOBE), a worldwide hands-on, primary- and secondary-school-based science and education outreach program. GLOBE is operated by UCAR and Colorado State University under a cooperative agreement with NASA. GLOBE also receives in-kind support from the State Department; NSF funds PIs to help oversee and provide quality control for GLOBE measurements and to use GLOBE data in their research. Dr. LeMone's salary is supported in part by NCAR and in part by the GLOBE program. Dr. LeMone is a fellow of the American Association for the Advancement of Science and AMS. She is also a member of NAE and a former member of BASC. She has served on the NRC's Panel on Improving the Effectiveness of U.S. Climate Modeling, the Special Fields and Interdisciplinary Engineering Peer Committee of the NAE, and the Committee on Weather Research for Surface Transportation. Dr. LeMone received her Ph.D. in atmospheric sciences from the University of Washington.

Dr. Ramón E. López received his Ph.D. in space physics in 1986 from Rice University. He is a professor of physics and space sciences at the Florida Institute of Technology. Prior to this appointment, he was the C. Sharp Cook Distinguished Professor in the Department of Physics at the University of Texas at El Paso. Dr. López is a fellow of the APS and was awarded the 2002 APS Nicholson Medal for Humanitarian Service. In 2003, he was elected vice chair of the APS Forum on Education and to serve as chair in 2005. Dr. López leads a research group that is working in both space physics and science education. His current research focuses on making detailed quantitative comparisons between the results of global three-dimensional magnetohydrodynamic simulations and observations during actual events, as well as student interpretation of visualizations. Dr. López receives research support from NASA and NSF. He is the author or coauthor of 86 scientific publications and 18 nonscientific publications, including the popular science book *Storms from the Sun*. From 1994 to 1999, he was director of Education and Outreach Programs of APS. Dr. López is active in science education reform nationally. He has served as an education consultant for a number of school districts around the country, for state education agencies in California, Maryland, North Carolina, and Texas, and for federal agencies such as NASA and the NSF; and he was a member the NRC's Committee on Undergraduate Science Education.

Dr. Kenneth Olden is the director of the National Institute for Environmental Health Sciences (NIEHS) and the National Toxicology Program (NTP). Trained as a cell biologist and biochemist, Dr. Olden received his master's degree from the University of Michigan and his doctorate from Temple University, with research at the University of Rochester. Before moving to NIEHS NTP, Dr. Olden conducted research into properties of cell surface molecules and their possible roles in cancer. He was director of the Howard University Cancer Center and professor and chairman of the Department of Oncology at Howard University Medical School. Dr. Olden was elected to the Institute of Medicine in 1994 and has received numerous other honors, including the Presidential Distinguished Executive Rank Award and the Presidential Meritorious Executive Rank Award.

Dr. Susan Solomon is widely recognized as one of the leaders in the field of atmospheric science. Since receiving her Ph.D. degree in chemistry from the University of California at Berkeley in 1981, she has been employed by NOAA as a research scientist. She made some of the first measurements in the Antarctic that showed that chlorofluorocarbons were responsible for the stratospheric ozone hole, and she pioneered the theoretical understanding of the surface chemistry that causes it. In March 2000, she received the National Medal of Science, the United States' highest scientific honor, for "key insights in explaining the cause of the Antarctic ozone hole." Her current research focuses on chemistry-climate coupling, and she serves as co-chair of Working Group I of the Intergovernmental Panel on Climate Change, which seeks to provide scientific information to the United Nations Framework Convention on Climate Change. Dr. Solomon was elected to the National Academy of Sciences in 1992.

Dr. John M. Wallace is a professor of Atmospheric Sciences at the University of Washington. His research has improved our understanding of global climate and its interannual and decadal variations, through the use of observational data. He has been instrumental in identifying and understanding a number of atmospheric phenomena such as the spatial patterns in month-to-month and year-to-year climate variability, including the one through which the El Niño phenomenon in the tropical Pacific influences climate over North America. Dr. Wallace receives research support from NSF and NOAA. Dr. Wallace is a member of the National Academy of Sciences and has chaired several NRC panels including the Panel on Reconciling Temperature Observations, the Panel on Dynamic Extended Range Forecasting, and the Advisory Panel for the Tropical Ocean/Global Atmosphere (TOGA). He has also served on committees addressing Abrupt Climate Change: Implications for Science and Public Policy and the Science of Climate Change.

Dr. Robert A. Weller received his Ph.D. in 1978 from Scripps Institution of Oceanography. He is the director of the Cooperative Institute for Climate and Ocean Research at Woods Hole Oceanographic Institution (WHOI), and has worked at WHOI since 1979. His research focuses on atmospheric forcing (wind stress and buoyancy flux), surface waves on the upper ocean, prediction of upper ocean variability, and the ocean's role in climate. He has served as the Secretary of the Navy Chair in Oceanography. He has been on multiple mooring deployment cruises and has practical experience with ocean observation instruments. Dr. Weller receives research support from NOAA, the Naval Research Laboratory, and NSF. He is currently a co-chair of the U.S. Climate Variability and Change (CLIVAR) Scientific Steering Group and a member of the international CLIVAR Scientific Steering Group. CLIVAR receives funding from NSF's ATM and Ocean Science Division. Dr. Weller has served on several NRC committees over the years, including the recent Committee to Review the U.S. Climate Change Science Program Strategic Plan and the Committee on Implementation of a Seafloor Observatory Network for Oceanographic Research; he was also a member of BASC. He is currently serving on the NRC Committee on Utilization of Environmental Satellite Data: A Vision for 2010 and Beyond.

Dr. Stephen E. Zebiak is director-general, as well as director of Modeling and Prediction Research, at the International Research Institute (IRI) for climate prediction, hosted at Columbia University. IRI is supported by NOAA, the U.S. Agency for International Development, the Department of Energy, NSF, and international sources. Dr. Zebiak has worked in the area of ocean-atmosphere interaction and climate variability since completing his Ph.D. in 1984. He was an author of the first dynamical model used to predict El Niño successfully. He has served as chair of the International CLIVAR Working Group on Seasonal to Interannual Prediction, co-chair of the U.S. CLIVAR Seasonal to Interannual Modeling and Prediction Panel, and member of numerous advisory committees for U.S. and international science programs. He has served as a member of AMS's Committee on Climate Variations, and as an associate editor for the *Journal of Climate*. Dr. Zebiak's expertise with intermediate-scale climate models and the interpretation of ocean and atmospheric modeling outputs on decadal and interannual scales will provide an important input to this study. Dr. Zebiak was a member of the NRC Advisory Panel for the Tropical Ocean and Global Atmosphere program and the Committee on Improving the Effectiveness of U.S. Climate Modeling.

NRC STAFF

Dr. Amanda C. Staudt is a senior program officer with BASC. She received an A.B. in environmental engineering and sciences and a Ph.D. in atmospheric sciences from Harvard University. Her doctorate research involved developing a global three-dimensional chemical transport model to investigate how long-range transport of continental pollutants affects the chemical composition of the remote tropical Pacific troposphere. Since joining the National Academies in 2001, Dr. Staudt has staffed the National Academies review of the U.S. Climate Change Science Program Strategic Plan and the longstanding Climate Research Committee. Dr. Staudt has also worked on studies addressing air quality management in the United States, research priorities for airborne particulate matter, the NARSTO Assessment of the Atmospheric Science on Particulate Matter, weather research for surface transportation, and weather forecasting for aviation traffic flow management.

Ms. Claudia Mengelt is an associate program officer with BASC. After completing her B.S. in Aquatic Biology at University of California, Santa Barbara, she received her M.S. in Biological Oceanography from the College of Oceanic and Atmospheric Sciences at Oregon State. Her Master's research focused on Antarctic phytoplankton species composition and their influence on biogeochemical cycles. She will receive a Ph.D. in the Marine Sciences from U.C. Santa Barbara where she was involved in harmful algal bloom research. She has recently joined the full time staff of BASC following a fellowship with the NRC Polar Research Board.

Ms. Elizabeth A. Galinis is a senior program assistant for BASC. She received her B.S. in marine science from the University of South Carolina in 2001. Since her start at the National Academies in March 2002, she has worked on studies involving next-generation weather radar (NEXRAD), weather modification, climate sensitivity, climate change, radiative forcings, the Global Energy and Water Cycle Experiment Americas Prediction Project, and polar icebreaker ships. Ms. Galinis is pursuing a master's degree in environmental science and policy at Johns Hopkins University.

C

Individuals Who Provided Input to the Committee

Over the past year, the committee has met four times to gather information and conduct deliberations. At several of these meetings, members of the atmospheric sciences community were invited to share their perspectives on study questions, both in sessions devoted to specific issues and in an "open mike" session when any comments were welcome. In addition, the committee made available a Web site through which members of the community could contribute comments (http://dels.nas.edu/basc/strat.shtml), met with the heads and chairs of the University Corporation for Atmospheric Research (UCAR) universities, and held town hall sessions at the December 2004 fall meeting of the American Geophysical Union and at the January 2005 annual meeting of the American Meteorological Society. This input has been quite helpful in shaping the committee's thinking. We acknowledge in particular the following individuals who made substantive comments in one or more of these venues:

Caspar Amman, National Center for Atmospheric Research (NCAR)
Richard Anthes, UCAR
Dave Atlas, NASA Goddard Space Flight Center
Robert C. Beardsley, Woods Hole Oceanographic Institution
Richard Behnke, National Science Foundation (NSF)
Aaron Brasket, Energy Velocity, Boulder, Colorado
Rob Brue, University of California, Berkeley
Richard Carbone, NCAR
Frederick H. Carr, University of Oklahoma
Ron Cohen, University of California, Berkeley

Ben de Foy, Massachusetts Institute of Technology
Lori Del Negro, Lake Forest College
Terry Deschler, University of Wyoming
Kelvin Droegemeier, University of Oklahoma
Jay Fein, NSF
Jack Fellows, UCAR
Carl Friedman, New Mexico Institute of Mining & Technology
John Gaynor, National Oceanic and Atmospheric Administration (NOAA)
Peter Gilman, NCAR
Maura Hagan, NCAR
Chuck Hakkarinen, Electric Power Research Institute, *Retired*
Kevin Hamilton, University of Hawaii
Ernest Hildner, Space Environment Center, NOAA
David Hofmann, Climate Monitoring and Diagnostics Laboratory, NOAA
Clifford Jacobs, NSF
Roberta Johnson, UCAR
Peter Kallay, University of California, Davis
Al Kellie, NCAR
Jeff Kiehl, NCAR
Timothy Killeen, NCAR
Joe Klemp, NCAR
Michael Knoeckler, NCAR
Paul Krehbiel, New Mexico Institute of Mining & Technology
Bill Kuo, NCAR
David Legler, CLIVAR Project Office
Doug Lilly, University of Oklahoma
Roland List, University of Toronto
Denise Mauzerall, Woodrow Wilson School, Princeton University
R. C. Mercure, Jr., CDM Optics, Inc.
Christopher Mooers, University of Miami
Jarvis Moyers, NSF
Sandy MacDonald, Forecast Systems Laboratory, NOAA
Chris McCormick, Broad Reach Engineering, Boulder, Colorado
Danny McKenna, NCAR
Natalie Mahowald, NCAR
William Neff, Environmental Technology Laboratory, NOAA
Raj Pandya, UCAR
Dave Parsons, NCAR
Annick Pouqet, NCAR
Lynn Preston, NSF
Gene Rasmusson, University of Maryland, College Park
Roy Rasmusson, NCAR

V. Ramanathan, Scripps Institution of Oceanography and University of California, San Diego
Alan Robock, Rutgers University
Steve Rutledge, Colorado State University
Cindy Schmidt, UCAR
Bob Serafin, NCAR
John Snow, University of Oklahoma
Tim Spangler, NCAR
Paul Sperry, Cooperative Institute for Research in Environmental Sciences
Pamela Stephens, NSF
Gene Takle, Iowa State University
Bruce Umminger, NSF
Gabor Vali, University of Wyoming
Susan VanGundy, National Science Digital Library
Robert M. White, Washington Advisors Group
Don Wuebbles, University of Illinois

D

Acronyms

AGU	American Geophysical Union
AMISR	Advanced Modular Incoherent Scatter Radar
AMS	American Meteorological Society
APS	American Physical Society
ATD	NCAR Atmospheric Technology Division
ATM	NSF Division of Atmospheric Sciences
C4	Center for Clouds, Chemistry and Climate
CAPS	Center for the Analysis and Prediction of Storms
CASA	Collaborative Adaptive Sensing of the Atmosphere
CAWSES	Climate and Weather of the Sun-Earth System
CCSM	Community Climate System Model
CCSP	Climate Change Science Program
CISM	Center for Integrated Space Weather Modeling
CLIVAR	Climate Variability and Change
COARE	Coupled Ocean Atmosphere Response Experiment
COLA	Center for Ocean, Land, and Atmosphere
COMET	Cooperative Meteorological Education and Training
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CUASHI	Consortium of Universities for the Advancement of Hydrologic Science, Inc.
DoD	Department of Defense

DOE	Department of Energy
EOL	NCAR Earth Observing Laboratory
EOS	Earth Observing System
EPA	Environmental Protection Agency
ERC	engineering research center
ESSL	NCAR Earth and Sun Systems Laboratory
EU	European Union
FAA	Federal Aviation Administration
FFRDC	federally funded research and development center
GAOS	Global Atmospheric Observing System
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GEO	NSF Geosciences Directorate
GEWEX	Global Energy and Water Cycle Experiment
GLOBE	Global Learning through Observations for the Benefit of the Environment
GPS	Global Positioning System
HAO	High Altitude Observatory
HIAPER	High-performance Instrumented Airborne Platform for Environmental Research
ICSU	International Council for Science
IGBP	International Geosphere-Biosphere Programme
IHOP_2002	International H_2O Project
INDOEX	Indian Ocean Experiment
IPCC	Intergovernmental Panel on Climate Change
IRI	International Research Institute
ITR	International Technology Research
JOSS	Joint Office for Science Support
LEAD	Linked Environments for Atmospheric Discovery
LORAN	LOng RAnge Navigation
MALT	Mesosphere and Lower Thermosphere
MLSO	Mauna Loa Solar Observatory
NAS	National Academy of Sciences
NASA	National Aeronautics and Space Administration

NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSWP	National Space and Weather Program
NTP	National Toxicology Program
OFCM	Office to the Federal Coordinator for Meteorology
ORION OOI	Ocean Research Interactive Observatory Networks Ocean Observing Initiative
PAGES	Past Global Changes
PI	principal investigator
REU	Research Experience for Undergraduates
S-Pol	S-Band Dual Polarization Radar
SBIR	Small Business Innovation Research
SCOSTEP	Scientific Committee On Solar TErrestrial Physics
SEC	NOAA Space Environment Center
SGER	Small Grants for Exploratory Research
SHINE	Solar and Heliospheric Interaction
SOARS®	Scientific Opportunities in Atmospheric and Related Sciences
STC	science and technology center
STTR	Small Business Technology Transfer
TAOS	Tethered Atmospheric Observing Systems
TOGA	Tropical Ocean and Global Atmosphere
UCAR	University Corporation for Atmospheric Research
“UCAR”	University Committee for Atmospheric Research
UNEP	United Nations Environment Programme
UOP	UCAR Office of Programs
USWRP	U.S. Weather Research Program
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WWRP	World Weather Research Program