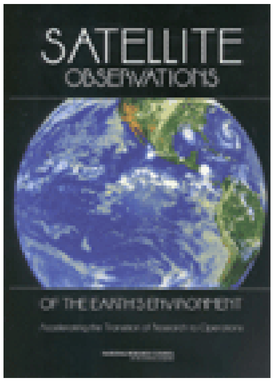

Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations

Committee on NASA-NOAA Transition from Research to Operations, National Research Council

ISBN: 0-309-52462-8, 182 pages, 7 x 10, (2003)

Satellite Observations of the Earth's Environment

Accelerating the Transition of Research to Operations

Committee on NASA-NOAA Transition from Research to Operations

Space Studies Board
Aeronautics and Space Engineering Board
Division on Engineering and Physical 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.

This study was supported by Contract 50-DGNA-1-90024 between the National Academy of Sciences and the National Oceanic and Atmospheric Administration (NOAA), with technical participation by the National Aeronautics and Space Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of NOAA or any of its subagencies.

International Standard Book Number 0-309-08749-X (Book)
International Standard Book Number 0-309-50782-0 (PDF)
Library of Congress Control Number 2003107186

Copies of this report are available free of charge from:

Space Studies Board
National Research Council
500 Fifth Street, N.W.
Washington, DC 20001

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. Bruce M. Alberts 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. Bruce M. Alberts and Dr. Wm. A. Wulf are chair and vice chair, respectively, of the National Research Council.

www.national-academies.org

OTHER REPORTS OF THE SPACE STUDIES BOARD

Assessment of Directions in Microgravity and Physical Sciences Research at NASA (prepublication) (2002)
Assessment of the Usefulness and Availability of NASA's Earth and Space Mission Data (2002)
Factors Affecting the Utilization of the International Space Station for Research in the Biological and Physical Sciences (prepublication) (2002)
Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology (2002)
New Frontiers in the Solar System: An Integrated Exploration Strategy (prepublication) (2002)
Review of NASA's Earth Science Enterprise Applications Program Plan (2002)
"Review of the Redesigned Space Interferometry Mission (SIM)" (2002)
Safe on Mars: Precursor Measurements Necessary to Support Human Operations on the Martian Surface (2002)
The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics (2002)
Toward New Partnerships in Remote Sensing: Government, the Private Sector, and Earth Science Research (2002)
Using Remote Sensing in State and Local Government: Information for Management and Decision Making (2002)

Assessment of Mars Science and Mission Priorities (2001)
The Mission of Microgravity and Physical Sciences Research at NASA (2001)
The Quarantine and Certification of Martian Samples (2001)
Readiness Issues Related to Research in the Biological and Physical Sciences on the International Space Station (2001)
"Scientific Assessment of the Descoped Mission Concept for the Next Generation Space Telescope (NGST)" (2001)
Signs of Life: A Report Based on the April 2000 Workshop on Life Detection Techniques (2001)
Transforming Remote Sensing Data into Information and Applications (2001)
U.S. Astronomy and Astrophysics: Managing an Integrated Program (2001)

Assessment of Mission Size Trade-offs for Earth and Space Science Missions (2000)
Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites (2000)
Future Biotechnology Research on the International Space Station (2000)
Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design (2000)
Issues in the Integration of Research and Operational Satellite Systems for Climate Research: II. Implementation (2000)
Microgravity Research in Support of Technologies for the Human Exploration and Development of Space and Planetary Bodies (2000)
Preventing the Forward Contamination of Europa (2000)
"On Continuing Assessment of Technology Development in NASA's Office of Space Science" (2000)
"On Review of Scientific Aspects of the NASA Triana Mission" (2000)
"On the Space Science Enterprise Draft Strategic Plan" (2000)
Review of NASA's Biomedical Research Program (2000)
Review of NASA's Earth Science Enterprise Research Strategy for 2000-2010 (2000)
The Role of Small Satellites in NASA and NOAA Earth Observation Programs (2000)

Copies of these reports are available free of charge from:
Space Studies Board
The National Academies
500 Fifth Street, N.W., Washington, DC 20001
(202) 334-3477
ssb@nas.edu
www.nationalacademies.org/ssb/ssb.html

NOTE: Listed according to year of approval for release.

COMMITTEE ON NASA-NOAA TRANSITION FROM RESEARCH TO OPERATIONS

RICHARD A. ANTHES, University Corporation for Atmospheric Research, *Chair*
SUSAN K. AVERY, University of Colorado, *Vice Chair*
MARK R. ABBOTT, Oregon State University
GRANT C. AUFDERHAAR, The Aerospace Corporation
GEORGE L. FREDERICK, Vaisala Meteorological Systems, Inc.
RUSSELL KOFFLER, National Oceanic and Atmospheric Administration (retired)
PETER R. LEAVITT, Weather Information, Inc.
WILLIAM L. SMITH, NASA Langley Research Center
RICHARD W. SPINRAD, Office of the Oceanographer of the Navy
PAUL D. TRY, Science and Technology Corporation
CHRISTOPHER S. VELDEN, University of Wisconsin, Madison

Committee on Earth Studies Liaisons

MICHAEL H. FREILICH, Oregon State University
WILLIAM B. GAIL, Ball Aerospace and Technologies Corporation

Staff

PAMELA L. WHITNEY, Study Director
RICHARD LESHNER, Research Associate
CARMELA J. CHAMBERLAIN, Senior Project Assistant
CATHERINE A. GRUBER, Senior Project Assistant

SPACE STUDIES BOARD

JOHN H. McELROY, University of Texas at Arlington (retired), *Chair*
J. ROGER P. ANGEL, University of Arizona
JAMES P. BAGIAN, Veterans Health Administration's National Center for Patient Safety
ANA P. BARROS, Harvard University
RETA F. BEEBE, New Mexico State University
ROGER D. BLANDFORD, California Institute of Technology
JAMES L. BURCH, Southwest Research Institute
RADFORD BYERLY, JR., University of Colorado
HOWARD M. EINSPAHR, Bristol-Myers Squibb Pharmaceutical Research Institute (retired)
STEVEN H. FLAJSER, Loral Space and Communications, Ltd.
MICHAEL H. FREILICH, Oregon State University
DON P. GIDDENS, Georgia Institute of Technology/Emory University
RALPH H. JACOBSON, The Charles Stark Draper Laboratory (retired)
MARGARET G. KIVELSON, University of California, Los Angeles
BRUCE D. MARCUS, TRW, Inc. (retired)
HARRY Y. McSWEEN, JR., University of Tennessee
GEORGE A. PAULIKAS, The Aerospace Corporation (retired)
ANNA-LOUISE REYSENBACH, Portland State University
ROALD S. SAGDEEV, University of Maryland
CAROLUS J. SCHRIJVER, Lockheed Martin Solar and Astrophysics Laboratory
ROBERT J. SERAFIN, National Center for Atmospheric Research
MITCHELL SOGIN, Marine Biological Laboratory
C. MEGAN URRY, Yale University
PETER W. VOORHEES, Northwestern University
J. CRAIG WHEELER, University of Texas, Austin

JOSEPH K. ALEXANDER, Director

AERONAUTICS AND SPACE ENGINEERING BOARD

MAJ GEN WILLIAM W. HOOVER, U.S. Air Force (retired), *Chair*
A. DWIGHT ABBOTT, Aerospace Corporation (retired)
RUZENA K. BAJCSY, National Science Foundation
ROBERT W. BAKER, American Airlines, Inc. (retired)
JAMES (MICKY) BLACKWELL, Lockheed Martin (retired)
ANTHONY J. BRODERICK, Aviation Safety Consultant
SUSAN M. COUGHLIN, Aviation Safety Alliance
ROBERT L. CRIPPEN, Thiokol Propulsion (retired)
LT GEN DONALD L. CROMER, U.S. Air Force and Hughes Space and Communications Company (retired)
JOSEPH FULLER, JR., Futron Corporation
RICHARD GOLASZEWSKI, GRA Incorporated
JAMES M. GUYETTE, Rolls-Royce North America
JOHN L. JUNKINS, Texas A&M University
JOHN M. KLINEBERG, Space Systems/Loral (retired)
ILAN M. KROO, Stanford University
JOHN K. LAUBER, Airbus Industrie of North America, Inc.
LT GEN GEORGE K. MUELLNER, U.S. Air Force (retired) and Phantom Works, The Boeing Company
DAVA J. NEWMAN, Massachusetts Institute of Technology
JAMES G. O'CONNOR, Embry-Riddle Aeronautical University (retired) and Pratt & Whitney
LT GEN MALCOLM R. O'NEILL, Lockheed Martin Corporation
CYNTHIA SAMUELSON, Logistics Management Institute
KATHRYN C. THORNTON, University of Virginia
HANSEL E. TOOKES II, Raytheon International, Inc.
DIANNE S. WILEY, Phantom Works, The Boeing Company
THOMAS L. WILLIAMS, Northrup Grumman–Air Combat Systems

GEORGE M. LEVIN, Director

BOARD ON ATMOSPHERIC SCIENCES AND CLIMATE

Preface

The operation of environmental data services is an important and challenging responsibility. The National Oceanic and Atmospheric Administration (NOAA), the agency charged with providing operational weather, climate, ocean, and space weather data, must ensure that these data are available 7 days a week, 24 hours a day, to a host of users around the world. Once of interest mainly to operational meteorological institutions and academic researchers, these data are now being used by a growing and increasingly diverse set of users for making business decisions, managing natural resources and the environment, mitigating and responding to hazards and emergencies, and planning recreational activities, among other uses. The growth in the number and types of data users is putting continued pressure on NOAA to meet new and evolving user needs and, at the same time, to satisfy the expanding requirements of existing data users.

The growing needs for environmental data are coupled with opportunities for more effective environmental information services, for new types of observations, and for improvements in prediction capabilities and in products offered by advanced technologies (both hardware and software) and by research that offers insights into improved understanding and use of the data. The National Aeronautics and Space Administration (NASA) plays a key role in this process as a provider of new technologies. Other agencies, such as the Department of Defense (DOD), have functioned both as technology providers to NOAA's environmental data system and as users of the system. How the process for transitioning NASA's research and technologies into NOAA's operational services could be improved is the subject of this report. Two forces—the mission to meet operational requirements and the opportunities to improve and expand predictive capability and services—create a dynamic tension that is inherent in decisions about how and to what extent NASA research and technologies can be transitioned into NOAA's operational service system.

Transitioning research opportunities into operational service can occur in several ways. One possibility is that the infusion of new technologies, through instruments or advanced sensors, satellite designs, numerical models, or algorithms, will take place within an agency—for instance, between agency research and operational centers. The transition process also involves external agencies and organizations, such as academic institutions and research and development (R&D) laboratories. NASA and NOAA have a history of successful transitions of research that have led to improvements in weather forecasts and climate monitoring. However, these transitions have often been of an ad hoc nature, and many have taken a number of years. A more rapid transition process would pay dividends in that the opportunities for societal benefit from publicly supported research would be more quickly realized.

In April 2001, the Space Studies Board and the Aeronautics and Space Engineering Board hosted a pre-project planning meeting at which outside experts and NOAA representatives discussed a range of topics relevant to a long-range vision of the architecture, technology, and customer base of NOAA's meteorological satellite program. As a result of this meeting, NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) requested that the National Research Council (NRC) convene a committee to study how to improve the process for transitioning research into operations at NOAA. NOAA invited NASA to become an equal partner in this endeavor, and the study was launched.

THE CHARGE

The NRC appointed the Committee on NASA-NOAA Transition from Research to Operations under the auspices of the Space Studies Board, together with the Board on Atmospheric Sciences and Climate and the Aeronautics and Space Engineering Board, to review the issue of the transition of research into operations and to recommend ways to improve the process. Specifically, NOAA/NESDIS and NASA tasked the committee to do the following:

- Review the potential layers of new users for future operational measurements and assess the implications of the future set of user communities in terms of future needs and approaches for transitioning from research to operations;
- Examine examples of the heritage of current NOAA satellite sensors, capture the lessons that can be gleaned from that history, and review possible approaches

that would smooth and speed the path from the conception of a research sensor to its eventual deployment in an operational satellite;

- Recommend principles for determining what levels of in-house capability will be required within NASA and NOAA and their government partners (including international partners) to ensure that there is a spannable distance between R&D experts and operational users;
- Identify opportunities for new approaches for evaluating new capabilities; and
- Identify possible approaches to enhance the infusion of new technology into the operational system in the future, and recommend means to implement a more systematic transition process that might shorten the cycle time for major program changes and make the system more responsive to user wishes. These might include still closer collaborations between NASA and NOAA, increased resources within NOAA for the conduct of instrument and satellite development, and the enlistment of international partners in a wide variety of possible roles.

STUDY APPROACH

In conducting its study, the committee held five meetings: the first three were devoted to gathering data, the fourth focused on preparing and revising the draft, and the final meeting was devoted to responding to reviewer comments. During these meetings, the committee considered input from a variety of sources. These included previous NRC reports; briefings and supplementary material provided by personnel from NASA, NOAA, and the DOD; discussions with individuals from international organizations such as the European Centre for Medium-Range Weather Forecasts, with representatives from private sector instrument and satellite development companies, and with public and private sector users of environmental data; discussions with representatives of the Office of Management and Budget and congressional staff; and the expertise and perspectives of members of the committee.

The committee's efforts have focused primarily on weather and climate because of the rich history of transitioning atmospheric research into weather forecasts and warnings, the importance of weather and climate to society, and the large amount of resources invested in weather and climate research and operations. However, the lessons learned and the recommendations contained in the report are likely to be applicable to transitions of research to operations concerning oceanographic and space weather data, and also to a broader range of federal government agencies, private sector companies, and other institutions.

The committee would like to acknowledge the many individuals who briefed the committee or provided other background material, information, or input. They include Ghassem Asrar, NASA Earth Science Enterprise (ESE); Ron Birk, NASA ESE

Applications Division; Dave Burridge, European Centre for Medium-Range Weather Forecasts (ECMWF); Marie Colton, NOAA Office of Research and Applications; Michael Crison, NOAA/NESDIS; Franco Einaudi, NASA Goddard Space Flight Center; Edward Frazier, TRW, Inc.; Wallace Harrison, NASA Langley Research Center; Jack Hayes, NOAA National Weather Service; Frank Herr, Office of Naval Research; Tony Hollingsworth, ECMWF; Sarah Horrigan, Office of Management and Budget, Science and Space Branch; Joseph Jenney, ITT (retired); Dave Jones, StormCenter Communications, Inc.; Jack Kaye, NASA ESE Research Division; Col. Lawrence Key, U.S. Air Force, Directorate of Weather, Air and Space Operations; Michael Luther, NASA ESE; Max Mayfield, National Weather Service, National Hurricane Center; Robert Murphy, NASA Goddard Space Flight Center; David Rogers, NOAA Office of Oceanic and Atmospheric Research; Richard Rood, NASA Goddard Space Flight Center; Stanley Scheidner, National Polar-orbiting Operational Environmental Satellite System Integrated Program Office; Ray Taylor, NASA Goddard Space Flight Center; William Townsend, NASA Goddard Space Flight Center; Louis Uccellini, NOAA National Centers for Environmental Prediction; Stan Wilson, NOAA/NESDIS; Robert Winokur, Earth Satellite Corporation; Greg Withee, NOAA/NESDIS; and Erin Wuchte, Office of Management and Budget, Commerce Branch.

Richard A. Anthes, *Chair*
Committee on NASA-NOAA
Transition from Research to Operations

Acknowledgment of Reviewers

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:

Farouk El-Baz, Boston University,
George J. Gleghorn, TRW Space and Technology Group (retired),
Brig. Gen. Albert J. Kaehn, Jr., U.S. Air Force (retired),
Ari Patrinos, Department of Energy,
Joyce Penner, University of Michigan,
Robert J. Plante, Raytheon Systems Company, and
Thomas Vonder Haar, Colorado State University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert A. Frosch, Harvard University, and Maj. Gen. Eugene Fox, U.S. Army (retired). 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

Observing and accurately predicting Earth's environment are critical for the health, safety, and prosperity of the nation. The United States invests heavily in making global measurements from satellites and in using these observations to create accurate weather forecasts and warnings, long-term climate records, and a variety of other environmental information products. Major opportunities exist for advances in prediction and in other weather, ocean, and climate information products. Realizing the potential benefits of the investments in satellites requires rapid, efficient transitions of measurement and modeling capabilities developed in the research community to the observing and prediction systems of the operational agencies. In the case of spaceborne environmental measurements, the National Aeronautics and Space Administration (NASA) conducts research into the development of measurement technologies and analysis techniques. The National Oceanic and Atmospheric Administration (NOAA) is responsible for civil operational observing systems and associated products, services, and predictions.

This report examines the NASA-NOAA research-to-operations transition process and provides recommendations for improvements that will lead to more rapid and efficient interagency transitions. The primary finding of the National Research Council's Committee on NASA-NOAA Transition from Research to Operations is that, while clear examples of successful transitions currently exist, the transition process in general is largely ad hoc. Some transitions are relatively successful, but many are less so, and no mechanism is available to ensure that the transition process in general is efficient and effective. The committee's primary recommendation is *that a high-level joint NASA-NOAA planning and coordination office should be established to focus specifically on the transition process.*

The ability to observe and predict Earth's environment, including weather, space weather, and climate, and to improve the accuracy of those predictions in a complex society that is ever more dependent on environmental variability and change, has heightened the importance and value of environmental observations and information. These observations, and the predictions on which they are based, are now essential to many components of society—including national defense, industry, policy-making bodies, and the people and institutions that manage natural resources—as well as to the comfort, health, and safety of the public. It is estimated that as much as 40 percent of the $10 trillion U.S. economy is affected by weather and climate annually.

Because satellites can observe the entire Earth at relatively low cost, they play an essential role in contributing to the global database that describes the Earth system and that is necessary for prediction. Advances in remote sensing technology and research have put the dream of an *Earth Information System* (EIS)—which would make available to a myriad of users valuable quantitative digital data about the complete Earth system—within reach in the next few decades. The scientific and technological foundation for the vision of the EIS rests on the opportunity to observe the complete Earth system with unprecedented resolution and accuracy and to assimilate the diverse observations into complex models. Satellites will provide many, though not all, of the future observations required to describe Earth completely.

Realizing the vision of the EIS and the predictive capabilities that it supports, however, is neither easy nor guaranteed. It depends on transferring the advances in research and technology—many of which are accomplished by NASA and its university and private sector partners—to useful products, applications, and operations, which are primarily the responsibility of NOAA and the Department of Defense (DOD). How to improve this technology transfer, or "transitioning," process in the area of weather and climate is the subject of this report. Although the report focuses on weather and climate and on NASA and NOAA, the lessons learned and the recommendations presented here are likely to be relevant to other satellite applications and to other agencies.

In the more than 40 years since the launch of the first weather satellite, the Television Infrared Observation Satellite (TIROS-I), on April 1, 1960, there have been many successful transfers of NASA research into NOAA and DOD operations. These successful transfers have led to a steady increase in forecast accuracy and to a variety of beneficial applications for society, including the protection of life and property as well as support for commerce, industry, resource management, the military, and personal activities.

Along with the successes, however—many of which have occurred in spite of a relatively ad hoc, unplanned, or inefficient process—there have been research missions with opportunities for practical applications that have been slow to be realized or that have gone unrealized altogether. Given the large cost (several billion dollars per year) of research satellites and operational weather and climate services and the increasing importance of and opportunities offered by satellite-based remote sensing, there is an increasing realization that greater attention should be paid to the technology transfer or transitioning process itself, in order to accelerate the rate of return on the research investment.

Transition pathways are the end-to-end set of processes assembled for achieving successful transitions. Each pathway requires a strong supporting infrastructure, which consists of a number of building blocks including a solid research foundation, laboratories, equipment, computers, algorithms, models, information technologies, and test beds. Robust and effective transition pathways are needed to bridge the *valley of death*—that is, the gap that can exist between research and operations for technologies with known applications—and the *valley of lost opportunities*—that is, unrealized potential in which unforeseen applications of new technologies are missed completely.

Bridging the valleys of death and lost opportunities can be done in various ways. It often depends on an appropriate balance between the "push" of new research results and opportunities from the research community and the "pull" from the perceived needs or requirements of the operational community and users. The process is hindered by a variety of obstacles, including these:

- Cultural differences between the research and operational communities,
- Organizational issues,
- Poor communication and coordination between the research and operational communities,
- Lack of adequate financial or educated human resources,
- Absence of effective long-range planning, and
- Inadequate scientific knowledge or technological capability.

The committee's examination of a sample of historical case studies in which the transition from NASA research to NOAA and DOD operations has occurred with varying degrees of success (see Appendix B) suggests ways to improve the transitioning process and so increase the rate at which the return to society on the research investment is achieved. These improvements include making the multiple processes that support the transition from research to operations more flexible and efficient.

The committee's overarching recommendation is to establish a strong and effective joint NASA-NOAA office to plan, coordinate, and support the transitioning of NASA research to NOAA operations.[1] The planning and coordination should include an early evaluation of each research mission, including new sensor capability and potential operational utility. Every appropriate mission, as defined by the formal evaluation process, should have a flexible strategic plan for transferring the research to operations.

The committee recognizes, however, and strongly emphasizes that not all NASA research missions are or should be driven by operational needs or requirements—a major and essential part of the NASA mission is to increase fundamental understanding of Earth and the universe, regardless of foreseeable operational opportunities. However, many NASA missions have both a fundamental research component and the potential for applications of the science and technology for the benefit of society. This report focuses on that type of mission.

The improved transitioning process should be based on a balance between research push and operational pull. This balance, which will vary from one mission to another, can be achieved through increased dialogue between the two communities and through overlap within their respective missions (i.e., research missions that have an operational component and vice versa). The data from research missions should be tested in operational settings and the operational impact assessed. Conversely, the collection, processing, and archiving of operational data should take into consideration the needs of the research community as well as the operational impact of the data. Test beds, in which assimilation methods and algorithms using research results and data are developed and evaluated prior to and during research missions, are an important component of the transitioning process. These test beds not only will help determine how best to use the research data and evaluate their impact, but also will enable experimentation with new models and products in parallel with the operations.

The user community should be involved early in the planning for research missions, and each mission should have an education and training plan. This plan

[1]Following its charge, the Committee on NASA-NOAA Transition from Research to Operations is making recommendations to NASA and NOAA to form and to be the primary participating agencies in this joint transition office. However, the committee recognizes the value of cooperation between NASA, NOAA, and other partners, including the Department of Defense and international organizations. Consequently, this joint office is intended to be and is offered as a flexible institution so that NASA and NOAA could invite the DOD or other U.S. agencies to become full participants when and if appropriate. See Recommendation 1 in the next section in this Executive Summary and the discussion in Chapter 6 for greater detail regarding the structure of this transition office.

should take into account the operational, research, and academic communities, including students.

Adequate resources must be devoted to the transitioning process. The committee has not attempted to determine the amount of the resources required (which would vary from mission to mission) but believes that compared with the support currently provided for research and operations separately, the additional amount would be small—perhaps on the order of 5 to 10 percent of the research and operational budgets. The committee believes that this investment would pay large dividends in increasing the intrinsic value of research missions, improving existing operational products, and creating new ones.

RECOMMENDATIONS

Recommendation 1: A strong and effective Interagency Transition Office for the planning and coordination of activities of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) in support of transitioning research to operations should be established by and should report to the highest levels of NASA and NOAA.

The proposed Interagency Transition Office (ITO) should have broad responsibility (not specifically related to sensor capability) for ensuring that appropriate research is efficiently and effectively transitioned to operational uses. However, the ITO itself should not implement the transitioning activities. The implementation should be carried out by appropriate NASA or NOAA entities (such as the National Polar-orbiting Operational Environmental Satellite System [NPOESS] Integrated Program Office, with its current charter for the acquisition of polar operational satellite systems) or by their partners in the academic community and private sector. The ITO is intended to support and simplify transitions by augmenting, enabling, and leveraging the existing infrastructure within NASA and NOAA rather than by introducing duplicative capability or bureaucracy.

The ITO should have an independent, high-level advisory council consisting of representatives from the operational and research communities as well as from the public and private sectors. The council should also serve as a forum for regular discussions between the leaders of the research and operational organizations.

An executive board, envisioned by the committee as including the NASA and NOAA administrators and the President's Science Advisor at a minimum, should provide high-level oversight and review of the ITO. NASA and NOAA should consider including as executive board members representatives at an equivalent level from DOD (for example, the undersecretary of defense for acquisition and technology) and from other agencies when appropriate to the mission of the ITO.

Implementation of the following recommendations is needed in order to support the mission of the proposed ITO. However, these recommendations are not specifically tied to the establishment of the ITO. They stand on their own merit and are necessary to strengthen any transitioning mechanism or pathway.

Recommendation 2: NOAA and NASA should improve and formalize the process of developing and communicating operational requirements and priorities.

2.1 NOAA should continuously evaluate and define operational user needs and formally communicate them to NASA on a regular basis.

2.2 NASA should formally consider the requirements of NOAA and other operational agencies in establishing its priorities (the "pull" side of the transition process). NASA should establish appropriate programs and budgets as needed to respond to selected NOAA requirements.

Recommendation 3: All NASA Earth science satellite missions should be formally evaluated in the early stages of the mission planning process for potential applications to operations in the short, medium, or long term, and resources should be planned for and secured to support appropriate mission transition activities.

The evaluation process should include engaging in dialogue with the research and operational communities and obtaining input from possible users of the observations. For appropriate missions, as determined by the assessment, a flexible plan or architecture for a seamless transition pathway, including the necessary financial and human resources, should be developed, regularly reviewed, and updated as necessary.

For a mission that is identified as having significant potential for providing data useful to operations, the following activities should be supported:

3.1 NASA and NOAA should work together to strengthen the planning, coordination, and management components of the mission. Teams of people with appropriate research and operational expertise should be assigned to the mission. A culture fostering aggressive and challenging approaches, risk taking, acceptance of outside ideas and technologies, flexibility, and a "can-do" attitude should be encouraged.

3.2 Adequate resources should be provided in order to support all aspects of the transitioning activities, as determined by the assessment and plans. Consideration should be given to establishing guidelines and mechanisms for encouraging transition efforts. For example, a small fraction (e.g., 5 to 10 percent) of each sensor or mission project budget might be allocated to transition activities. Principal investigators might be asked to submit plans or concepts for transitional activities, with significant points being allotted in scoring this aspect of the proposals.

3.3 Research into *how* to use new types of observations should be supported well in advance of the launch of the research or operational mission that acquires the observations. In parallel with the acquisition program, this research should include developing and testing algorithms to convert sensor data to environmental products (including environmental data records) and data-assimilation methods, as appropriate to the mission. The research may be carried out in a variety of institutions, including universities, national laboratories, cooperative institutes, and test bed facilities. The institutional mechanism(s) to conduct the research should be identified early in the mission.

3.4 Each research mission should have a comprehensive data-management plan. The plan should include the identification of potential users and approaches for processing the data, converting the raw data to information, creating metadata, distributing data and information to users in real time, and archiving and the subsequent accessing of data by users.

3.5 NASA and NOAA, through the ITO as defined in Recommendation 1, should develop a plan to include the use of NPOESS and Geostationary Operational Environmental Satellite (GOES-R) sensor data by the appropriate government agencies. A collaborative arrangement and at least one demonstration/pilot or benchmark project should be developed with each primary user agency (e.g., the U.S. Geological Survey [USGS], the U.S. Department of Agriculture [USDA], and the Environmental Protection Agency [EPA]) using NPOESS and GOES-R products.

3.6 Each research mission should have an associated education and training plan. This plan should be addressed to the operational, research, and academic communities, including students. It could include, for example, scientific visitor exchange programs, support for collaborative research, workshops, and a plan for the timely flow of research data to operational and academic institutions.

3.7 The evaluation process and resulting transition plans should consider potential roles in the research-to-operations transition process for the academic community (including principal-investigator-led projects) and the private sector, both of which have relevant capabilities and knowledge not available within NASA and NOAA.

Recommendation 4: NASA and NOAA should jointly work toward and should budget for an *adaptive* and *flexible* operational system in order to support the

rapid infusion of new satellite observational technologies, the validation of new capabilities, and the implementation of new operational applications.

4.1 Operational satellite programs should provide for the capability of validating advanced instruments in space and of cross-calibrating them with existing instruments, in parallel to the operational mission, by the most efficient means possible (e.g., by reserving approximately 25 percent of the payload power, volume, and mass capability; through "bridge" missions; and so on).

4.2 To the extent possible, observations from research missions should be provided in real time or near real time to researchers and potential users. Operational centers or associated test beds should use and evaluate the research observations in developing their products and should provide feedback to researchers. Test beds such as the Joint Center for Satellite Data Assimilation and the Joint Hurricane Testbed should be supported as a way to bridge the final steps in the gap between research and operations. The primary mission of such test beds should not be to conduct basic research or operations, but rather to develop and test new real-time modeling and data-assimilation systems to use the new observations. The test beds should include participation by the academic research community and should be quasi-independent from the operational agencies.

4.3 Senior personnel responsible for transition activities should be located at major operational centers of NOAA and at the major research segments of NASA.

1

Introduction

Exploration, understanding, and prediction of Earth's environment, especially its weather and climate, have been a dream of humankind for ages. Until the 20th century, this dream was largely unrealized. In the 20th century, however, and especially in the second half, progress in both understanding and prediction has been rapid. This progress has been made possible by discoveries based on observations, theory, and models as well as on technologies, including in situ and remote sensing observations, computers, and other information technologies such as communications systems. In a society that is more dependent on weather and climate than ever before, the increasing ability to observe and predict the atmosphere, oceans, and related elements of the Earth system has shown significant value in protecting life and property and in allowing society to mitigate the effects of, adapt to, and take advantage of the variability and extremes in weather and climate.

Satellite observations provide a unique vantage point from which to study the Earth system. Providing a vast range of observations—from measurements of atmospheric and oceanic circulation, to observations of ocean and land productivity, to measurements of upper-atmospheric temperatures, to space weather—satellites are sentinels of the global system. Moreover, they observe rapid changes, such as severe storms, floods, and even harmful phytoplankton blooms in the coastal ocean.

Because of the importance of Earth's environment to society, the United States spends large amounts of resources on research into the Earth system and on operational prediction of the environment, particularly the prediction of weather and climate. This investment has paid great dividends, as general forecasts and warnings of severe weather have improved steadily over the years. Yet there is a realization that the practical application of research achievements to the improvement of operations (a complex process loosely called *transitioning research results into operations*) is often less efficient and slower than it could be, resulting in a loss of return on the research investment (NRC, 2000a; GAO, 2002; Hertzfeld and Williamson, 2002). For example, it took more than 25 years after the launch of the first infrared (IR) sounding sensor to successfully use the data operationally (see Appendix B, "Case Studies of Transitions from Research to Operations"). The reasons are as complex as the transitioning process itself, and a number of other studies have addressed this and related issues (see Chapter 2, "The Research-to-Operations Context").

This report, building on previous studies, looks at the transitioning process in the context of the current fiscal and technological environment and suggests ways to improve that process. It focuses on weather and climate because of the rich history of transitioning atmospheric research into weather forecasts and warnings, the great impact of weather and climate on society, and the large amount of resources invested in weather and climate research and operations. In response to the needs of the study's sponsors, the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA), the report focuses on the transition of NASA satellite research to NOAA operations. However, the lessons learned and the recommendations made are likely to be applicable to a wide range of environmental issues as well as to the mission and operational needs of other government agencies and the private sector.

The Committee on NASA-NOAA Transition from Research to Operations recognizes that an important part of NASA's mission is to carry out fundamental research on Earth and the universe—research for which there are no immediate or known applications. However, the emphasis of this report is on the many NASA missions that have both a fundamental research component and the potential for applications to benefit society and on ways in which the research results from these missions can be more effectively transitioned into operations.

Chapter 2 sets the research-to-operations context by reviewing previous studies related to the charge of this committee, the research-to-operations process in general, and the missions and roles of NASA, NOAA, and the Department of Defense (DOD). Many of the recommendations from the related studies (see Appendix A) are directly relevant and appropriate for this study, and they should be reviewed, considered, and responded to by policy makers.

Subsequent chapters consider the increasing impact of weather and climate on society, provide examples of the progress in understanding and predicting weather and climate over the past several decades, and describe the increasing applications and users of weather and climate information. Chapter 3 presents a vision for the next 25 years—an *Earth Information System* (EIS)—in which quantitative, geo-referenced digital information about the Earth system (atmosphere, biosphere, hydrosphere, lithosphere) is available to a myriad of users for the benefit of society. Supporting the vision of an Earth Information System are many exciting new opportunities in space-based remote sensing (Chapter 4). A summary of these opportunities is followed by a discussion of past and present approaches, or transition pathways, from research to operations (Chapter 5). Case studies of successful and unsuccessful transitions from research to operations (Appendix B) provide empirical evidence of the problems and, more importantly, the best practices, associated with the transitioning process. The report concludes with a proposal for a mechanism for achieving more effective transitions (Chapter 6) and a summary of the committee's findings and recommendations (Chapter 7). Information about U.S. missions, biographical information on the committee members, and a list of acronyms are included as Appendixes C, D, and E, respectively.

Advances in the ability to observe Earth from space and to assimilate these observations into high-resolution, coupled Earth system models form the scientific and technological basis for the vision of an *Earth Information System*—a complete, geo-referenced quantitative description of the Earth system that supports a variety of applications and users. A robust and flexible mechanism for transitioning research and technological advances quickly into operations is necessary to achieve the vision in a timely fashion and to maximize the return on research investment.

2

The Research-to-Operations Context: Bridging the Valleys of Death and Lost Opportunities

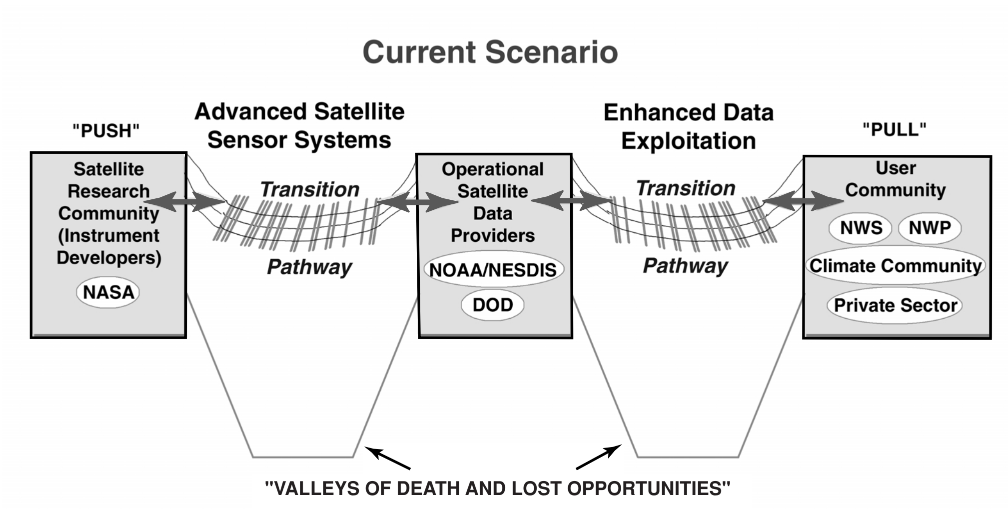

FIGURE 2.1 Illustration of a transition pathway from research to operations and the “push-pull” dynamic. Currently the valleys of death and lost opportunities are spanned by relatively ineffective bridges. The goal is to strengthen these bridges and their supporting infrastructure, making the transition pathways quicker and more efficient.

BOX 2.1

***From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death*—A Brief Summary**

A recent NRC report, *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (NRC, 2000a), is highly relevant to the present study. The earlier report discusses the need for improved transitioning of research and development in the areas of numerical weather prediction and environmental satellites. It notes the increasing sensitivity of many sectors of society to weather and climate and therefore the increasing value of accurate weather and climate information. It discusses the difficulties of transitioning research results to operations across the "valley of death," which is a metaphor for the barriers and obstacles separating research results and operational applications. The report notes that successful transitions require an understanding of the importance and risks of transition, the development of appropriate transition plans, adequate resources for the transitions, and continuous communication and feedback between the research and operational communities. The 2000 report makes a number of important recommendations (see Appendix A in the present report) to NASA and NOAA with respect to improving the transitioning process. The Committee on NASA-NOAA Transition from Research to Operations supports those recommendations, and builds upon them.

Several previous National Research Council (NRC) studies have addressed the issue of transitioning research results into operations, or technology transfer (see Box 2.1). Appendix A presents some of the findings and recommendations from these studies, which are generally consistent and emphasize the importance of improving the technology-transfer process. In addition, they recognize that there is no unique way to effectively transition research results into operations; the process is complex, often inconsistent, not formalized, and consequently depends very much on the individuals in various leadership positions during the process.

This chapter describes the mission and roles of NASA, NOAA, and DOD and then discusses research-to-operations transition pathways in general.

MISSION AND ROLES OF NASA, NOAA, AND DOD

In order to meet the present and future needs of the growing number of users of satellite observations of the Earth environment, it is necessary to continually develop satellites that can reliably provide the observations necessary to support the information database for the envisioned Earth Information System and the growing capability for predictions. Satellites and the data products that are developed in conjunction with them have historically been outgrowths of research programs that develop new sensor technology and make new kinds of observations. In the federal government, these research programs are usually the responsibility of NASA. The operational use of remote sensing satellites, as well as the dissemination of useful information associated with them, is a responsibility of NOAA. Another important agent in the research-to-operations process is the DOD, which has a legacy of infusing advanced research and technology into operational programs and which actively participates with NOAA in weather and climate monitoring.

The mission of NASA's Earth Science Enterprise (ESE) is to "develop a scientific understanding of the Earth System and its response to natural or human-induced changes to enable improved prediction capability for climate, weather, and natural hazards."[1] NASA spends approximately $1.5 billion annually on developing satellites to observe and learn about the Earth system, and NASA's contributions to the understanding of Earth over the years have been substantial (see NRC, 2001d, and its bibliography).[2] In addition, many of the NASA research satellites and instruments have provided advanced measurement and satellite technologies that contribute to operational monitoring programs and satellite systems at NOAA and DOD. The transition of NASA research and technology capabilities (satellites, instruments, data-assimilation techniques, and scientific understanding) into NOAA programs has led to major improvements in weather forecasting, warning, and climate monitoring (Hertzfeld and Williamson, 2002). However, some of the transitions have taken many years to complete, and given the increasing importance of weather and climate to society, there is a strong desire to increase the rate of transitioning from research to operations.

The mission of NOAA includes describing and predicting Earth's environment in order to protect lives and property and to contribute to the nation's economic and environmental health. According to the *Report to Congress on the Status and Challenges for NOAA's Environmental Data Systems* (NOAA, 2001a), NOAA spends almost $1 billion each year collecting environmental data from around the world and space in support of this mission. NOAA's data products and information help the agency fulfill its mission in various ways: by supporting decisions that save lives and protect property, by assisting in the development of public policy for environmental stewardship, by helping in the management and conservation of marine resources, and in general by enhancing the economic prosperity and quality of life in the United States. Colgan and Weiher (2003) describe how NOAA's role as a provider of environmental information supports the "knowledge economy" and the creation of economic wealth across a very broad range of U.S. sectors.

---

[1]See the NASA ESE Web site at <http://www.earth.nasa.gov/>. Accessed February 3, 2003.

[2]The total budget for NASA's Office of Earth Science is provided for developing satellites, research and technology, mission operations, education, and other investments. See the Web site at <http://ifmp.nasa.gov/codeb/budget2003/>. Accessed February 3, 2003.

The Department of Defense invests approximately $1 billion per year in operations, research, and development related to the collection of environmental data and the use of these data in support of national security. Geostationary and polar-orbiting satellites are critical platforms for this data acquisition. The U.S. Air Force and U.S. Navy (and their respective support to the U.S. Army and U.S. Marine Corps) apply meteorological and oceanographic products to a full range of activities, including mission planning (e.g., force prepositioning), operational support (e.g., air tasking orders), and tactics (e.g., target selection).

Operational agencies such as NOAA have traditionally been conservative in the introduction of new sensors and sensor technologies (NRC, 1997, 2001e), an understandable approach given the consequences of failed operational systems or flawed data. Research agencies such as NASA, however, tolerate and indeed embrace greater risk. The previous NASA administrator (Goldin, 2000) made statements encouraging NASA to accept a 30 percent failure rate for space missions in order to balance acceptable risk with technology innovation. A research instrument with the potential for operational use must be designed so that residual risk in the research configuration can be effectively mitigated in a low-risk transition to the operational version. The research design phase may require planning in order to specifically accommodate the operational transition.

RESEARCH, OPERATIONS, AND THE "PUSH-PULL" DYNAMIC

The delineation between research and operations is sometimes blurred, making it important in this report to clarify the terms and definitions (see Box 2.2).

Both weather and climate have their own particular operational data requirements. To illustrate the terms in Box 2.2, "operational weather" data must be acquired globally and processed in real time and often do not have the need for consistency in measurement characteristics that is required for climate observations. "Operational" in the climate context, however, includes a long-term commitment to certain key observations, ensuring that there are few gaps in the data record, that the data are acquired and preserved, and that acquisition costs remain affordable. Although long time series are generally used to detect climate change, many processes, such as ocean circulation, are only revealed on decadal scales. These long-term, systematic measurements may need to be "operationalized" within either NASA or NOAA in order to provide a secure, consistent observation base. Previous NRC reports (NRC 2000c, 2001e,f) have focused on these issues.

The end-to-end set of processes for transitioning research results into operations is called a *transition pathway*. Pathways may vary depending on the type of research and the potential application. A complete pathway begins with basic research and ends with operational application of the research results and the generation of

BOX 2.2

Definition of Terms

For the purposes of this report, the following definitions of research, operations, and transitioning activities are adopted:

- **Research activities**—*develop* scientific understanding of important processes and/or *demonstrate* the capabilities of new analysis, modeling techniques, or measurement technologies, typically through acquiring, calibrating, and characterizing a specific set of measurements.
- **Operations activities**—*routinely and reliably generate* specific services and products that meet predefined accuracy, timeliness, and scope/format requirements, as well as *disseminating* or making them available to a variety of users in the public, private, and academic sectors.
- **Transitioning activities, or processes**—*transfer* new or improved scientific knowledge or technologies produced by research to operations. The end-to-end set of processes for transitioning research results into operations is a *transition pathway*.

products that meet the needs or requirements of end users. Ideally, the research-to-operations process related to observational technologies includes (1) the demonstration that useful measurements can be acquired, quantitatively calibrated, and characterized; and (2) the development and implementation of the observing, data processing, modeling, and dissemination systems, allowing the measurements to be routinely obtained and used.

The transition process should involve a "push-pull" dynamic in which research and technology development programs respond to the requirements (pull) of the operational user and the operational system takes advantage of new research results and technologies (push) that emerge as a result of science and technology evolution.

A full transition requires that the measurements be acquired routinely and reliably by an operational observing system. While it is possible and even desirable to use data obtained by research systems in operations, the production of operational products and services cannot *rely* on measurements obtained by research systems, which generally lack the mechanisms needed to ensure timeliness, stability, and longevity.

Transition pathways and challenges depend on whether the fundamental impetus originates from operational needs (pull) or research capabilities (push). In the most straightforward but rare cases of pull transitions, the operational entity determines, through numerical simulations or some other means, that measurements with specified characteristics could contribute to improvements in operational products or services. The operational agency then communicates specific and complete measurement requirements to the research community, including the observing system resources that would be needed for acquiring the data. The operational entity also evaluates and controls optimization across all requirements, including measurement accuracies, resolution, and costs. The research community has clear responsibility for developing the science and technologies within the requirements and constraints established by the operational entity.

Efficient transition pathways are needed to enable the continuous infusion of new scientific results and technologies into the operational environmental satellite observing system.

The transition pathway is significantly more difficult when the initial transitioning impetus results from research and new capabilities—the push side of the process. In this scenario, the measurement or analysis capability is often demonstrated with little or no regard for specific operational utility or for the availability of resources in the operational data-acquisition-and-analysis system. The operational entity must plan, fund, and carry out the demonstration of utility before the new technology can be considered for inclusion in the operational system. The European Centre for Medium-Range Weather Forecasts[3] (ECMWF) has done an excellent job in aggressively and rapidly demonstrating the utility of measurements developed in the research community. The NASA-NOAA Joint Center for Satellite Data Assimilation (JCSDA)[4] promises to be a substantial improvement over the existing approach for demonstration of the use of environmental research data in the United States.

TIME SCALES IN THE TRANSITIONING PROCESS

Managing multiple and often conflicting time scales for transitions is one of the most difficult pathway challenges. In planning a transition, time scales may include 1-year budget cycles, 2-/4-/8-year political cycles, 3- to 8-year satellite lifetimes (with accompanying uncertainty), lengthy procurement cycles, obsolescence cycles, the doubling of computational power every 18 months, and many other issues. A well-defined transition pathway carefully balances these time scales in establishing schedules and planning for resources.

[3]More information on the European Centre for Medium-Range Weather Forecasts is available online at <http://www.ecmwf.int/>. Accessed February 3, 2003.

[4]More information on the Joint Center for Satellite Data Assimilation is available online at <http://jcsda.gsfc.nasa.gov>. Accessed February 3, 2003.

When the time scale for transition is short (for example, some months to a couple of years), the processes and interfaces are relatively straightforward. The transition process can be managed much as a "product improvement" process, during which research and operations work closely together. The requirements are generally well understood, and the resources necessary to support the improved product can be identified and acquired.

For transitions occurring on a medium time scale (for example, 2 to 5 years), the technical and administrative issues become more complicated. The process is analogous to "product development," during which a research and development (R&D) center is attempting to develop and refine a potential product and bring it to market. The product requirements may not be well understood, and the operational/production side may be skeptical of the actual costs that may be incurred. Time schedules may be poorly defined, and the project may run late, thus incurring more costs. Continuous evolution in the research requirements may also add to complexity and uncertainty. The transfer of programmatic responsibility for a research satellite mission to an operational agency is an example of such a midrange transition.

At long time scales (5 to 15 years), the transition process resembles "market development," during which needs and capabilities are poorly known but often evolve rapidly as research proceeds and new ways are discovered to use the research data.

SPANNING THE VALLEYS OF DEATH AND LOST OPPORTUNITIES

Borrowing from the language of technology transfer, there needs to be a "spannable distance" between the research and operational communities, as well as a mechanism that bridges this distance and connects the researchers to the end users of the data and technologies (NRC, 2001b). The gap between research and operations is often called the *valley of death* (NRC, 2000a).

Closely related to the valley of death, the *valley of lost opportunities* represents the gap between research and unknown or unrecognized applications. The valley of lost opportunities represents the chasm between what might have been possible and what is actually realized. It represents the missing of opportunities that are presented by the push side of the transition process. For example, the operational community may be slow to recognize the potential of new technologies because it cannot foresee uses for them, their impact on operations, or new users created by these technologies (the example of the Global Positioning System is discussed in Chapter 3). The valley of death represents the barrier between research and recognized operational needs (the pull impediment), whereas the valley of lost opportunities represents the gap between research and unknown or unrecognized applications (the push impediment). The combined impediments are referred to here as the *valley of death and lost opportunities*. There may be more than one such valley in the long transition pathway from research to operations.

Figure 2.1 illustrates the valleys of death and lost opportunities—the gap between researchers and operational satellite data providers and the gap between the satellite data providers and end users. Each valley can be measured in several dimensions, including those of organizational structure and culture, mission objective and design, planning and coordination, communication, and financial and human resources, as well as that of the limitations associated with scientific understanding and technical capability.

Ideally, the organizational structure of the research and operational agencies would be efficiently aligned to support technology transfer across the transition pathway. Staff would be highly educated, trained, and motivated. The cultures would be open to new ideas from other organizations, as well as being cooperative, team-oriented, and supportive of the technology-transfer process. Planning for technology transfer would occur from the very beginning of a research mission and would be updated continuously as the mission progressed. Communication and coordination would occur between the researchers and the operational personnel throughout the mission. The necessary scientific and technological underpinnings of the mission would be solid, including the scientific understanding required to use the mission results (e.g., observations) effectively to improve operational products and services (e.g., numerical weather forecasts). And finally, adequate financial and human resources would be available, not only to the research and operational sides but also to the transitioning process that bridges the gap.

Given the complexity of the transitioning process, there are many ways in which the pathway can be slow and inefficient, or it might break down altogether. The absence of ab initio plans to transfer research results into operations will delay the process when the research results emerge, or it may prevent them from ever being used. Even with good plans from the beginning, poor communication and coordination or cultural issues may prevent the implementation of the plans and their modification as necessary throughout the mission. If the scientific and technological underpinnings are weak, the research/technology part of a mission can fail altogether; or, the operational community may not have the scientific basis to use the research results and observations when they become available. Of course, the success of the entire end-to-end process depends on adequate financial and human resources. In general, financial resources can be invested to obtain the necessary human resources, but this is not guaranteed. It takes time to develop the necessary human resources through education and training, so the human resource needs must be anticipated explicitly throughout the process: "Well trained people are, therefore, one of the most important components of the remote sensing technology transfer process" (NRC, 2001b).

SYNERGIES BETWEEN RESEARCH AND OPERATIONS

As has been recognized in previous studies (NRC, 2000a, 2001b), the needs and issues that drive the development and use of research satellites are in many ways distinctly different from those that drive their operational counterparts. These differences constrain transition pathways in important but often subtle ways. For example, while systematic research and operational measurements are commonly viewed as being synonymous, in reality, resolving their differences (see Table 2.1) is critical to the success of the research-to-operations transition. Operational measurements are driven by the need for uninterrupted availability; systematic research measurements are driven by the need for long-term stability and are less sensitive to occasional data loss.

In spite of their differences, research and operations often experience strong synergies and positive feedbacks. While research is a key to advancing operational capability, operational data in turn provide essential support for research. For more than a hundred years, observations collected primarily for the purpose of operational weather forecasting have been used by scientists to study the structure and behavior of the atmosphere and to monitor climate. Evidence of the real-time access of environmental data by the research community can be seen in the Web sites of many university departments and research laboratories. Improved understanding of the atmosphere-Earth system from this research has been as important to the progress of operational weather forecasting as the data themselves.

The quality of research data sets must be based on calibrated and validated data, as their impact on theories, models, and algorithms may last indefinitely. Because the type of data required for research is generally the same type required for operations, the research data sets will often come from the same sensors used to support operational applications, or from experimental prototypes of future operational

TABLE 2.1 Key Differences Between Research and Operational Satellites

	Approach	
Issue	Research Satellites	Operational Satellites
Replace on failure?	Rarely	For high-priority sensors
Uninterrupted operation	Usually desired	Nearly always required
Spare satellite on-orbit or rapidly available	No	Yes
Data format and collection	May change over mission	No change over mission
Risk tolerance	Moderate	Low
Data latency	Hours to months	Hours or less
Impact of reduced data quality	Reduced science	Lower-value products
Time value of data	High long-term value	High immediate value
Calibration drivers	Long-term stability	Pixel-to-pixel stability

Because long-term research data sets are primarily derived from operational systems, NOAA and NASA should jointly develop an approach for generating research-quality data sets from next-generation operational satellite sensors.

instruments. Thus, a validation and quality-assurance approach should be adopted that enables the near-real-time generation of research-quality data, which can be archived for future research. At the same time, research data should be made available to operational users to test and evaluate their potential value in operations. The involvement of operational centers in the early testing and use of research data sets has provided invaluable feedback to mission researchers. Early and continual data-management planning is essential if NASA and NOAA are to satisfy the multitudes of research and operational users.

The relationship involving dynamic, positive feedback between research and operations highlights the importance of a strong cooperative relationship between NASA, NOAA, and DOD. As the rate of technological change increases and society becomes more dependent on the products and information provided by satellite remote sensing, these agencies' ability to quickly transfer new satellite and sensor technologies, models and algorithms, and scientific knowledge into new applications and user products becomes even more critical (NRC, 2003).

3

The Impact of Weather and Climate on Society and a Vision for the Future

This chapter discusses ways in which society is becoming increasingly sensitive to weather and climate. At the same time, better understanding, observations, and numerical models are leading to improvements in the accuracy of weather and climate information. Together, the increased sensitivity and the availability of more accurate information are creating more and new users of environmental information and are heightening the value of this information. Satellites provide an essential component of a global observing system that serves as a foundation for an Earth Information System, a comprehensive environmental database that will support a large variety of users for the benefit of society. The trends highlighted above call for a more rapid transitioning of NASA research to NOAA operations in order to increase the rate of return to society from the public investment in research.

THE IMPACT OF WEATHER AND CLIMATE ON SOCIETY

There is widespread appreciation for the fact that the value of weather, climate, and environmental data, information, and forecasts is growing in importance to the U.S. economy (e.g., Colgan and Weiher, 2003). According to some estimates, up to 40 percent of the approximately $10 trillion U.S. economy is affected by weather and climate events annually (NRC, 1998a; NOAA, 2001b; Dutton, 2002). The cost of U.S. disasters related to weather and climate is rising rapidly, a consequence of population growth, rising wealth, and social behavior (Changnon, 2000; Pielke and Carbone, 2002). Approximately 90 percent of all presidentially declared disasters in the United States are weather-related (Kelly, 2001). Weather affects aviation, air quality, health, ground and marine transportation, defense, agriculture, fisheries, water, energy, construction, tourism, and many other sectors of the economy. Even "good" weather can cause problems in this complex society; for example, one unexpectedly warm winter day in the Northeast can cost utility companies millions of dollars a day in unused energy.

There is also a growing awareness of the impact of climate variability and change, on time scales ranging from months to decades (NRC, 2001a). Shifts in rainfall patterns associated with climatic variability, such as those accompanying El Niño and La Niña, result in a nation and a world that is often plagued by drought and floods at the same time. Demand for climate data, information, and forecasts is growing rapidly, with NOAA's National Climate Data Center (NCDC) receiving nearly 2 million online contacts from users in the year 2000, 77 percent from industry.[1]

As society becomes more sensitive to weather, the importance of weather prediction for the protection of lives and property and continued economic growth increases. For example, the U.S. population that resides within 50 miles of the nation's coastlines and is most threatened by hurricanes and flooding is growing rapidly. Such population growth in these and other high-risk areas significantly increases the need for improved weather predictions and warnings to minimize risks to life and property. Another consideration is that the new economic concept of "just-in-time manufacturing" uses computer-timed and -directed supply systems to eliminate the warehousing of parts and products at ports and factories. However, even minor weather disruptions of land, sea, and air-supply-system pathways caused by snow, ice, and high-wind weather systems can now have large, leveraged impacts on these production systems, whereas previously they had little effect.

IMPROVEMENTS IN WEATHER INFORMATION PRODUCTS

The last several decades have seen major advances in the scientific understanding of weather and climate, and these advances, enabled by observational and computer technologies, have led to major improvements in warnings of severe weather, in short- and medium-range weather forecasts, and in climate outlooks on time scales ranging from a month to a year or longer. For example, the warnings of flash floods, tornadoes, and severe thunderstorms by the National Weather Service (NWS) have been improving steadily over the past two decades (Figure 3.1).

[1]Thomas Karl, NOAA National Climate Data Center, Boulder, Colorado, personal communication with Richard A. Anthes, February 6, 2002.

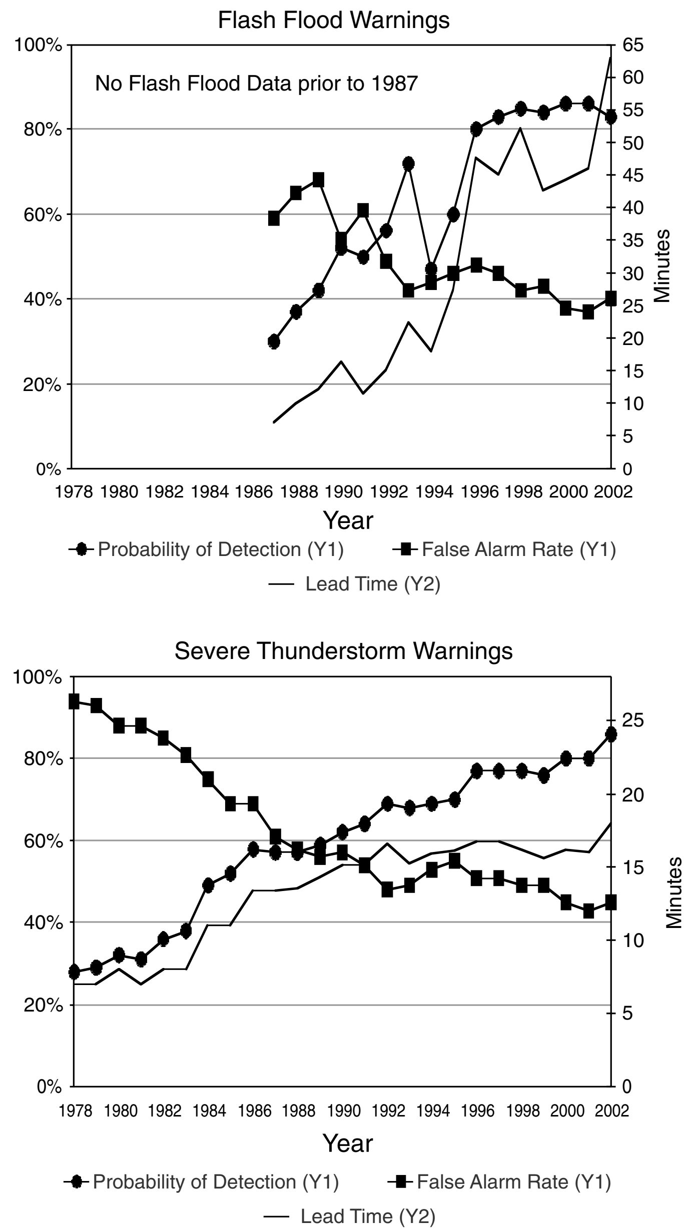

FIGURE 3.1 Improvement in National Weather Service (NWS) warnings of flash floods (1986-2002), warnings of tornadoes and severe thunderstorms (1978-2002), and forecasts of hurricane paths (1985-2000). (Y1, left axis; Y2, right axis.) SOURCE: NOAA, April 2002.

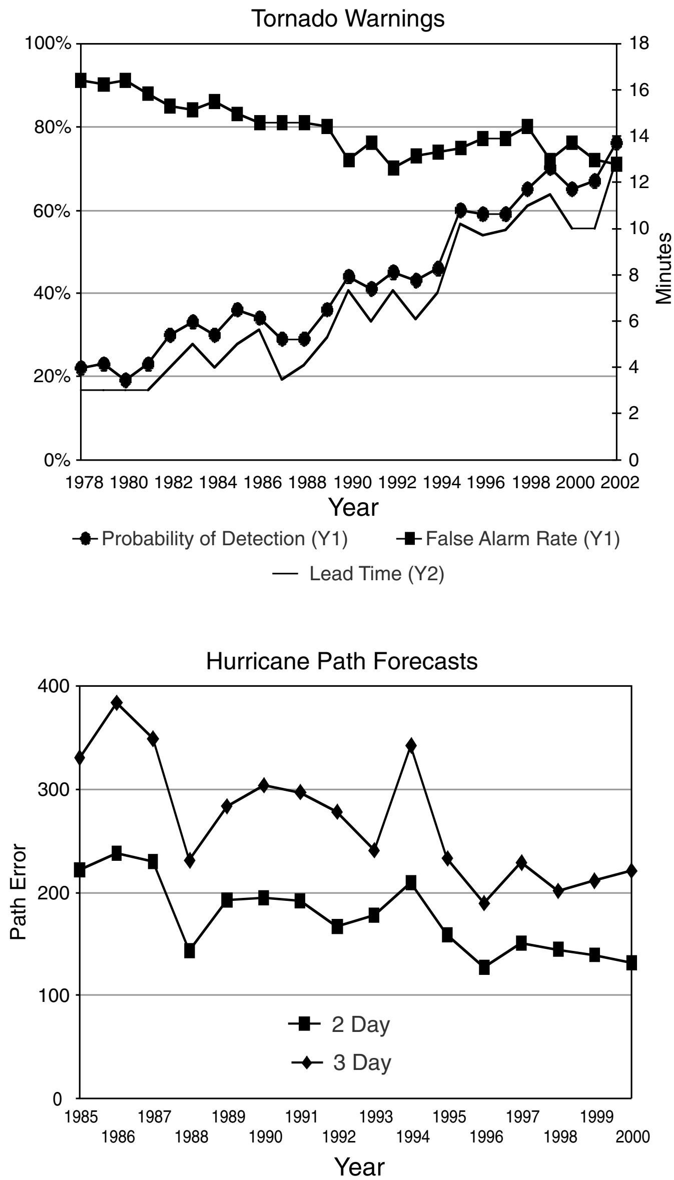

FIGURE 3.1 Continued

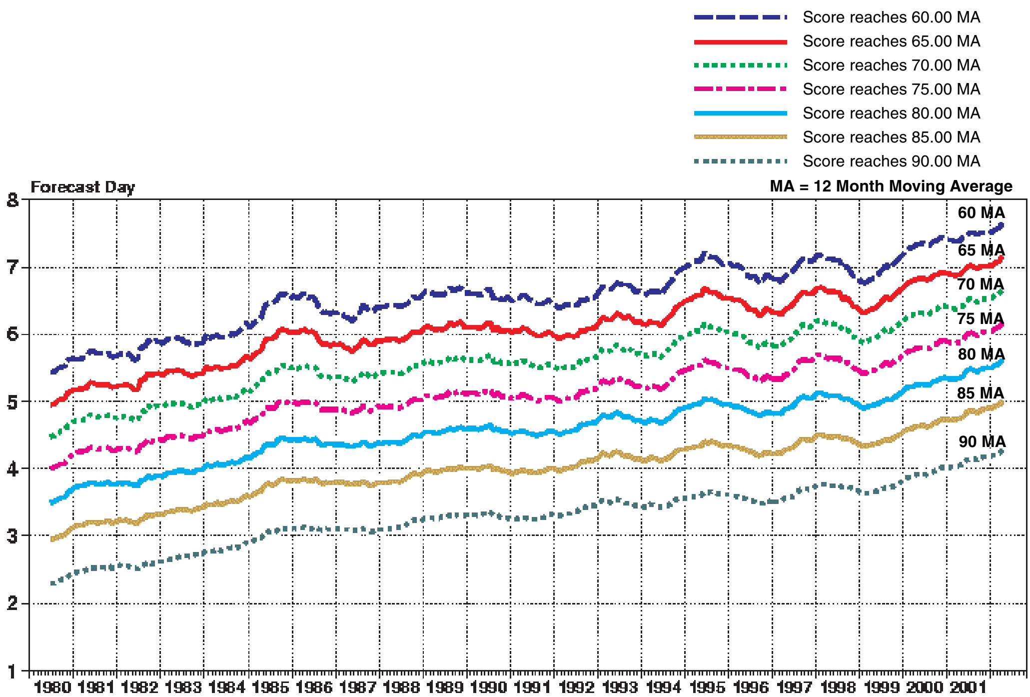

FIGURE 3.2 Trends in 500 hPa geopotential height anomaly correlations from 1980 to 2001 at the European Centre for Medium-Range Weather Forecasts (ECMWF). The graph shows the monthly moving average of the forecast day at which the forecast reaches a certain value of anomaly correlation (the correlation of observed and forecast anomalies) at the 500 hPa pressure level in the atmosphere (about 5.5 km or 18,000 ft). In 1980 it took a little over 2 days to reach an anomaly correlation of 0.90 (lower curve). By 2001 it took more than 4 days to reach this value; thus 4-day forecasts in 2001 were about as accurate as 2-day forecasts were in 1980. SOURCE: Anthony Hollingsworth, European Centre for Medium-Range Weather Forecasts, personal communication to Richard A. Anthes, November 2002.

NOAA's statistics for the warnings show that the probability of detection and lead times are increasing while the false-alarm rate is decreasing. Errors in forecasts of hurricane paths have been decreasing. On longer time scales, 4-day forecasts today are as accurate as 2-day forecasts were 20 years ago (Figure 3.2).

Improvements such as these are leading to an increase in the value of weather and climate data for users, for example in the public sector and the various economic sectors mentioned above. They are also leading to significant savings in life and property. For example, since the discovery of wind shear associated with thunderstorm downdrafts and the implementation of the Low-Level Wind Shear Alert System

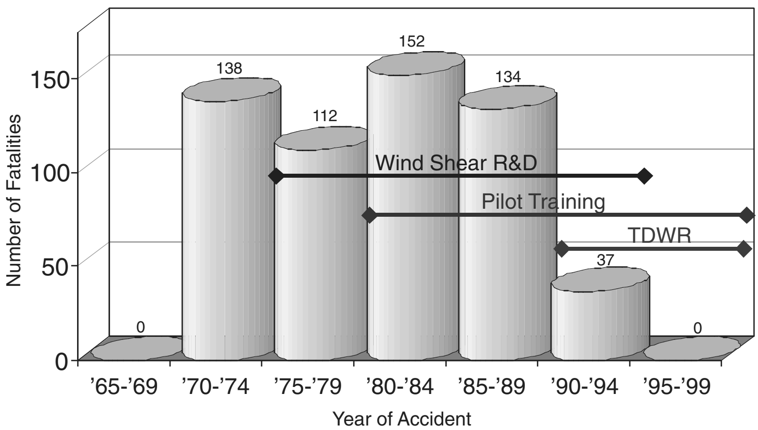

FIGURE 3.3 Number of fatalities associated with U.S. aviation wind-shear accidents from 1965 to 1999. Zero fatalities due to wind shear are reported in the 1965-1969 period because wind shear was not known to be a cause of aircraft accidents before 1970; thus, the actual number of aircraft accident fatalities due to wind shear before 1970 is unknown. Accidents did not begin to be documented until the number of jets flying became sufficiently large relative to this rare event. TDWR, Terminal Doppler Weather Radar. SOURCE: National Research Council (1983); updated by National Center for Atmospheric Research (NCAR) after 1983 (Richard Wagoner, NCAR, personal communication with Richard A. Anthes, August 2002). See <www.rap.ucar.edu/applications/llwas/index.html> for more information on the Low Level Wind Shear Alert System; accessed April, 2, 2003.

(LLWAS) and the Terminal Doppler Weather Radar (TDWR), to date there have been no aircraft accident fatalities due to wind shear after 1994 (Figure 3.3).

USERS OF WEATHER AND CLIMATE INFORMATION

New and improved weather and climate products are leading to new users, such as the "weather derivatives" industry (Dutton, 2002; Hertzfeld and Williamson, 2002; Colgan and Weiher, 2003). Weather derivatives are financial instruments that allow energy and other companies sensitive to weather and climate variability to spread out the risk associated with these uncertainties by purchasing "insurance" against such risks (Zeng, 2000; Rosenfeld, 2001). A multibillion-dollar industry that provides this protection against weather risks has emerged: it is an industry that is very sensitive not only to accurate weather forecasts but also to accurate historical climate data. It is notable that this weather- and climate-related industry was not foreseen before it suddenly emerged.

There have been many studies of the state of satellite remote sensing capabilities and of how progress can be used for greater benefit to society. Previous studies have shown that present and future users will require access to data that are more detailed and available in less time. For example, business customers will use worldwide environmental information to plan operations in a global marketplace while at the same time requiring information with respect to specific times and locations (NRC, 2001b). New users will require access to environmental data and information within minutes, hours, or days of the recorded observations (NOAA, 2001c), depending on the type of application for the data.

Some applications for environmental data are still being defined (see Box 3.1). These include operational satellite oceanography and forecasts of solar ultraviolet radiation, air pollution, lightning, space weather, conditions leading to disease outbreaks, and water quality and availability (NOAA, 2001c; NRC 1999, 2000a).

The Department of Defense has been active in operational utilization of space-based products for decades. The legacy of DOD programs is founded on essential applications for intelligence, mission planning, and operations. New products are constantly sought and being developed. Remotely sensed environmental parameters have great potential for improving predictive capabilities (nowcast and forecast) of operationally important models. Imagery and derived parameters will provide highly resolved observational data in a near-real-time, quasi-synoptic manner where our national security forces need support. Some important information products will include highly resolved nearshore sea surface height, solar coronal emissions, ocean color, precipitable water, shallow water bathymetry, full wind profiles (including light and variable winds, which are critical for aircraft-carrier operations, especially in tropical areas), highly resolved aerosol characterizations, highly resolved ocean currents and waves, and sea surface salinity.

As weather and climate information increases in accuracy, users' expectations and demands grow concurrently. Users want not only more accurate information, but also information that is higher-resolution (in both space and time). And they want the information packaged and displayed in ways that meet their specific needs and delivered in a timely fashion. While there is still significant room for improvement in the accuracy and quality of information and forecasts, there is also a great

BOX 3.1

Increased Emphasis on Satellite Observations for National Security

With the now-constant threat of terrorism, there is increasing demand for accurate observations and forecasts of winds and atmospheric stability, which would control the transport of toxic gases and particles if they were released into the atmosphere at any location, at any time. This demand can be better supported by the continuous assimilation of higher-resolution and more accurate satellite data and other observations in advanced numerical models in a timely and efficient manner.

deal of confidence that scientific and technological advancements provide an opportunity to satisfy the new and growing demands. A continually increasing demand for new and better data, high confidence in technological advances, and unpredictable market developments (such as the weather derivatives industry) combine to suggest that, in a nation as sensitive to weather and climate as the United States is, the value of future information and forecasts will increase, perhaps nonlinearly (NRC, 1999).

There is every indication that continuing advances will not only enable greater protection of life and property but will also result in greatly expanded opportunities to benefit economic activity, stimulate economic competitiveness, and improve environmental management (Pielke and Kimpel, 1997; NRC, 1999, 2000a; Dutton, 2002; Hertzfeld and Williamson, 2002; Colgan and Weiher, 2003). As summarized in the report *From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (NRC, 2000a, p. 17):

> The potential is enormous. The demand for new and diverse forecasting products will continue to grow and, with implementation, these expanded products will promote increased human safety and stimulate economic benefits in the United States and elsewhere.

Given the great potential for increased societal benefits from improved weather and climate information, it is important not only to support the R&D required to realize the potential, but also to speed up the process by which research is transferred into operations. Serafin et al. (2002) suggest ways in which the weather service communities can remain abreast of the new opportunities and can implement those possibilities that are most promising. These suggestions include, for example, using expert systems in preparing forecasts, continuing the positions of science operation officers in National Weather Service field offices, and conducting joint research projects involving both research and operational communities. Key to an enhanced technology-infusion process is much more extensive interaction between the research and operational communities.

The two specific examples of progress cited above—providing a solution to the problem of wind-shear hazard to aircraft and making steady improvements in medium-range weather forecasts—have important lessons for accelerating the technology-infusion process. The wind-shear problem was solved by a focused effort involving researchers at universities, MIT Lincoln Laboratory, and the National Center for Atmospheric Research (NCAR), working closely with the Federal Aviation Administration (FAA). The spectrum of effort, ranging from basic to applied research to timely applications of the LLWAS and TDWR technologies at more than 100 airports around the country, was seamless—there were strong bridges across the valley of death in this example. The wind-shear problem was relatively easy to address because of the local nature of the phenomenon and the availability of technologies to observe it in real time. Sustained governmental research support was assured because of the highly visible impact of the problem to society.

The other example of progress, the slow but steady increase in medium-range forecast skill, is quite different from the wind-shear problem. Medium-range forecasting is inherently global in nature and requires a wide variety of observing systems. It further requires many scientists to develop the observing systems, highly complex numerical models, and data-assimilation techniques. Rather than serving a limited specific customer, medium-range forecasting serves a very broad range of users. But, like the wind-shear problem, it also requires sustained governmental support for the research necessary to improve the operational forecasts, as well as focused and committed resources to carry out the transition to operations and the operations themselves.

THE UNPREDICTABLE NATURE OF THE VALUE OF NEW TECHNOLOGIES

As the goal of providing the Earth Information System is realized, many products, with both personal and commercial value, will be generated from the EIS's comprehensive databases. The nature of many of these products is unpredictable (Box 3.2); they will emerge through the creative minds of entrepreneurs who sometimes may be only vaguely aware of the needs and the desires of end users. For example, Obermann and Williamson (2002, p. 3) point out: "Strange as it may seem today when satellite images are part of the daily news, the possible value of satellite data for U.S. weather forecasting was unclear before the dawn of the space age."

User needs are not static. They evolve considerably as the state of the art advances around them and as new opportunities and capabilities present themselves. User needs are moderated by the ancillary conditions of availability, timeliness, reliability, and cost—all of which are constantly changing. The Global Positioning

BOX 3.2

The Unpredictable Nature of the Value of New Science and Technology

"[D]espite considerable research on the topic, no accurate metrics exist that enable economists to determine both the quality and the future monetary value of economic benefits that may arise from the acquisition of new knowledge. Indeed, even the use of peer review and other methods of selecting future scientific missions cannot predict with accuracy the success of such scientific pursuits."[1]

[1]H.R. Hertzfeld and R.A. Williamson. 2002. Socioeconomic benefits of earth science research. Paper presented at 53rd International Astronomical Congress, World Space Congress 2002, October 10-19, Houston, Texas.

System (GPS) is a recent illustration of the enormous applicability and use of a technology that was neither foreseen nor part of most users' set of requirements. The GPS provides precise latitude, longitude, and altitude data to receivers at any location on the planet. When these data, developed under the aegis of DOD, were released to the general public even before the GPS had become fully operational in 1995, it was done so without fees and with only minor degradation for security purposes. At the time, there were no extensive studies on what the utility or ultimate value of GPS to the public would be, although it was known that information about one's precise location in real time would likely be of value to many users. What was not imagined, however, was that entrepreneurs would be able to take these data and integrate them into user-friendly, mounted, or handheld instruments in such an economical and compelling way that the research community and a huge portion of the public would suddenly become enthusiastic users. Nor was atmospheric sounding using the GPS as demonstrated in the Global Positioning System/Meteorology (GPS/MET) experiment (Ware et al., 1996) foreseen by the meteorological community. Thus, the availability of GPS data today serves a variety of interests, including those of the scientific community, commercial companies, a host of rescue and public safety organizations, and thousands of individuals who routinely employ GPS devices for recreational purposes. GPS has become a multibillion-dollar industry. It would not be unreasonable to extend this GPS exploitation scenario to the potential evolution of the utility of precise environmental information available to everyone on demand, all the time, anywhere on Earth.

In summary, it is often difficult to anticipate specifically the new ways in which the user community will employ enhanced environmental information, or even to estimate how the number of users may change as such information becomes available. But past experience, typified by the GPS example, indicates that new technologies and information will create new opportunities and applications that will be exploited by a variety of former and new users.

A VISION FOR THE FUTURE: TOWARD AN EARTH INFORMATION SYSTEM

Atmospheric weather and climate data are an important part of the overall characterization and understanding of the Earth system. Observations from other parts of the Earth system, including the oceans, freshwater, land surfaces, ice, biosphere, and space environment, are also growing in importance (NRC, 2003). A long-range vision, or goal, implicit in many plans and reports and in the missions of NASA and NOAA is to observe the

Improved satellite observations and their more effective use in numerical models are essential because the satellite uniquely provides the global perspective required for the Earth Information System.

Earth system in order to support the scientific understanding of this complex planet *and* to make useful predictions of its components for the benefit of life on the planet. The vision is an Earth Information System (EIS)—a four-dimensional (three spatial dimensions and time—past, present, and future) gridded set of quantitative, geo-referenced digital data that describe the Earth system. The EIS would be widely distributed and evolutionary, much like the experience in the early days of the Internet and the World Wide Web. The EIS prototype that exists today will be continuously updated in the future with new observations and analyses and will include the atmosphere, biosphere, hydrosphere, and lithosphere. As the EIS is updated, it will become ever more valuable and will support a larger and broader range of users. As Colgan and Weiher (2003, p. 6) put it with respect to environmental information: "On both the supply and demand sides, information permeates the creation of economic wealth in an unprecedented way."

One of the keys to providing better and more useful weather and climate information and forecasts is to advance the capability for observing the atmosphere, oceans, freshwater, ice, and land surfaces. Satellites, with their unique global view, will play a crucial though not exclusive role in realizing these advances. A new era is about to begin in remote sensing (see Chapter 4, "Opportunities in Satellite Remote Sensing to Realize the Vision"). An international system of polar-orbiting and geostationary satellites is expected to lead to dramatic improvements in weather and climate analysis and forecasting. New infrared remote atmospheric sounding systems, cloud-penetrating microwave radiometers, GPS radio occultation measurements, active spaceborne radar and light detection and ranging (lidar), as well as in situ and remote sensing observations from the ground, balloons, and aircraft, will create a sensor web around the globe for future Earth observations.

For this vision of the Earth Information System to become a reality and maximize the return on the satellite research investment, a much more efficient means of transitioning from satellite research experiments to operational systems is required.

Essential for realizing this vision is continuous assimilation of the high-resolution satellite data into advanced numerical prediction models of the atmosphere and oceans to enable complete diagnoses of their states at all times. Numerical models fill in the space and time gaps in the global observing system through spatial and temporal interpolations of the observations (Figure 3.4). The models also predict the future state through the numerical integration of the dynamical equations governing the changing state of the coupled atmosphere-ocean system. The future global numerical models are envisioned to have a spatial resolution of 1 kilometer or better in the horizontal dimension and about 100 meters in the vertical dimension

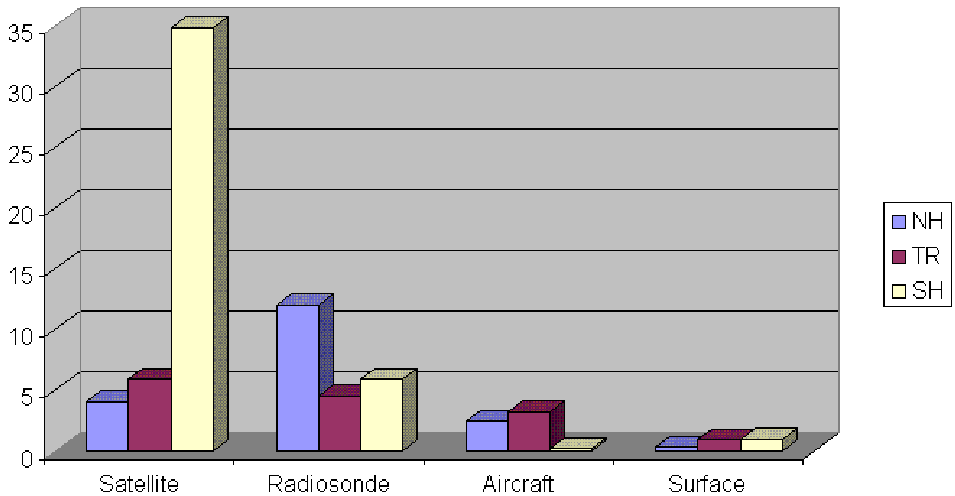

FIGURE 3.4 Example of the mean impact of various observing systems on U.K. Met Office global model forecasts. The results are obtained from an Observing System Experiment (OSE) using observations from July 2001 and January 2002. The figure shows the average (over 60 forecasts) change in root-mean-square (RMS) error of the 24-hr forecast (versus verifying rawinsondes) of 250-hPa vector wind when the observing systems listed are removed entirely from the global assimilation system. The vector RMS error has been averaged over three geographical areas: Northern Hemisphere (NH), 90°N–20°N; Tropics (TR), 20°N–20°S; and Southern Hemisphere (SH), 20°S–90°S. Results from the OSE indicate that satellite data (radiances and winds) have a particularly large impact in the Southern Hemisphere. A Met Office Technical Report describing the results in more detail is in preparation. Courtesy of United Kingdom Met Office.

(NRC, 1999).[2] With the appropriate physics and data-assimilation procedures, the models will take advantage of the satellite observations specified with very high spatial resolution, producing both nowcasts and forecasts for a diverse user community.

Variations of the same numerical models will produce research-quality historical climate data sets through a continual "reanalysis" process. In this process, improved models will use data sets that are also improving through data cleaning or data curation. The resulting global, regional, and local climate data sets will have a

[2] Today's operational global models have horizontal resolutions of 50 to 100 km, while limited-area or regional models have horizontal resolutions ranging from 10 to 30 km.

multitude of research and commercial uses. Wireless communications technology and handheld computer display terminals will enable anyone to receive these environmental products and predictions in real time, regardless of his or her geographical location, for immediate application and decision making.

For this vision of the EIS to become a reality and maximize the return on the satellite research investment, a much more efficient means of transitioning from satellite research experiments to operational systems is required.

4

Opportunities in Satellite Remote Sensing to Realize the Vision

Advances in remote sensing systems, data communications and processing technologies, and numerical models—including data-assimilation techniques—present a rich set of "push" opportunities for realizing the vision of the Earth Information System and associated enhanced weather and climate observations and predictions.

A variety of advanced and complementary instruments on a constellation of satellites in different orbits (e.g., geostationary, polar and inclined low-Earth, highly elliptical or Molniya, and Sun-stationary), combined with ground-based, balloon, and aircraft in situ and remote sensing systems, will eventually form an intelligent sensor web. The data from this web can be continuously assimilated into high-resolution numerical models of the atmosphere. The observation and analysis process will yield a quasi-continuous digital representation of Earth on a global basis. This global database, which will include a complete and accurate representation of the atmosphere, ocean, and land and ice surfaces, is needed in order to enable much more accurate weather forecasts, to characterize the climate, and to advance understanding of the Earth system.

This chapter describes some of the new and improved observations that are planned as part of future missions (Appendix C describes upcoming missions with U.S. involvement). Some of them are scheduled for transition into operations; others are not. Yet all of these planned observations and missions have the potential for eventual transition into operations and hence represent a plethora of "push" opportunities. Each of these opportunities can be identified and evaluated for transition potential, but each has its own transition pathway. Successful transition of these opportunities needs to be accompanied by supporting advances in infrastructure, including computers, communication technologies, and data-assimilation methods.

This chapter is not meant to be a comprehensive description of all important technologies or missions. It concentrates on technologies and missions that are currently scheduled to be transitioned into operations or tested in real time in order to determine their impact on operations.

ADVANCES IN SPACE-BASED MEASUREMENT TECHNOLOGIES

New space-based remote sensing, communication, and processing technologies are being demonstrated through a number of research and development programs. The next-generation National Polar-orbiting Operational Environmental Satellite System (NPOESS), a joint program of the DOD, NOAA, and NASA, represents a giant step forward in global weather sensing capability. Imaging Fourier transform spectrometers, providing hyperspectral imagery of the atmosphere with unprecedented resolution, are being developed to observe the dynamics of the three-dimensional thermodynamic structure of the troposphere with high spatial and temporal resolution from geostationary satellites. Complementing these thermodynamic observations, a constellation of small, polar-orbiting satellites will retrieve thermodynamic profiles from the tracked GPS radio signals as they are occulted behind Earth's limb. Doppler light detection and ranging systems, or lidars, which observe aerosol motion from the spectral frequency change of the backscattered light generated by a laser, are under development for polar-orbiting satellites in order to observe the global tropospheric wind structure.

Scatterometers will provide surface wind data over the oceans. Lidars and radars will fly on low-altitude satellites for cloud, aerosol, and precipitation measurements, with the future possibility for high-vertical-resolution water vapor profiling. NPOESS will carry advanced instruments that detect the natural microwave radiation emitted by Earth's surface and atmosphere. These instruments will enable atmospheric profiling through clouds and will provide surface wind and precipitation observations. Large, lightweight antenna systems are also under development, to enable similar microwave measurements from geostationary orbit for the monitoring of precipitation. These would also provide thermodynamic information below clouds in support of the infrared imaging spectrometer sounding systems. Dual-frequency radars will measure precipitation and associated latent heating rates. A visible-wavelength digital camera, which will sense lightning strokes, is also being developed to monitor convective storm dynamics from geostationary satellites. These new technologies (Kramer, 2001) are being developed during this decade through the U.S. New Millennium Program (NMP) and Earth System Science

Pathfinder (ESSP) missions, the European Atmospheric Dynamics Mission (ADM), and the Japanese Advanced Earth Observation Satellite (ADEOS) program.

ADVANCES IN SUPPORTING INFRASTRUCTURE

The space-based observations from existing and planned missions will be voluminous, exceeding several terabytes per day. The observations will have both nowcasting and numerical weather prediction applications. As mentioned earlier, the full potential of many of these observations is not realized until they are assimilated in models along with other measurements. In order to take full advantage of all these data as well as to satisfy the diverse range of applications, an elaborate and highly efficient space-based communications system must be implemented. It is envisioned that before the end of this decade such a communications network will exist, to permit data to be transmitted around the globe to any desired location on Earth (Serafin et al., 2002). The products to be received and their frequency of receipt will depend only on the frequency and bandwidth of the ground-based receiver. The ground system will consist of both small, low-bandwidth receivers and larger, high-bandwidth receivers. The former will receive a limited number of products generated onboard spacecraft and intended for real-time strategic decisions. The latter will acquire the entire raw data stream, provided by the global observation system for numerical weather prediction, and will develop and distribute derived products to the user community.

ADVANCES IN DATA PROCESSING AND ASSIMILATION

Recent improvements in satellite data-assimilation techniques at modeling centers such as the National Centers for Environmental Prediction (NCEP) and the ECMWF have produced advances in numerical weather prediction as a result of improvements in the way these data are incorporated in the analysis/prediction operation. For example, the direct assimilation of satellite radiances, which represent volume-averaged temperature and moisture information rather than atmospheric soundings retrieved from the radiances, has led to a consistent, positive impact on the forecasts of these data in both hemispheres. Despite these promising trends, there remains an urgent need to continue developing better assimilation methods. These methods should be designed to effectively use the high spatial- and temporal-resolution satellite sounding observations that will be available operationally within the next decade.

Rapidly increasing computer power is allowing for higher-resolution numerical models, which in turn demand data at higher spatial and temporal resolution in order to adequately describe the initial state of the atmosphere. Improved model physics is putting increased demands on data density and reliability. Advances in four-dimensional variational analyses (4DVAR) that can assimilate continuous data flow offer great hope for revolutionary improvements in the use of high-volume data sets. These advances will be coming from the new generation of satellite sounding instruments. The transitioning of such innovative observing technologies into operational applications must be rapid. Otherwise, the improvements in model forecasts that could come about with better observations will be slow to be realized.

The time scale for the development of advanced satellite observing systems should be consistent with the evolving requirements and capabilities of numerical prediction models. Computer capability and numerical methods of data assimilation are evolutionary. As a consequence, the transition of new satellite technologies into the operational satellite systems must also be evolutionary, and designed to enable more frequent technology updates (i.e., "plug and play" modular satellite system designs, in which individual components have much shorter lifetimes than do current satellite instrument designs). Also, aggressive studies of satellite data assimilation and observing system simulation must be initiated well before the targeted launches of new observing capabilities if the numerical tools (i.e., radiative transfer models, expected error characterization, product development, and model initialization strategies) are to be in place when these new, advanced satellite data become available.

PROGRAMS PROVIDING TRANSITION OPPORTUNITIES

Existing programs within NASA and other agencies provide established and very rich sources of transition opportunities for NOAA operational programs. Current and planned missions within these programs can be readily evaluated for their transition potential, and in some cases they already have transition plans in place.

National Polar-orbiting Operational Environmental Satellite System (NPOESS)

The NPOESS program was instituted in 1994 as an interagency (NOAA, DOD, NASA) activity to merge the capabilities of the existing NOAA Polar-orbiting Operational Environmental Satellite (POES) program and DOD Defense Meteorological Satellite Program (DMSP). Over the past several years, the NPOESS program has established the requirements for and has begun the development of sensors to fly on the NPOESS satellites. The sensors are:

- *Visible/Infrared Imager/Radiometer Suite (VIIRS)*—VIIRS collects visible and infrared radiometric data from the atmosphere, ocean, and land surfaces.

- *Cross-track Infrared Sounder (CrIS)*—CrIS provides high-resolution measurements of the vertical distribution of atmospheric temperature, moisture, and pressure.
- *Conical Microwave Imager/Sounder (CMIS)*—CMIS provides microwave imagery and soundings of the atmosphere and oceans.
- *Ozone Mapping and Profiler Suite (OMPS)*—OMPS measures the vertical and horizontal distribution of ozone.
- *Global Positioning System Occultation Sensor (GPSOS)*—GPSOS measures the refraction of signals from the Global Positioning System and the Global Navigation Satellite System to characterize the ionosphere.
- *Space Environment Sensor Suite (SESS)*—SESS provides measurements of space environment variables, including particles, fields, and auroral conditions.
- *Aerosol Polarimetry Sensor (APS)*—APS measures characteristics of atmospheric aerosols.

Each of these sensors represents a significant technological advance over predecessors on the POES and DMSP satellites (or, in the case of GPSOS and APS, other heritage systems), and the sensors have been developed largely through direct contracts with industry. The NPOESS program has an ongoing process to plan system improvements, including the development of new sensors to meet future NPOESS system needs.

Geostationary Operational Environmental Satellite (GOES) System

The Geostationary Operational Environmental Satellite (GOES) system consists of a series of geostationary satellites that provide high-temporal-resolution environmental measurements. Current GOES instruments include a visible/infrared imager, an infrared sounder, a solar x-ray imager, and a space environment monitor. The GOES spacecraft and sensors are procured from industry through contracts managed for NOAA by NASA. The specifications for new capabilities, technologies, and instruments are determined within the NASA GOES office at Goddard Space Flight Center (GSFC) in response to NOAA requirements and are implemented through contracts with industry. In some cases, sensors developed within NASA are specifically identified as candidates for transferring technology to the GOES program. The GOES program has formally maintained capacity to accommodate demonstration instruments funded from external sources, but the capacity has gone unused primarily because of the long lead times, lack of funding (including that for spacecraft integration), and absence of formal statements of operational requirements.

Earth Observing System (EOS) and Post-EOS

The NASA Earth Observing System (EOS) program, with its extensive set of research-oriented sensors on multiple satellites, has provided and will continue to provide an important source of technologies with strong potential for transitioning to operational use. Many of the sensors selected for flight on EOS missions were designed to provide data with long-term monitoring and climate research objectives.

The Moderate-resolution Imaging Spectroradiometer (MODIS), currently flying on the EOS Terra and Aqua missions, is a multispectral imaging radiometer designed for imaging a variety of atmospheric, land, and ocean phenomena. This instrument provided the research basis for some of the requirements established for the NPOESS VIIRS sensor.

The Atmospheric Infrared Radiation Sounder (AIRS) (Pagano et al., 2002), currently flying on the EOS Aqua satellite, initiated the new era of hyperspectral atmospheric sounders and is theoretically capable of measuring temperature and water vapor profiles with accuracies of 1 K and 15 percent, respectively, at a vertical resolution of approximately 1 km. AIRS, the forerunner of the NPOESS CrIS sensor, may provide a basis for future GOES sounders.

The Global Precipitation Measurement (GPM) is a coordinated set of spacecraft planned to provide measurements of precipitation similar to those produced by the highly successful Tropical Rainfall Measuring Mission (TRMM), but with significantly higher revisiting time. To achieve this, it is planned that GPM will use a novel combination of a primary spacecraft with both a microwave radar and microwave radiometer and smaller secondary spacecraft carrying only radiometers.

Earth System Science Pathfinder (ESSP) Program

The NASA ESSP program funds missions designed to perform innovative and exploratory science. Measurements selected under ESSP often have significant operational potential, typically providing information on environmental variables that had not been previously measured from space.

The Gravity and Climate Experiment (GRACE) was the first ESSP mission to be launched; it is currently providing detailed measurements of Earth's gravity field. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) is a lidar mission designed to provide vertical profiles of clouds and aerosols. CloudSAT is a related mission that measures cloud profiles using a millimeter-wavelength radar. Both are expected to launch in 2004-2005. The Aquarius and Orbiting Carbon Observatory missions were selected in 2002 to provide measurements of ocean salinity and atmospheric carbon dioxide, respectively.

New Millennium Program (NMP)

The NASA NMP program was established to provide flight validation of new technologies. One mission, NMP Earth Observing (EO-1), has been launched and is operating successfully, with sensors designed to demonstrate technologies applicable to hyperspectral land imaging. A second mission, NMP EO-3, or GIFTS-IOMI (Geosynchronous Imaging Fourier Transform Spectrometer–Indian Ocean METOC [Meteorology and Oceanography] Imager), is currently under development in collaboration with NOAA and DOD; it is scheduled for launch in 2005. GIFTS will generate four-dimensional measurements of the atmosphere, providing more than 80,000 closely-spaced-horizontal (4 km), high-vertical-resolution (~1 km) temperature and moisture soundings every minute (Smith et al., 2002). NASA and NOAA expect GIFTS to provide candidate technologies for use in developing the next-generation GOES sounder.

NPOESS Preparatory Project (NPP)

The NASA NPOESS Preparatory Project (NPP) was established to bridge the gap between the expected operational life of the EOS Aqua satellite and the launch of the first operational satellites in the NPOESS series. It will also provide risk reduction of sensors scheduled for flight on the NPOESS satellites. NPP sensors include the VIIRS and CrIS instruments and the Advanced Technology Microwave Sounder (ATMS), being developed by NASA to transition the capability of the NASA Advanced Microwave Sounder Unit (AMSU) for use on NPOESS. NPP is expected to be a one-time project, but it is an excellent example of the use of “bridge” missions to transition research capability into operational systems.

Other Programs

A variety of other national and international programs provide valuable opportunities for the transition of research capabilities to operations.

Relatively low cost, accurate, and high-vertical-resolution thermodynamic soundings of the atmosphere using radio occultation (RO) of GPS signals have been demonstrated on several missions (GPS/MET, Challenging Minisatellite Payload, and Satelite de Aplicaciones Coemtofocas-C). The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission (Anthes et al., 2000) plans to test in real time the impact of up to 3,000 global RO soundings daily with the launch of a constellation of six satellites in 2005. COSMIC is sponsored by the National Science Foundation (NSF), NASA, NOAA, DOD, and the National Space Program Office of Taiwan.

Advances in lidar technologies provide a wide range of opportunities for new atmospheric measurement capabilities. In addition to the lidar technologies being developed for the Ice, Clouds, and Land Elevation Satellite (ICESat) and CALIPSO missions within the United States, the Atmospheric Laser Doppler Instrument (ALADIN), aboard the European Atmospheric Dynamics Mission, promises to advance the use of lidar for measuring tropospheric winds. Differential absorption lidar (DIAL) can enable the next advance, after that being achieved with high-resolution infrared spectrometers, for the profiling of water vapor as well as temperature. The use of passive microwave imaging sounders from geostationary orbit offers a promising new measurement capability. As with polar-orbiting systems, microwave sounders on geostationary satellites would complement existing infrared sounding sensors to provide temperature and moisture profiles through clouds and measurements of cloud liquid water and convective precipitation.

ACHIEVING THE VISION OF THE EARTH INFORMATION SYSTEM

As a result of the rapid advances in sensor, data processing, and communications technologies, the future is bright for space-based observing systems. New and improved sensors flown in a constellation of satellites in a variety of orbits will produce several terabytes of data per day. These data will be assimilated in numerical models—producing global analyses of the atmosphere, ocean, land surfaces, and cryosphere—advancing progress toward the Earth Information System.

Communications and computing capacity are increasing at a rate that will accommodate this explosion of data. Emerging new information technologies, including new visualization tools, will be employed to enable effective human interpretation and use of the information. While it is an enormous task and challenge to assimilate the wealth of data to come from future satellite systems, the efficient conversion of these data into usable information remains the key for unlocking the still-unresolved mysteries of Earth's environment and, ultimately, enabling its accurate prediction.

The combination of new measurement technologies, enhancements in supporting infrastructure, and advances in data processing and assimilation provides the technological "push" for transitions. Existing programs within NASA and other agencies provide a rich but readily understood source of these opportunities. Achieving the vision of the Earth Information System requires efficient and effective processes for transitioning these coming technologies and capabilities into operational use.

5

Pathways from Research to Operations

Over the past several decades, many NASA research capabilities have been successfully transitioned to NOAA operational use, and NASA and NOAA have developed a variety of processes to accomplish these transitions (Obermann and Williamson, 2002). However, there is no overarching or consistent set of processes covering all transition activities. This chapter summarizes lessons learned from 10 case studies, and then describes NASA-NOAA transition approaches and compares these with approaches used by other U.S. agencies and foreign space organizations.

Transition pathways between NASA and NOAA will continue to require a wide-ranging set of approaches, as each research concept and operational need will be associated with its own matrix of both opportunities and obstacles. NASA and NOAA have worked for more than two decades to improve these modes of transferring research into operations,[1] but have been faced with "too many degrees of freedom" in trying to match the NASA research and NOAA operational programs as a whole.[2] In the past 10 years, NASA has focused on climate monitoring and, consequently, separated itself to some extent from its historical role of transitioning

[1]For example, the 2001 NESDIS (National Environmental Satellite, Data, and Information Service) Strategic Plan includes the following Objective 1.6: "Take advantage of opportunities for transition of remote-sensing technology developed by NASA for research that meets NOAA's operational needs" (NOAA, 2001d).

[2]Presentation by Ghassem Asrar, Associate Administrator, NASA Earth Science Enterprise, to the Committee on NASA-NOAA Transition from Research to Operations, January 2002, Washington, D.C.

weather prediction research capabilities to NOAA operations.[3] While the relationship between NASA and NOAA is "excellent,"[4] both agencies recognize that current processes for transitioning research capabilities to operations could be improved.

CASE STUDIES AND LESSONS LEARNED

The committee examined 10 case studies of transitions, the details of which appear in Appendix B, "Case Studies of Transitions from Research to Operations." These case studies were chosen because they contained lessons learned in transitioning research to operations. A summary of the lessons learned is presented in Table 5.1. (Obermann and Williamson [2002] discuss other case studies and similar lessons learned.)

A common theme of these studies was the need for a *management structure* and a *formal set of processes* that could speed the transition of research to operational use. In the case of the early days of the Defense Meteorological Satellite Program (DMSP), an efficient, compact management structure and process allowed the program to far exceed expectations and outpace parallel efforts in NASA. In the case of the infrared sounder, NOAA did not fully exploit this instrument's potential for more than 25 years after the sounder first flew, because of resistance to change and lack of knowledge about how to use the observations effectively in numerical modeling. In the cases of the Volcanic Ash Mapper (VOLCAM), lightning detection, and the Solar X-ray Imager (SXI), no plan was in place to make the transition to operations until very late in the process, if at all. In the cases of the Special Sensor Microwave/Imager (SSM/I), Very High Resolution Radiometer (VHRR)/Advanced VHRR, and Tropical Rainforest Measuring Mission (TRMM), the involvement of the research and operations community early in the process was extremely important to their success. The value of research advocacy and operational involvement was evident in the ocean altimetry and scatterometry cases. Throughout all of these cases, the need for oversight at the highest levels of the transition process cannot be overemphasized.

From these case studies, some general conclusions about transition pathways and their associated processes can be drawn. These are discussed in the following sections.

---

[3]Presentation by Ghassem Asrar, Associate Administrator, NASA Earth Science Enterprise, to the Committee on NASA-NOAA Transition from Research to Operations, January 2002, Washington, D.C.

[4]"NASA-NOAA Transitions from Research to Operations," presentation by G.W. Withee, Assistant Administrator for Satellite and Information Services, to the Committee on NASA-NOAA Transition from Research to Operations, January 2002, Washington, D.C.

TABLE 5.1 Summary of Lessons Learned from 10 Case Studies

Case Study	Lessons Learned
Infrared sounder	The extended period between the first flight of a sensor such as the infrared sounder and the full operational use in numerical models can be attributed to many factors: resistance to change in the operational organization (e.g., insistence that the data look like radiosonde data); lack of a technology-transition plan or process (the operational centers were not prepared to use the data when they were first available); and incomplete research (the development of mathematical methods to use raw radiance values in numerical modeling took more than 25 years).
Very High Resolution Radiometer (VHRR)/ Advanced VHRR (AVHRR)	The operational agency (in this case NOAA) cared enough about the potential utility of the instruments to help fund their development. It is important to involve the research and operational community early in the process. The researchers communicated with potential users, educated them about the observations and their potential use, and "marketed" the mission. Near-real-time availability of research data to users is a valuable part of the transitioning process.
Defense Meteorological Satellite Program (DMSP)	The novel management scheme was made possible by a small program office, consisting of a few key energetic people with strong ties to the user (USAF Air Weather Service) and the research community (University of Wisconsin, Madison, primarily), that exercised technical direction. It could make decisions and act quickly. The office achieved an excellent success record at low cost. Incorporating the needs of the user into early instrument design and data-processing systems pays big dividends in transitioning systems from research to operational use. Involvement of the academic community in missions can lead to stronger scientific underpinnings, help infuse science with new ideas and concepts, and educate and train the next generation of space scientists and engineers.
Lightning detection from space	No transition pathway was established, in part because there was insufficient push from the research community and pull from the operational community. As a technology advances past a proof-of-concept stage, there should be a parallel investment made to determine its viability for use by either direct or intermediate users, to push the development of an operational requirement for the proven technology. The result of the proof-of-concept demonstration must be a documented user requirement for the new observation capability in order to create the pull needed to transition the experimental capability into an operational measurement system.
Ocean altimetry	There can be a positive synergy between research and operations. Apparently conflicting science and operational requirements can be overcome through communication and leadership at all levels, including administration and the research community. For example, the research community continued to show the value of ocean altimetry and how continuous improvement can lead to new insights. The highly visible success of TOPEX/ Poseidon encouraged senior management to take risks and seek new initiatives for follow-

continues

TABLE 5.1 Continued

Case Study	Lessons Learned
	on missions. The operational community recognized the value of these measurements and was willing to examine new technologies such as wide-swath altimetry to continue to expand the understanding of ocean circulations.
Scatterometer	Near-real-time data return from research missions is required in order to interest the operational numerical weather prediction agencies. Although graphical products from research missions can be produced rapidly for subjective forecasting use, the assimilation of new observations into numerical weather prediction forecast/analysis systems requires detailed knowledge of the measurement error characteristics and testing in the operational setting. This has generally not been achieved for at least 1 or 2 years after calibrated geophysical data become available from new instruments. Test beds such as the NASA-NOAA Joint Center for Satellite Data Assimilation can play a significant, positive role in speeding the transition of research to operations. Notwithstanding successful exploitation of scatterometer data by meteorological researchers and operational use of scatterometer measurements (acquired by both U.S. and international missions), the incorporation of surface vector wind measurements into the operational observing constellations has taken 10 to 15 years and is not yet a reality.
Special Sensor Microwave/ Imager (SSM/I)	It is important to consider how data will be used well in advance of a launch, and to develop algorithms that will process the raw data to generate useful products. The responsibility and funding for delivering sensor data in a form useful for operational users should be borne by the space segment of the process. The space segment cannot be allowed to have the limited responsibility of only acquiring hardware; it must also have an integrated responsibility that includes continuing calibration and validation of SDRs and a baseline of EDRs. The full release and open availability to the research community of new operational data in both SDR and EDR form provide significant benefit through development of improved and new uses of the original data and feedback to the operational users.
Solar X-ray Imager (SXI)	Inadequate financial and human resources can prolong the transition from research to operations for many years after a technology has been demonstrated and a need established. Funding difficulties for SXI prolonged the transition process to nearly 30 years.
Volcanic Ash Mapper (VOLCAM)	VOLCAM was developed out of a long-standing interagency collaboration at the working level, a result of the NASA-led geophysical science and natural hazards programs' having produced information of value to the operational agencies. Nevertheless, collaboration between agencies at the working level was not sufficient to establish agency commitment for the VOLCAM transition. NOAA has a very limited capacity or budget to evaluate new sensing concepts internally, so advancements in observational measurements are difficult to make unless they involve extending the capabilities of NOAA's few core instruments.

TABLE 5.1 Continued

Case Study	Lessons Learned
	The lack of an organizational transition mechanism between NASA and NOAA makes direct transfer of technology between the agencies difficult.
	Other than the GIFTS mission, NASA has not funded any geostationary sensor proposals in recent years. Opportunities to evaluate new research sensors or measurements for geostationary operational use have thus been extremely limited.
Tropical Rainfall Measuring Mission (TRMM)	Availability of research data in real time fosters use and testing by operational users.
	Research data can have a positive impact on operations.
	Feedback from operations has a positive impact on research.

NOTE: Details of the 10 case studies are presented in Appendix B, "Case Studies of Transitions from Research to Operations."

TRANSITION PATHWAYS AND PROCESSES

As noted, NASA and NOAA share the motivation and need to improve the research-to-operations transition process. The need encompasses new products, including (1) technologies, (2) instruments, (3) measurement techniques, and (4) data products and data systems. An *end-to-end set of processes* for achieving transitions, whether formal or informal, is a *transition pathway*. Transition pathways vary depending on the science, technology, and applications involved, but they all contain *building blocks,* which constitute the *infrastructure* of the pathway. Building blocks may include, for example, a solid research foundation, laboratories, equipment, computers, algorithms, models, information technologies, and test beds.

A transition pathway might begin with basic research supported by NSF or NASA. Based on sound theoretical and engineering principles, the pathway could include demonstration or proof-of-concept experiments that lead to the design of a NASA research mission. Ideally, research missions would include an overarching architecture, or plan, for the transfer of the research to operations. The transition pathway would include research on the necessary methods of using the data in numerical models (i.e., data assimilation) as well as in other uses, such as monitoring climate. Toward the end of the transition pathway, test beds would demonstrate the use of the research data in near real time, evaluate their operational impact, and provide feedback to the researchers. After a demonstration of positive impact, future operational missions would produce the data in real time, and operational centers and other users would incorporate the new data into their operations, completing the transition pathway.

Transition pathways can be characterized in terms of four elements:

1. ***Objectives****—What is the purpose of the transition process, and what are its objectives? Is there a plan for a complete end-to-end set of processes (a transition pathway) that will achieve the objectives?*

2. ***Organizational structure****—Who or what has the authority and responsibility for achieving the objectives? Is the authority effective, and is it adequately supported by the sponsoring agencies?* "Organizational structure" includes the mechanics of formal reporting as well as the definition of the functional roles and responsibilities at every level of the organization. Necessarily, this implies a degree of "corporate" shared understanding; an individual's understanding of his or her own job description alone is insufficient. Rather, each individual must understand how his or her roles and responsibilities relate to the mission and goals of the organization.

3. ***Procedures****—What processes exist for establishing the necessary plans, schedules, and resources? What are the plans, and are they sufficient? Are requirements carefully developed and adequately documented?* The set of organizational procedures or way of operating is the "machinery" that must be run, maintained, and occasionally redesigned to enable an organization to produce research results for transition or to create products for particular applications. The organizational procedures include guidance, documents, rules, processes, communications systems, measures of effectiveness, and tools for assessment that will, if designed correctly, optimize the transition pathway. The challenge is to design these procedures consistent with the requirements of a bureaucracy (e.g., rules regarding personnel or acquisitions), while remaining flexible enough to accommodate agency mission requirements.

4. ***Resources****—Are adequate resources available, including personnel, funding, and schedule?* Because they are subject to the executive and legislative budget processes, resources that may be inadequate often determine the limits on research and operational opportunities. These resources include the dollars available for research and operations (including any limitations on the reprogramming of such distributions) and the availability and distribution of appropriately educated and trained people. Additionally, an agency's infrastructure (adequate laboratory space, necessary scientific and technical equipment, computational hardware and software) represents another important resource that factors in to both opportunities and obstacles to transition.

TRANSITION CHALLENGES

As with any complex process, transition pathways from research to operations and applications are characterized by a variety of challenges and potential barriers. No single barrier is the primary limiting factor in the ability to transition research to operations, and no simple cure or "silver bullet" can eliminate all of the various impediments to successful technology transfer. Rather, these factors often combine with varying degrees of significance for any particular case to produce a formidable barrier to successful transition.

Table 5.1 and Appendix B provide examples of transition needs that for various reasons have not been met. NASA selected VOLCAM as a flight candidate under the ESSP program in part because of its own expectation that the research flight of this instrument would lead to a demonstrated operational capability. But NOAA was unable to provide the long-term commitment required by NASA prior to approving the research mission, and so the research capability has not been successfully transitioned into operations. The Lightning Imaging Sensor (LIS) has flown on TRMM and appears to have support for transition, but it is not currently planned for operational use. Spaceborne tropospheric wind measurements, one of the highest-priority requirements of the operational community, have achieved neither research nor operational status owing to disagreement within the community about what research is needed, how it should be transitioned, and whether or not wind measurements should be purchased through the private sector.

The limiting factor in transitioning research to operations can be inadequate scientific understanding or the difficulty of extending scientific understanding and/or technological capability to operational utility. There may be limits to the observing technologies, to the understanding of how to use the observations effectively (as in the case study of the infrared sounder), or to the computational power required to use the observations in operational models.

A critical element of operations is the ability of a system to perform routinely under adverse environmental conditions—that is, to have operational robustness. Until new capabilities develop in other research sectors (e.g., computer science or mathematical analysis), a particular technology might be shelved rather than transitioned. This translates into a need to ensure that those programs engaged in advancing related technologies (e.g., materials or information technology) are kept aware of the impacts of their developments on the feasibility of transitioning environmental remote sensors from research into operations.

Traditional processes and expectations often form impediments to instituting changes of the magnitude required to improve NASA-NOAA transitions. NASA has historically focused on the internal development and implementation of large projects. NOAA has tended to set long-term goals and requirements for its observing system capabilities, with limited flexibility for adapting to changing constraints or to the emergence of new capabilities. It appears that both organizations recognize these issues and are working to improve their flexibility.

The inability to deal with massive volumes of remotely sensed data streams may be a technological barrier to transitioning. On July 24, 2002, the House Science

Subcommittee on Environment, Technology, and Standards recognized the risk associated with the $6.5 billion NPOESS program, scheduled to begin operating in about 2008. The subcommittee heard from a General Accounting Office (GAO) report that NOAA lacked a robust plan to handle the approximately 200 terabytes of data per year that NPOESS will deliver. Congressmen Vernon Ehlers (R-Mich.) and Mark Udall (D-Colo.) hit the nail on the head:

> Given these huge investments and the importance of satellites to so many aspects of our lives, it is our duty to ensure that the taxpayers are getting their money's worth. But getting our money's worth is not simply contingent on a satellite being successfully launched and data being beamed down. The key factor is being able to use the data. (Ehlers, 2002)
>
> NOAA's investments in satellite technology have vastly expanded our ability to measure features of the earth, the oceans, and the atmosphere. Parallel progress in data processing and management is enabling us to utilize these measurements to improve weather forecasting and to better understand the global environment. The good news is we have a lot of data. On the other hand, the bad news is we have a lot of data. We must ensure that investments in technology and research to manage information keep pace with our investments in technology to gather it. (Udall, 2002)

Thus, there is need for robust strategies to address the volumes, quality, and diversity of remotely sensed environmental data. There is a tendency to emphasize stand-alone observations rather than trying to optimize ways in which one set of observations might complement others. And, in some cases, there is a potential contradiction between the operational community's eagerness for a robust data stream and the scientific community's reluctance to compromise the accuracy or completeness of the data.

Foreign collaborations are an increasingly important element of both research missions (e.g., TRMM, GRACE, Jason, CALIPSO, CloudSAT, COSMIC) and operational programs (e.g., NPOESS, Ocean Surface Topography Mission). (See also Appendix C regarding future missions.) These international collaborations—while valuable in many respects, including leveraging of scarce resources and sharing of scientific and technical expertise—often introduce complications such as national restrictions on trade and technology assistance, management complexities, and cultural differences. These complications can increase the difficulty in carrying out effective transitions.

TRANSITION TYPES

Within the current NASA-NOAA system, five primary research-to-operations types can be identified: (1) meteorological system upgrades, (2) algorithm and data product improvements, (3) NASA systematic measurements that transition to NOAA operational measurements, (4) NASA exploratory measurements that transition to NOAA operational measurements, and (5) technology demonstrations that transition to operational systems. As described in the following subsections, each of these transition types is associated with a typical transition pathway, which has characteristic building blocks and processes.

Meteorological System Upgrades

Prior to 1981, NASA and NOAA cooperated effectively in developing new operational satellite systems. At that time, NASA typically funded "first unit" builds of weather satellites and their instruments and then transitioned proven capabilities to NOAA (and its predecessor, the Environmental Science Services Administration) for operational use. This cooperation was guided by a formal agreement established in 1973, the Operational Satellite Improvement Program (OSIP), which was funded at about $15 million per year. The budgets for NASA and NOAA reflected this agreement. NASA used its funding to develop prototype sensors, fly them on high-altitude aircraft, and transition them to research spacecraft for evaluation. Successful instruments were then provided to NOAA for transition to operational status. The program fell victim to NASA budget pressures and an Office of Management and Budget (OMB) desire to offload "routine" functions from NASA, and was canceled in 1982 (OTA, 1993; NRC, 2000a).

Since 1982, there has been a formalized upgrade process for supporting NOAA sensor capability, primarily for the polar and geostationary satellite systems. Its objective is to provide incremental upgrades to existing sensors, major design upgrades to those sensors, and development and insertion of new sensors as needed. NASA has the authority, delegated from NOAA, to implement the procurement of the POES and GOES systems on the basis of NOAA requirements and budgets. Established processes exist for important parts of this activity, but they are largely derived from historical precedent developed over the multidecade POES and GOES collaboration rather than being carefully developed and documented procedures. Limitations in the processes, combined with budget or schedule constraints, have led to plans that have in some cases proven difficult to implement or have not been established in a timely manner (OTA, 1993; GAO, 1997). The POES program is currently being combined with DMSP into the NPOESS program,[5] with NOAA and DOD as joint funding partners and NASA as a third unfunded partner focused on technology infusion.

[5]"NPOESS Risk Reduction: The NPOESS Preparatory Project," presentation by Stanley Schneider, Associate Director for Technology Transition, NPOESS Intregrated Program Office, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.

The upgrade process has worked well for incremental upgrades (such as the evolution of the GOES imager channel selection), but it has been less successful with major advances or block upgrades that require the introduction of new systems or significant changes to sensors, spacecraft, or other mission systems (such as the introduction of the next-generation GOES sounder). Block upgrades have historically required technical, programmatic, and contractual decisions that limit the ongoing infusion of new capabilities. Technical decisions, such as the choice of spacecraft architecture for GOES-NEXT in the 1980s, can set constraints for many years on the nature of the new observational capabilities that can be accommodated. Programmatic or contractual decisions, such as the decision to procure follow-on units through fixed-price contracts on NPOESS, may minimize life-cycle costs, but they also reduce the flexibility to incorporate research- and technologically-driven advances as they become available. The IR sounder and scatterometer case studies (see Appendix B) are also examples in which the first type of transition, the system upgrade, did not work well. Time periods of up to 25 years elapsed before effective use was made of these technologies. In contrast, the DMSP and VHRR/AVHRR case studies show that this type of transition can work well. The key is effective and clear coordination between the operational and research entities.

In summary, the objective in this first type of transition—meteorological system upgrades—is clear, and the structure and procedures are well documented. Overcoming the complications created by different agency cultures and obtaining the necessary resources are still a challenge.

Algorithm and Data Product Improvements

Operational employment of satellite data implies the use of the data by either an "end" user (usually a nonscientist) or an intermediate user (usually a scientist or a numerical model). An essential part of the transition pathway is the development of appropriate algorithms to transfer the raw measurements, or sensor data records (SDRs), into environmental data records (EDRs)—forms of environmental data that the user requires. Alternatively, algorithms can be developed that use the SDRs directly, as in data-assimilation schemes. The focus of the operational community has historically been on the EDRs. The direct use of the sensor records by the operational numerical models has only been a recent (last decade) development, after more than 30 years of satellite data availability. Observed cloud and precipitation data from any source (e.g., satellites or radars) have only recently been considered for input into numerical models.

Two significant changes are occurring that have a major effect on the use of satellite data for operational purposes: first, the development of data-assimilation systems that incorporate sensor data directly in Numerical Weather Prediction (NWP) models and, second, the acceptance of cloud and precipitation data as input parameters into these models. These changes shift the emphasis on operational use from focusing on EDRs to including SDRs as well. The significance of this evolution is that, whether in a "push" or a "pull" situation, the operational use of any proposed sensor data needs to be demonstrated. This demonstration should include the development of the appropriate algorithms, data-assimilation schemes, or other data products, to the point that soon after launch, the data can be used—in days to weeks, not months to years—by either the direct or the intermediate users. Therefore, a critical element in the transition of research capabilities to operational use is the development not only of the retrieval schemes to produce EDRs, but also of the assimilation methods for the proposed sensor data. In either case, parallel development and funding are required in order to achieve operational use of the satellite data. In the past, a lack of funding for the development of the necessary retrieval and assimilation algorithms has been a key reason for failures to quickly transition research satellite sensor data into operationally useful data.

NASA and NOAA both perform research and development in the area of algorithms for operational applications and product generation. Recently, it was recognized that the complementary capabilities of the two organizations, the challenges to assimilate upcoming, large volumes of data, and the limited resources available to each agency provided motivation for establishing a joint capability.

In response to these needs, the Joint Center for Satellite Data Assimilation (JCSDA) was recently chartered. With authority provided through an agreement between NASA and NOAA,[6] JCSDA leadership has established clear objectives for the center as a facilitator in transitioning research algorithms and data products to operational status, has developed processes and plans for accomplishing these transitions, and has identified existing resources to support transition activities. JCSDA projects have included the transition of Quick Scatterometer (QuikSCAT) data to operational use. JCSDA is planning for similar transition of AIRS data and has selected GIFTS as a trial project.

In summary, the objectives of this second transition type—algorithm and data product improvements—are clearly stated. There is an organization in place, procedures are drafted, and resources are becoming available.

[6]"Joint Center for Satellite Data Assimilation," presentation by Richard B. Rood, Director (Acting), Joint Center for Satellite Data Assimilation, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.

NASA Systematic Measurements to NOAA Operational Measurements

As support for the planned follow-on missions to the EOS spacecraft series faltered in the mid-1990s, NASA looked to NOAA as the implementation agency for the EOS systematic (climate) measurements. By the end of the 1990s, NOAA had begun to institutionally accept this role within the context of adding climate observations to its operational charter. This third transition type, which involves many subtle issues unique to systematic data, has already been the subject of substantial review (NRC, 2000b).

As this charter issue has evolved, NASA and NOAA have developed a variety of activities to transition NASA systematic measurements to NOAA operational measurements. The translation of EOS measurements to NPOESS requirements is the focus of this type of transition, and the NPOESS Preparatory Project (NPP) is a key element.[7] Particular activities include the enhancement of the NPOESS VIIRS instrument to incorporate MODIS channels, and NASA development of the ATMS instrument for NPOESS based on the AMSU/MHS (Microwave Humidity Sounder) heritage.

While formal activities, including those described above, exist within this type of transition, it has had no overall coordination, and agreements have been established on a case-by-case basis. In part, this case-by-case approach has arisen because no long-term NASA-NOAA agreement exists outlining which systematic measurements are to be transitioned to operational status or suggesting how the transition is to be accomplished. Although the objectives are defined for this third transition type—NASA systematic measurements to NOAA operational measurements—no procedures exist for the transition, and no resources are identified.

NASA Exploratory Measurements to NOAA Operational Measurements

NASA's Office of Earth Science has flown many exploratory missions that are candidates for transition to operational status. Within the past 5 years, NASA has focused on the ESSP program as the source of exploratory missions. NASA establishes the objectives for this program, but to those submitting proposals it provides only limited guidance about which exploratory measurements are candidates for transition to NOAA. The establishment of prioritized measurement needs within the

[7]"Transitioning from Research to Operations: NPP Case Study," presentation by Robert Murphy, National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) Project Scientist, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.; "NPOESS Risk Reduction: The NPOESS Preparatory Project," presentation by Stanley Schneider, Associate Director for Technology Transition, NPOESS Integrated Program Office, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.

NPOESS system (including measurements not expected to be made within the current system procurement [the "unsatisfied EDRs"]) provides a sense of which exploratory measurements could lead to operational counterparts. However, there is no plan for linking exploratory missions to subsequent operational ones.

The inability of VOLCAM,[8] proposed as an ESSP exploratory mission, to develop a transition path is an example of the difficulty of this transition type. The SXI[9] succeeded in making the transition, but only after considerable effort and strong commitment by individuals. The use of the peer-review process in selecting exploratory missions can be a transition impediment. While peer-reviewed selection is certainly appropriate for ESSP and similar NASA missions, the uncertainty associated with determining which measurement proposals will be selected makes planning by NOAA difficult.

In summary, this fourth transition type—NASA exploratory measurements to NOAA operational measurements—is limited by a lack of clear, agreed-upon objectives and adequate procedures to define an efficient transition pathway.

Technology Demonstrations to Operational Systems

Although NASA's role as a technology development agency for operational missions is clearly identified in programs such as NPOESS,[10] NASA does not have a formal program for developing or demonstrating technology for NOAA sensors. Nevertheless, technology transitions are being performed on a case-by-case basis. The GIFTS instrument is being developed for flight validation under the New Millennium Program (NMP), with joint support from NASA and NOAA, in recognition of its value to the GOES-R sounder program.[11] GIFTS was selected by NMP in 1999, with specific direction in the selection letter from NASA to establish closer ties with operational agencies. The mission for the GIFTS instrument has since been renamed GIFTS-IOMI, the operational content has been increased, and the mission now includes substantial contributions from NOAA and DOD.

This transition type has evolved considerably as NASA and NOAA have worked to define the role of GIFTS in preparing for the GOES-R sounder. In particular, NOAA has targeted its contributions to provide for algorithm and data system modifications that support the assimilation of GIFTS data into operational systems of the

[8]See the case study on the Volcanic Ash Mapper in Appendix B.

[9]See the case study on the Solar X-ray Imager in Appendix B.

[10]Presidential Decision Directive/National Science and Technology Council-2 (1994).

[11]"Transitioning from Research to Operations: The GIFTS-IOMI Case Study," presentation by F. Wallace Harrison, GIFTS-IOMI Project Manager, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.

National Centers for Environmental Prediction. It is less clear which aspects of the GIFTS sensor architecture or technologies will transition to the GOES-R sounder.

In summary, the ad hoc evolution of the GIFTS-IOMI mission reflects the lack of an established and documented pathway for the fifth transition type—technology transitions from NASA to NOAA. The result is an unwieldy GIFTS-IOMI organizational structure with multiple partners having inadequately defined roles, procedures that have to be established as issues arise, and budget uncertainties that require each participating agency to plan resources without firm commitments from the other agencies.

COMPARATIVE APPROACHES

Research-to-operations processes in DOD, other U.S. institutions, and foreign organizations, as described in the following subsections, provide opportunities to compare transition approaches to those used by NASA and NOAA.

Department of Defense

The Department of Defense operates under a rigorous transition process based on operational requirements. The process is structured in a manner intended to optimize the formal definition of needs while maintaining a legally mandated arms-length relationship between acquisition and operations. It is also important to note that all of the research conducted by DOD is justified by and focused on the provisions of *United States Code*, Title X, consistent with the mission of the armed services. Within the individual services, the acquisition activities (including basic research, exploratory development, and advanced technology development—collectively defined as science and technology) are conducted under the secretariats (e.g., the Secretary of the Navy). The operations, which include the "demonstration and evaluation" components of research, are administered by the service chiefs (e.g., the Chief of Naval Operations).

The process begins with the definition of mission needs and requirements by the operational forces. These needs and requirements are generally defined in broad terms (such as the need for an ability to assure access to any coastal area), but may include more specifics (such as the need for a near-real-time capability for characterizing the environment of that area) in support of operations. The Mission Needs Statement (MNS) can be an overarching document. More specific definition of requirements is developed through an Operational Requirements Document (ORD). In the joint arena in which multiple services are involved—analogous, say, to a NOAA and NASA relationship—a Capstone Requirements Document, or CRD, is the relevant document. The ORD is the working document that provides a very detailed definition of what systems and platforms are needed and what their performance specifications should be.

The MNS and the ORD are each subjected to formal review by the operational and acquisition leadership of the services. The ORD, once formally approved, is a "sacred" reference for the subsequent activities of planning, programming, and budgeting. It is this set of prioritized missions and requirements that is presented to the acquisition (including R&D) community. The system recognizes that the definition of an operational need might sometimes arise from emerging and unexpected technologies. The potential operational utility of radar, for example, came from research in physics, not from a specific requirement from the fighting forces. Thus, there must be some allowance for taking research risks in areas that are indirectly related to immediate operational requirements.

Notwithstanding this robust process for connecting basic research with operational requirements, there is a potential downside. In the absence of strong tolerance for risk taking within the basic research, much of the fundamental science and technology can become too closely aligned with the immediate operational needs. In that case, the longer-term research investments could become marginalized, resulting in lost opportunities for introducing novel concepts that might translate to new operational capabilities. Within a structure such as that used in DOD, it is critical that there be a clearly stated policy of risk tolerance in research, as long as there is some potential payoff operationally. The challenge for the DOD research community is to assess the right balances of risk, relevance, and responsiveness in its research programs. Overall, however, the "system" expects that the research program will be in direct alignment with the operational requirements.

The DOD approach provides all of the elements needed in a research-to-operations transition pathway—objectives, organizational structure, procedures, and resources. It is being used today in the NPOESS program.

European Space Agency Transitions to EUMETSAT

The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) is the European equivalent of NOAA/NESDIS. It is funded by 18 European member states to operate the European polar and geostationary satellite systems and to provide the satellite data to the weather and environmental services of the member states. The Global Monitoring for Environment and Security (GMES) initiative is a European Commission activity to coordinate geospatial information to support the decision-making process at European parliament and council of minister levels in environmental and security issues (ESA, 2000).

Research and operational development is supported by the European Space Agency (ESA) for EUMETSAT. ESA provides funding for the first of a new generation of satellites to meet EUMETSAT requirements, including Meteosat Second Generation and the Meteorological Operational Polar satellite (METOP 1). This arrangement is similar to that of the OSIP program in the early years of the NASA-NOAA collaboration. The objectives of ESA and EUMETSAT are clear, appropriate organizations are in place, the procedures are developed for the cooperative effort, and the resources have been acquired for these current programs.

European Centre for Medium-Range Weather Forecasts

The European Centre for Medium-Range Weather Forecasts (ECMWF) was established in 1973 to provide medium-range (out to 10 days) forecasts to the European member states. ECMWF has developed a well-defined pathway for transitioning research capabilities and data sources to operational status.[12] The center uses a trial-model approach in which new data sources or capabilities can be evaluated through comparison with the same model without the trial data or algorithms. ECMWF makes less of a distinction between research and operations than is done in the United States, and is willing to incorporate research-quality data into operational systems before a thorough operational need or performance enhancement has been demonstrated. The center is also willing to incorporate research data into operations for periods of several years without assurance that the measurements will be continued. ECMWF has already successfully assimilated data from research sensors from the scatterometers on the European Remote Sensing satellites (ERS-1 and ERS-2) and TRMM and is planning transitions for the ESA Environmental Satellite ozone/wind-wave data, AIRS, CloudSAT, and Jason-1.

The culture of ECMWF has been to push the envelope. The organization is flexible and open to challenges, the procedures are in place, and resources are available for quick transitions.

Office of the Federal Coordinator for Meteorological Services and Supporting Research

The Office of the Federal Coordinator for Meteorological Services and Supporting Research, more briefly known as the Office of the Federal Coordinator for Meteorology (OFCM), is an interdepartmental office. It was established because

[12]"ECMWF Responses to Inquiries from the NAS Study on NOAA/NESDIS Transition from Research to Operations," presentation by David Burridge and Anthony Hollingsworth, European Centre for Medium-Range Weather Forecasts, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.

Congress and the Executive Office of the President recognized the importance of full coordination of federal meteorological activities. The Department of Commerce formed the OFCM in 1964 in response to Public Law 87-843—the Appropriations Act for State, Justice, Commerce, and Related Agencies (1963). The mission of this office is to ensure the effective use of federal meteorological resources by leading the systematic coordination of operational weather requirements and services, and supporting research, among the federal agencies.

Fifteen federal departments and agencies are currently engaged in meteorological activities and participate in the OFCM's activities. The OFCM carries out its tasks through an interagency staff working with representatives from the federal agencies. This infrastructure supports all of the federal agencies that are engaged in meteorological activities or that have a need for meteorological services. In addition to providing this coordinating infrastructure, the OFCM prepares operations plans, conducts studies, and responds to special inquiries and investigations.

The successful development and deployment of the Weather Surveillance Radar-1988 Doppler (WSR88-D) and the Automated Surface Observing System are examples of multidepartmental programs successfully coordinated through the OFCM using the program council approach. OFCM program councils include high-level representatives from the appropriate participating agencies (for a particular project or process), coordinated and administratively staffed through the OFCM. However, the council members respond and provide budget commitments according to their respective agency procedures and structures.

Integrated Program Office (IPO)

Presidential Decision Directive NSTC-2 (1994) created the Integrated Program Office (IPO) and its oversight Executive Committee (EXCOM) to converge the NOAA and DOD polar-orbiting weather satellite programs into a national polar-orbiting operational satellite system, with the objective of reducing cost. The directive states that additional savings may be achieved by incorporating appropriate aspects of NASA's Earth Observing System.

The IPO is responsible for the management, planning, development, fabrication, and operation of the converged polar-orbiting satellite system. The EXCOM (formed at the undersecretary level) ensures that (1) both civil and national security objectives are satisfied; (2) program plans, budgets, and policies are coordinated; (3) agency funding commitments are equitable and sustained; and (4) the Senior User Advisory Group (with EXCOM representation) provides regular and frequent oversight of the IPO. NOAA has the lead for operations, DOD for procurement, and NASA for facilitating the development and insertion of cost-effective technologies.

In implementing its mission, the IPO generates Integrated Operational Requirements Documents (IORDs), which define the EDRs needed to meet the civil and national security missions. The IORD is signed by the EXCOM and forms the basis for all planning, program, and budget activity.

Although the objectives for transitions are defined in Presidential Decision Directive NSTC-2 and the organization is functioning effectively, procedures for the transition process are not clearly spelled out, and the resources for transitioning have been pieced together on an ad hoc basis.

TRENDS AND CHANGES IN TRANSITION PROCESSES

NASA and NOAA are taking a variety of actions to improve the current transition pathways. NOAA's National Environmental Satellite, Data, and Information Service has been reevaluating the architectures and requirements process for the entire meteorological observing system.[13] This effort is driven in part by the near-term need for requirements that support procurement of the GOES-R series. NASA is undergoing a planning process, initiated in part by the mission plan established at the August 1998 Easton, Maryland, workshop held by NASA's Earth Science Enterprise to assess candidate mission programs for the 2002-2010 period (Kennel et al., 1998) and furthered through ongoing dialogue with OMB.[14] In response to the requirements for GOES-R, a Research Strategy and Strategic Plan (NASA, 2000) has been established by NASA, and mission road maps are being developed. A variety of standing meetings have also been set up to facilitate communications about transition issues. Nevertheless, there is no joint plan or document that describes measurements that are planned for transition, nor is there a process for creating them.

In addition, ongoing changes in the space industry and meteorological community have introduced influences that could have long-term impacts on the approach to transitions. NASA experimented in the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) program by procuring ocean color data through a data purchase, and is exploring a similar approach in the Landsat Data Continuity Program to obtain land surface data. NESDIS has already purchased synthetic aperture radar (SAR) data from the Canadian Radarsat satellite for use in ice monitoring, and NASA has recently

[13]Presentation by Michael Crison, NOAA's National Environmental Satellite, Data, and Information Service, to the Committee on NASA-NOAA Transition from Research to Operations, June 2002, Washington, D.C.

[14]Presentation by Sarah Horrigan, Office of Management and Budget, Science and Space Branch, to the Committee on NASA-NOAA Transition from Research to Operations, April 2002, Washington, D.C.

considered the development of a variety of SAR systems that could provide similar data. Opportunities for flying NOAA sensors on geostationary communications satellites, either as payloads-of-opportunity or as data buys, have also been explored.

The continuously evolving diversity of users and user needs increases the demand for a faster transition process from R&D to operational applications. A process that provided for the quick and affordable transition of demonstrated technologies would respond to the "lessons learned" that are documented in the case studies in this report (Appendix B). Such a process can be facilitated by promoting the satellite observing system as adaptive and flexible so that R&D innovations can be quickly validated and then transferred into routine operational systems. In effective research-to-operations transition pathways, it is important that researchers have the resources (i.e., the "telescopes") to allow them to be innovative. Research satellites are needed to test and validate revolutionary remote sensing ideas. However, DOD and NOAA want clearly defined and consistent observations that meet their known requirements. These contrary requirements of the research and operational user agencies need to be reconciled.

One approach to satisfying both research and operational needs is to make every operational satellite capable of carrying advanced technology research instruments that can be space-validated in parallel with the operational mission. Once the advanced technologies are validated, the older and less capable satellite instruments can be retired from subsequent operational satellites, thereby making room for another round of new technology experiments. This approach (often supported by reserving some portion of the operational mission, e.g., 25 percent) would allow a steady infusion of new observing capabilities into operational satellites.

Finally, coupled with the continuous validation of new instrument technologies, there is a need for applied research units at operational numerical prediction centers or associated *test beds,* which have the mission and capabilities to demonstrate the utility of the new observing technologies. In the concept of test beds, new data-assimilation and modeling algorithms are developed and evaluated prior to the launch of particular satellites and the arrival of their observations. Test beds can provide the infrastructure (computational facilities, numerical models, databases, and so on) for researchers to develop improved models and data-assimilation techniques and test the likely impact of future observations. Two test beds have recently been established in support of space weather and hurricane prediction (Boxes 5.1 and 5.2).

BOX 5.1

Transition from Research to Operations in Support of "Space Weather" Forecasting

The transition from research to operations in the area of space weather and climate—that is, *space meteorology*—has many similarities to research-to-operations transitions in the area of weather and climate near Earth's surface. However, space meteorology is significantly less mature than its near-Earth equivalent. The records are much less extensive, the sampling of the Sun-Earth system is much sparser, and many of the fundamental processes are yet to be understood. Until our understanding of space meteorology has matured to the point of being comparable to current understanding in meteorology, a successful early transition from research to operations will benefit not only from the lessons learned, findings, and recommendations in this report but also from particular attention to the following:

1. *Significant participation of researchers in all aspects of the transition process.* Many of the links in the complex chain of processes between the solar interior and the near-Earth environment remain to be adequately explored. Close involvement of the scientific community in the transition process will be critical to ensuring early identification and evaluation of useful observables, early development of partial forecast models in preparation for comprehensive ones, and efficient use of resources.
2. *Stimulation of early development of partial forecast tools.* Research models for space meteorology exist at present only for parts of the Sun-Earth system—for example, the National Center for Atmospheric Research community's Thermospheric Ionospheric General Circulation Model.[1] The development and validation of *forecast* models for parts of the system should be stimulated by efforts that run parallel to and interact with research projects. That development will provide early useful information to the user community and foster expertise and interest within the research community in the development of robust forecast tools.
3. *Use of instrumentation for both operations and research.* In view of the enormity of the volume to be studied—spanning the Sun, the inner heliosphere, and all of geospace—the ensemble of research and operational instrumentation should be viewed as complementary in order to effectively increase the available research resources. Receiving input from both the research and user communities in the definition of instrumentation and having adequate funding to meet the joint requirements are important to catalyze progress.

Other than these differences, the requirements to transfer proven, operationally needed space measurement capabilities from NASA research to NOAA operations and establish test beds for research models (e.g., the Community Coordinated Modeling Center at NASA's Goddard Space Flight Center) are similar to the overall needs of the tropospheric weather support community (NRC, 2003). The National Space Weather Program has the transition of research to operations as a goal: "The overarching goal of the National Space Weather Program is to achieve an active, synergistic, interagency system to provide timely, accurate, and reliable space environment observations, specifications, and forecasts within the next 10 years."[2]

---

[1]More information on the Thermospheric Ionospheric General Circulation Model is available online at <http://www.hao.ucar.edu/public/research/tiso/tgcm/tgcm.html>.

[2]Further background on the National Space Weather program is available online at <http://www.spacescience.org/SWOP/NSWP/>. For more information on research in space weather, see

continues

BOX 5.1 continued

National Research Council, *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (NRC, 2003). That report provides a more detailed discussion of issues related to the transition from research to operations for "space weather" forecasting. Of particular interest is its recommendation that NOAA assume responsibility for the continuance and distribution of solar wind data from spacecraft at the L1 location as well as near Earth.

See also the Web site <http://www.spacescience.org/SWOP/NSWP/1.html>. Accessed March 13, 2003.

BOX 5.2

The Joint Hurricane Testbed

The U.S. Weather Research Program (USWRP) is a coordinated effort among four agencies (NOAA, NSF, DOD, and NASA) that provides the essential focal point and organizational driver for moving ideas and technology from the research arena to operations. The USWRP's Hurricane Landfall implementation plan proposed a feasibility demonstration in which "facilitators"—individuals designated to interact with researchers and the National Hurricane Center (NHC)—would transfer research to operations more efficiently and more effectively than is currently being achieved.

The USWRP funding for the Joint Hurricane Testbed (JHT) began in Fiscal Year 2001. The JHT project funded about 15 research-to-operations projects during its first 2 years of existence. Several projects are already up and running at the NHC. The NHC Technical Support Branch has worked with the affiliated research groups selected to develop test bed projects to provide access to the databases, communications systems, and display systems at the NHC. However, the new USWRP investments in the transition of promising hurricane research into operations have required many adjustments at the NHC.

As indicated from the first 2 years of the JHT test bed experience, the NHC can become overwhelmed by too many test bed projects. The saturation point is a function of the lack of NHC staff available to manage the test bed projects and the numbers and characteristics of the transition projects. The capabilities and availability of technical staff to handle the test bed projects have limited NHC's ability to interact with researchers on project testing and evaluation.

During the second year of the JHT operation, a JHT facilitator was added to the NHC staff to assist in managing the test bed projects, especially the requirements from the individual research teams for access to the NHC computing infrastructure. It is critical that the personnel requirements for these tasks—directing the efforts of the transitions and the ongoing operational evaluation support—be resolved to avoid any negative impact on the operational forecast and warning system.

In summary, the JHT project is designed to expedite promising research on improving hurricane forecasts into the NHC operations and has infused important funding toward this issue, leading to initial success. The most important lesson emerging from the JHT project is—Don't forget the end user in the transition process. In this case, the human resources at the NHC were not sufficient to receive and evaluate properly all of the incoming research projects. An effective distribution of the JHT funds among the transition participants, the NHC, and the researchers will help to ensure the best-possible result.

SUMMARY OF TRANSITION ISSUES

NASA and NOAA share the motivation and need to transition research capabilities to operational status. Analyses of case studies indicate that effective transition pathways incorporate strong management, well-defined transition objectives and plans, effective processes for performing the transition, and adequate human and fiscal resources to accomplish the transition.

Transitions have been largely implemented on an ad hoc, case-by-case basis rather than as part of an overall plan. While an effective relationship between NOAA/NESDIS and NASA/GSFC has been established for procurement and incremental upgrades of the POES (and now NPOESS) and GOES satellites, the relationship has been less successful in planning and implementing major system upgrades. The potential for NOAA to develop data-assimilation algorithms has been significantly increased by the establishment of the Joint Center for Satellite Data Assimilation.

There is no well-defined agreement regarding which NASA systematic measurements will be transitioned to NOAA and which NOAA operational measurements require NASA research precursors. There is also no formal NOAA process in place to identify requirements for which NASA research measurements would be beneficial (although the committee is aware of efforts in NOAA toward the development of a strategic plan, including mechanisms to identify operational and policy requirements), and there is no NASA guidance for determining how research measurements should be prepared as candidates for operational transition. The mismatch between a NOAA planning process that requires a well-defined set of exploratory measurements and the unpredictability of the NASA research peer-review process is an impediment to this transition. Finally, there is no established program in either NOAA or NASA to infuse new technologies and to reduce technology risk for operational satellites, and there is no formal means for prioritizing transition activities other than on a case-by-case basis.

The environment in which research-to-operations transitions occur is changing rapidly. Important influences include the increasing use of international partnerships, accelerating technological progress, the emergence of commercial data sources, and the increasing importance of numerical weather prediction and data assimilation using sensor data directly.

The institutional and budgetary separation of NASA and NOAA makes effective research-to-operations transitions challenging. Effective transitions require close collaboration, planning based on mutual interests, jointly developed resources, and singular authority to make decisions that bind both parties. Neither NASA nor NOAA has the authority to establish plans that depend critically on decisions made in the other agency. With the current organizational constraints, the research-to-operations transition is likely to continue to be characterized as "passing issues over the wall," with operational needs and research capabilities planned and executed largely independently of each other. Thus, although NASA and NOAA desire a smooth transition of research to operations, the current environment is characterized by the lack of an overarching mechanism to ensure that transitions benefit from a common process and are, in general, efficient and effective.

6

A Mechanism for Achieving Effective Transitions

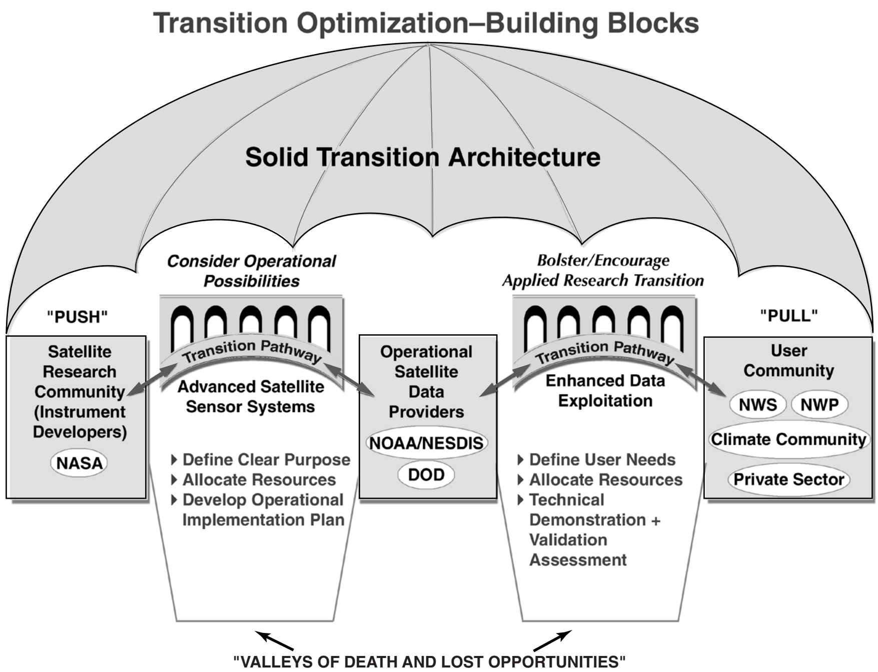

FIGURE 6.1 An efficient transition pathway is based on a solid overarching architecture with strong building blocks supporting all the processes that make up the pathway.

As discussed in Chapters 2 and 5, effective transitioning of research and technology to operations requires a supportive organizational structure and culture; effective planning, communication, and coordination; a strong scientific and technological foundation; a balance between research "push" and operational "pull"; and adequate infrastructure and financial and human resources. Case studies show that complete transitions of environmental measurements have often taken a decade or more, although there is considerable variability (see Chapter 5, the section entitled "Case Studies and Lessons Learned," and Appendix B). Partial transitions—typically involving measurements acquired by research missions that are then incorporated into operations (e.g., scatterometry)—have occurred frequently. There are also examples in which instruments have been flown routinely on operational satellites prior to completion of the data reduction algorithms and the development of techniques for assimilating the measurements into operational prediction models.

The committee recognizes that there are many different ways to accomplish transitions and that valuable transitions would continue without any changes to the present system. However, to speed up the rate of transitions and thereby increase the return on the research investment, there is need for a more *organized and focused* mechanism for transitioning NASA research into NOAA operations. Specifically, the transition process could be dramatically improved by a mechanism that is systematic and transparent (i.e., has well-understood processes and structures), robust (i.e., can influence and drive the transition), and universal (i.e., may be applied to a diverse set of scientific opportunities, technological capabilities, and operational requirements rather than being case-specific).

The elements and building blocks for successful transition architectures described in Chapter 5, in the section entitled "Transition Pathways and Processes," constitute the criteria against which a candidate transition architecture can be evaluated (see Figure 6.1). To be valuable, any proposed architecture must provide a comprehensive solution to the problems imposed by the valleys of death and lost opportunities, in effect establishing a reliable bridge over which the transition from research-to-operations can proceed in an efficient and coordinated manner. Furthermore, the architecture must address the relevant transition communities from end to end, including the research community, the sensor systems community, the data-analysis and data-assimilation community, and the users. (See Box 6.1 for a descriptive analogy of research-to-operations transition pathways.)

The committee considered several approaches to improving the end-to-end transitioning process. After evaluating the strengths and weaknesses of each approach, the committee found that one approach best addresses the objective of establishing a mechanism to develop effective transition architectures without introducing new and equally challenging issues. The committee has identified the need for the creation of an *Interagency Transition Office* that will both support the research and operational efforts in NASA and NOAA and strengthen the transitioning process.

BOX 6.1

Research-to-Operations Transition Pathways: An Analogy

Every transition from research to operations follows a *transition pathway*—an end-to-end set of *processes* for achieving the transition, whether formal or informal. Every technology that is transferred from research to operations has its own particular transition pathway, though pathways for different technologies are often similar and contain similar processes.

Each pathway requires a strong infrastructure, which consists of building blocks that support the pathway. The building blocks include a solid research foundation, laboratories, equipment, computers, algorithms, models, information technologies, and test beds. Some transition pathways are well thought out and planned in advance; others occur in an unplanned, ad hoc fashion.

The *overall design* of the pathway is the *architecture,* and the *Interagency Transition Office* (ITO) is the "architecture firm." This firm designs, costs out, and oversees the entire transition pathway, but it does not build the pathway, nor does it transfer the various technologies across the pathway. NOAA and NASA do the latter. The *elements* of the architecture of the pathway are these: the objectives of the transition, the definition of the organizational structure, the set of procedures or processes, and the resources required to carry out the transition. The necessary resources include funding, people, schedule, and the infrastructure (building blocks) of the pathway.

A transition pathway is analogous to the transfer of science and technology results, or products, from a research and development (R&D) company to end products that are used by a variety of customers. Suppose that a creative and imaginative R&D company builds many different, sophisticated technologies. The value and application of some of the technologies are well known, and operational versions of the technologies are wanted by customers (the "pull"). The ITO, with the help of the company and the customers, designs a transition pathway from the R&D company to the customer to get a technology designed to meet the customers' needs in the most efficient way possible (considering time and cost). The pathway may include transportation by trucks over highways, across bridges, or through tunnels. Part of the pathway may include transport by ships or airplanes and, therefore, must include docking facilities and airports. The pathway for each individual technology varies, but all include various combinations of the above processes and building blocks. The ITO designs the pathway for transporting each technology from the company to the customer, but it does not build the highways, airplanes, trucks, or ships, nor does it drive the various vehicles along the pathway.

The R&D company also builds some novel technologies with new capabilities but for which uses and customers are unknown or have not yet been identified (the "push"). The ITO, together with potential users/customers, evaluates each of these technologies for operational use and, if a user/customer is identified, designs an appropriate pathway for the novel technology.

Highly educated and trained people are needed to drive the complex transition vehicles across the pathway. They must have adequate resources (fuel) and must be fully supported by the infrastructure or building blocks of the pathway. They must have clear objectives and a comprehensive plan (overarching architecture or road map) to follow; yet they must be vigilant for unforeseen problems along the way (e.g., ice on the road, running out of fuel, breakdowns in the infrastructure), as well as open to new and unexpected opportunities (e.g., shortcuts, unexpected tailwinds, breakthroughs in technology) that present themselves. The architecture must be flexible, to account for unexpected problems and opportunities along the pathway.

continues

BOX 6.1 continued

The *processes* are the transport of the technologies across the highways and bridges, through the tunnels, over the oceans, through the air, and so on. The *architecture* is the *design* of the entire pathway: the bridges, highways, tunnels, and so on, that make up the pathway; the various vehicles that cross the pathway; the human resources needed to drive the vehicles; and the financial resources needed to build and support the pathway. The *infrastructure* of the pathway includes *building blocks*—the bridges, highways, tunnels, and the vehicles that transport the technologies. The ITO is the *mechanism* that develops the architecture and reviews and reports on the progress of the transition pathway.

THE RECOMMENDED APPROACH: ESTABLISH AN INTERAGENCY TRANSITION OFFICE

The committee recommends the formation of an Interagency Transition Office (ITO) that would have responsibility for *strategic planning and coordination,* but *not implementation,* of all transition activities. This office is intended to support and simplify transitions by augmenting, enabling, and leveraging the existing infrastructure within NASA and NOAA rather than by introducing duplicative capability or bureaucracy.

The ITO should be chartered through a formal agreement, such as a Memorandum of Agreement, between the agencies, and signed at least one level above the highest level at which transition-related activities occur. The responsibilities and authorities of the ITO should encompass transitions required by NPOESS, GOES, and all NOAA operational spaceborne systems and should explicitly reflect the needs and capabilities of all parts of both agencies that are responsible for the transition of research to user applications. As envisioned (see the description below), the ITO would *strengthen* the partnership between NASA and NOAA and *support* the missions and activities of both agencies.

The ITO should be a small but permanent, full-time office (the committee anticipates approximately 10 people)—staffed half by NOAA and half by NASA. It would include representatives from the NOAA operational entities (such as the National Weather Service and the National Ocean Service) that use the research products and the NASA entities that carry out the research. It should receive input from the broad scientific and user communities through a high-level advisory council with membership drawn from the relevant research and operational communities outside the participating agencies. Funding should come equally from both agencies. The lead ITO person from each agency should report directly to the person who has the highest authority for transition-related activities at NOAA and at NASA headquarters, respectively. An executive board, envisioned by the committee as including the NASA and NOAA administrators and the President's Science Advisor at a minimum, should provide high-level oversight and review of the ITO. NASA and NOAA should consider including as executive board members representatives at an equivalent level from DOD (for example, the undersecretary of defense for acquisition and technology) and from other agencies when appropriate to the mission of the ITO.

In its role as a strategic planning and coordination office, the ITO would provide the systems engineering guidance and oversight which ensure that all aspects of each transition are identified, properly incorporated into the transition plan, and effectively implemented. In particular, the ITO should be a champion for transition elements such as data-archiving and information-extraction systems that traditionally "fall through the cracks." The ITO should have the following responsibilities and authorities associated with the architecture (or design) and oversight of the *entire transition pathway*, including the necessary building blocks for successful transition. Specifically, the ITO should carry out these tasks:

- Review long-term (0 to 20-year) NASA and NOAA plans in order to identify requirements, mission/instrument needs and capabilities, and related activities that require transition support or are candidates for transition. The ITO should formally evaluate all NASA missions for their potential for operational applicability. On an annual basis, the ITO should produce a *NASA-NOAA Transition Planning and Status Report*, summarizing the plans, status, and prioritization of the agreed-upon transition projects and associated budgets, with signature approval by authorities at the highest levels at which transition-related activities are budgeted and implemented at NOAA and NASA, respectively.
- For each identified transition project, establish a *NASA-NOAA Project Transition Plan* for accomplishing the transition, with signature approval by authorities at the highest levels at which transition-related activities occur at NOAA and NASA headquarters, respectively. Each plan should define measures of transition effectiveness and should describe the activities associated with the transition, including the operational requirements to be satisfied, scientific validation of the measurement technique, technology development requirements, any need for pre-operational test beds or flight validation, algorithm and assimilation needs, a data-management plan, and other, related activities. The plan should describe (in detail appropriate to the time frame of the activity) how each activity is to be accomplished; it should include the following:

  —A schedule of transition activities, to include the training and education necessary for full operational capability;

  —The responsibilities of NASA and NOAA and other participating agencies or partners for each transition activity;

—A description of the financial and human resources required for each transition activity, as well as an estimate of expected resources required for operations and maintenance after the acceptance of initial operational capability; and

—A description of the necessary interfaces with other NASA, NOAA, and participating agencies' or partners' activities.

- Identify the infrastructure and in-house capability required within NASA and NOAA and their government partners to ensure that transitions can be accomplished effectively, and recommend needed changes within the *NASA-NOAA Transition Planning and Status Report*.
- Define measures of transition effectiveness and systematically monitor the progress of NASA and NOAA projects in implementing the agreed-upon transitions. On an annual basis, the ITO should describe the progress of each identified transition project in the *NASA-NOAA Transition Planning and Status Report*.
- Provide a forum for identifying transition-related weaknesses in the NOAA requirements and in the NASA research plans, describe transition issues, and present candidate solutions for resolution at the highest level of authority required at NOAA and NASA headquarters, respectively.

The annual *NASA-NOAA Transition Planning and Status Report* should be recognized as a supporting document in the budget requests of each agency. Implementation—that is, project and program management—of the activities described by the plan should be carried out *not* by the ITO but rather by each agency, as agreed to in the plan and as budgeted by the agency. It is anticipated that the ITO will not replace the existing transition approaches and processes, but rather employ these when beneficial and strengthen them where necessary and feasible. On a regular basis (e.g., every 5 years), the ITO should be reviewed through an independent process.

A significant advantage of the ITO approach is that it provides a neutral *honest broker* in the transition planning and coordination process because the ITO has equal high-level representation from both NASA and NOAA, as well as an independent external advisory council. This approach has the following additional benefits with regard to the NASA-NOAA transition process:

- It is well integrated in the leadership structure of both NASA and NOAA, supporting, rather than competing with, NASA and NOAA priorities.
- It provides jointly developed specific guidance (budgetary and programmatic) to assist the agencies in producing well-coordinated plans.
- It replaces the current ad hoc process with a formal process that facilitates all transitions (both push- and pull-driven) and can be readily reviewed and evaluated for effectiveness.

- It provides a clear point of contact for research-to-operations transitions.
- It is straightforward to establish. It does not require a presidential directive or an act of Congress to create a new organization. It does not create a new bureaucracy that takes authority from NASA and NOAA.
- Since the annual *NASA-NOAA Transition Planning and Status Report* is approved at high levels in the agencies, it will be accompanied by the appropriate implementation resources allocated within each organization. All involved in the transition activities will understand their responsibilities.
- The people who best know the research (NASA) and operational needs (NOAA) are the ones providing input to the transition plan.
- It provides an open and fair process, with input from the broad external scientific and user communities, for prioritizing, developing, and monitoring transition-oriented efforts.
- It can incorporate and expand on the existing transition approaches rather than disruptively replacing them.
- It is consistent with the existing NASA research peer-review process. The peer-review process introduces uncertainty into transition planning but is central to the integrity and quality of NASA research. An appropriate balance between these needs could be achieved by encouraging the pursuit of ITO-generated priorities in proposals, but evaluating the proposals using normal peer-review processes.
- It invents a proactive forum for advertising and marketing emergent research push and operational pull.
- It has the additional benefit of being sufficiently flexible to support the future inclusion of other agencies (e.g., DOD) that could be interested in becoming the operational beneficiaries of NASA research. Representatives of the new member agency would simply be added to the ITO, that agency would produce its own planning documents, and the ITO would produce an additional document concerning agreed-upon transitions.

The approach has potential disadvantages, including these:

- Redirecting existing resources to establish and staff a new office; establishing a new bureaucracy, if the ITO is not implemented properly;
- The need for two agencies to reach agreement before a particular transition project can be implemented; and
- Giving the appearance that transition responsibilities are now exclusively the responsibility of a dedicated office.

This recommended approach is consistent with and builds upon the recent NRC report *From Research to Operations in Weather Satellites and Numerical Weather*

Prediction: Crossing the Valley of Death (NRC, 2000a). In particular, that report recommends creating a replacement for the Operational Satellite Improvement Program (OSIP), which was terminated in 1982. The functions of the ITO include those of OSIP but go beyond them by considering the entire end-to-end process for transitions. This end-to-end process supports many of the recommendations in the NRC (2000a) report. The approach and recommendations presented here are also consistent with a recent study of the socioeconomic benefits of Earth science research, especially the recommendations that NASA and other government agencies should expend sustained resources on better understanding and on improving the flow of information from science to applications (Hertzfeld and Williamson, 2002). The Hertzfeld and Williamson study recommended that "a detailed analysis of the research to applications should be conducted in each applications area in order to achieve the best return on investment in Earth science research," which is what the *NASA-NOAA Transition Planning and Status Report* will accomplish. A discussion of how the ITO would work in practice is provided in Box 6.2.

BOX 6.2

The Interagency Transition Office in the Real World—An Example

The success of the proposed Interagency Transition Office (ITO) would depend largely on how well it functioned *in practice* and on whether it improved the efficiency of both NASA and NOAA in performing transitions rather than hindering them. To understand how the ITO would function, consider the example of the "Instrument of Opportunity" extra payload capacity that is currently going unused on the GOES satellites. The availability of this "demonstration" payload capacity is a tribute to NASA and NOAA in their efforts to improve transitions, but the inability to find users illustrates the difficulty of matching needs with capabilities across two agencies having different schedule constraints, funding priorities, and planning structures.

The ITO would assist in resolving this problem by first identifying it as a transition-related issue. Then the ITO would develop an internal plan, agreed to by both NASA and NOAA ITO members, for resolving the problem. This plan would include such things as solutions for ensuring that the NOAA schedule for integration on GOES is aligned with NASA program schedules acceptable under Earth System Science Pathfinder or other solicitations; that a NOAA operational requirement is available at the appropriate time to justify a transition of the instrument to operational status; and that all cost and budgeting issues are known and their allocations across the agencies are agreed to. The plan would be presented to both NASA and NOAA, iterated if needed, and agreed to at the appropriate levels. NASA and NOAA would then implement their portions of the agreement separately, with the ITO acting in an ongoing review capacity to identify issues as they arise and to recommend solutions to ensure effective implementation.

An important element of the ITO plan would be suggestions for more effective communications channels or simplified processes. These would allow the involved NASA and NOAA parties to coordinate more effectively and thus limit the need for further ITO involvement.

ALTERNATIVE APPROACHES CONSIDERED

The committee considered four alternatives to its recommended approach. It found that all had greater difficulties in achieving one or more of the necessary critical elements for managing the research-to-operations transition in a continuous, robust, and influential manner. The alternative approaches are outlined in the following subsections.

Alternative Approach 1: Establish a New Transition Agency

The first alternative approach considered by the committee is that of establishing a new *transitioning* agency, with full responsibility for research in support of environmental remote sensing operations and the concomitant transition of capabilities. The responsibilities of the new agency would include research and planning, and it would have programming and budgeting authority, as well as responsibility for implementing the transitions. Such responsibility translates into having the resources to conduct research, development, testing, and evaluation and demonstration, as well as to procure, operate, and maintain the space and ground segments used for environmental remote sensing. This agency would function in an independent capacity, with accountability at the highest level of government, similar to the way in which NASA, the NSF, and other independent agencies function.

There are advantages to establishing such an agency:

- Those inefficiencies that result from different agencies having separate research and operational missions could be overcome. Under the current structure, separate plans, progress reports, and budgets must be submitted through different bureaucracies to support the same ultimate operational capability.
- The new agency would facilitate centralized reporting of the national status and plans for civil applications of satellite-based environmental observations. This "one-stop shopping" would minimize the chances of ambiguity in conveying our nation's environmental remote sensing program to all interested parties in government, industry, academia, and internationally.

The establishment of a new agency under this approach also has distinct disadvantages:

- It would be extremely difficult in the present budgetary and political climate to establish such a new agency.
- Focusing the responsibility for transitioning research to operations would release mission agencies from the responsibility for transition and would also remove

the influence and control that these agencies enjoy under the current organization. That is, there is no mechanism under this proposed structure to ensure that NOAA's mission needs (notably in the National Weather Service and the National Ocean Service) would receive adequate attention from the new agency.

- Many current efficiencies in the use of research resources would be lost. Assuming that there are no new resources to support this new agency, resources for it would have to be allocated from existing sources. As a result, there would undoubtedly be losses of efficiencies and duplication of investment. This would be especially pronounced within the research component, where current resources (i.e., laboratory and computational facilities) are being used to support a multitude of efforts, only some of which are oriented toward environmental remote sensing.

Creating a new agency as described here is very similar to the approach of placing all of the research and operational activities, including the applications, within one existing agency (such as NOAA). The primary difference is that one of the existing agencies could not be an "honest broker" (the importance of which is described above). If the responsibilities were given to NOAA, for example, NASA would not be an equal partner, likely leading to poor communications and coordination, budget inconsistencies, prioritization disagreements, and inadequate joint planning.

The benefits defined above are small, and they would be attainable through means other than the difficult processes associated with establishing a new agency or placing all transition activities within one existing agency. Similarly, the advantages described above could be realized without a major bureaucratic reorganization.

Alternative Approach 2: Retain But Improve the Current Case-by-Case Transition Approach

The second alternative approach considered by the committee is that of retaining the status quo of case-by-case transitions (described in Chapter 5) and instituting improvements where desirable and feasible. The committee recognizes that some existing transition activities have been effective and efficient. The existence of successful transitions (as shown by the case studies discussed in Chapter 5 and Appendix B) illustrates that transitions can be accomplished in certain cases, when properly planned and coordinated by the mutual agreement of NOAA and NASA along with the strong individual involvement of those wielding resource authority.

However, the case-by-case approach on the whole is inefficient, inconsistent, and fiscally unpredictable; it leaves critical elements unaddressed; and it is not a robust, long-term solution. Moreover, as described in Chapter 4, scientific and technological opportunities are increasing rapidly, and the complexity of research-to-operations transitions is also expected to increase significantly over the next two decades, with issues such as multiple national and international partners. Therefore, even an improved ad hoc approach will become increasingly unable to systematically assess and ensure the existence of all the critical elements necessary for successful operational transition.

Alternative Approach 3:
Expand the Role of the NPOESS Integrated Program Office

The third alternative approach considered by the committee is that of expanding the role of the NPOESS Integrated Program Office (IPO) to include all of the transition-related activities that occur between NASA and NOAA. It is reasonable to consider broadening the IPO charter to explicitly include overall responsibility for the planning and implementation of NASA-NOAA transition activities. This approach has the objective of establishing a single entity with centralized responsibility for the planning and implementation of transitions. The IPO is an appropriate candidate to lead this activity, given its charter for operational environmental systems. However, several significant issues arise with this approach.

The committee believes that the ITO would perform a function fundamentally different from that of the IPO, and that consolidation of NASA-NOAA transition activities with the IPO would adversely impact the nature and effectiveness of NASA and NOAA. Figure 6.2 illustrates the differences. In this figure, the vertical axis

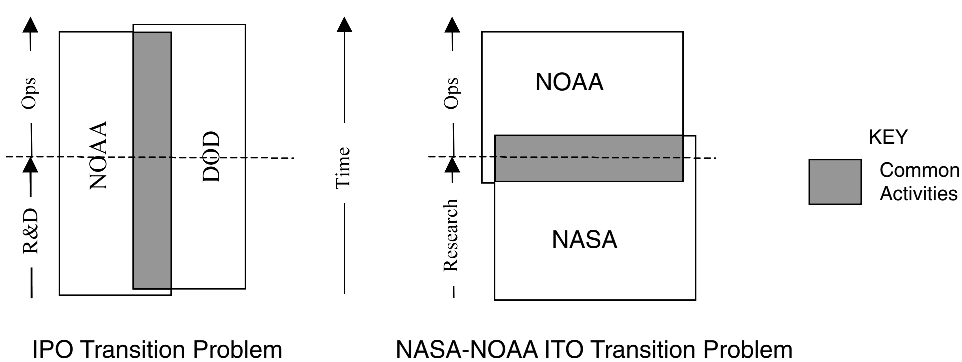

FIGURE 6.2 Differences between the existing NPOESS Integrated Program Office (IPO) and the Interagency Transition Office (ITO). (See discussion in text.)

represents the progression with time from research, or R&D, to operations. In the IPO case (left), both NOAA and DOD perform R&D and operations within their respective charters. In most cases, these R&D and operational activities do not overlap (e.g., NOAA does not develop weapons). An important exception is the development and operation of the polar satellites, where there is a clear overlap (the vertical gray area). The primary objective in forming the NPOESS IPO was to address the *duplication problem* caused by largely similar NPOESS and DOD operational polar environmental satellite programs—not to address the *broad research-to-operations transition problem* that is the subject of this study.

The NASA-NOAA transition problem in general (right side of Figure 6.2) is orthogonal to the IPO situation. NASA primarily carries out research, while NOAA mostly conducts operations. The horizontal "gray area" covers a wide range of missions and capabilities, and occurs at the handoff between research and operations.

The IPO charter included a broadly worded role for NASA to provide research and development activities in support of NPOESS,[1] and NASA has responded to this role through development programs such as the Advanced Technology Microwave Sounder (ATMS) and the NPOESS Preparatory Project (NPP). Despite these examples, the IPO charter does not specify that NASA, the IPO, or any joint office has ultimate responsibility for overall planning and implementation of transition activities. As a result, even apparently successful transitions such as the ATMS and NPP were planned and accomplished on an ad hoc basis, through case-by-case negotiations between NASA and the IPO. With limited exceptions, future IPO requirements (such as the list of unsatisfied EDRs[2] or plans for Pre-Planned Product Improvement) are not coordinated with a NASA research plan in order to investigate and develop operational solutions. Similarly, NASA research capabilities are not formally evaluated for their operational potential to NPOESS. Furthermore, as the current IPO charter responsibility formally ends with the provision of EDRs, the IPO does not itself represent the needs and requirements of the user community, but rather must seek them elsewhere within NOAA and DOD.

[1]The language concerning the role of NASA from Presidential Decision Directive/National Science and Technology Council-2 (1994) states: "NASA will have lead agency responsibility to support the IPO in facilitating the development and insertion of new cost effective technologies that enhance the ability of the converged system to meet its operational requirements."

[2]Comments such as, "The three centers that are the heaviest planned users of NPOESS EDRs reported that about 45% of the EDRs they plan to use would require major advances in science in order to be used" (GAO, 2002) imply that not all elements of the transition process are being addressed by this approach.

Specific disadvantages with the assignment of the entire transition role to the IPO include these:

- Without strong IPO influence over NASA research activities, the ability of the IPO to identify candidate research and to plan associated transitions is no more effective than the current system, unless transition authority is given to the NASA IPO representative or unless a joint NASA-IPO office with authorities similar to those envisioned for the ITO is established.
- In order to centralize NASA-NOAA transition authority, the IPO charter would have to be expanded to include GOES and other NASA-NOAA transition activities.
- An IPO-led transition entity would not be perceived as an "honest broker" of the transition process, placing transition authority on the operations ("pull") side of the research-to-operations balance.
- Unless the IPO role is further expanded beyond that designated by the current charter, the IPO is not an entity with responsibility for the end-to-end transition process, particularly with regard to representing the end user. An IPO-led transition entity would require additional interfaces with other planning entities.
- While the IPO has extensive experience in developing and procuring an operational environmental satellite system, it does not have experience in performing research. It would either have to develop this experience or limit its transition role to that of planning but not implementation, similar to the role proposed for the ITO.

Alternative Approach 4: Use the Office of the Federal Coordinator for Meteorological Services and Supporting Research

The fourth alternative approach considered by the committee is that of using the existing Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) to facilitate transitions. As discussed in Chapter 5, the OFCM has an existing federal infrastructure, relevant mission responsibility, and a past record of successfully coordinating multiagency projects. A NASA-NOAA Transition Program Council could be established, with high-level representation from NASA and NOAA (and probably DOD),[3] that would provide the means to develop transition plans and obtain the budget commitment needed, through the agency representatives as the agencies directed. Other federal agencies could be added as appropriate, since they would have fundamental representation within the overall OFCM infrastructure, although not initially on the NASA-NOAA Transition Program Council.

[3]Agency representatives would attend regular council meetings to make decisions.

However, as an existing *staff* organization, the necessary direct *line* organizational and budgetary authority links needed to achieve the funding commitments and focus required over the longer term may not be achievable. Dedicated agency staffing, with full-time, high-level agency representatives, may be required to provide the necessary greater focus on transition planning and implementation.

SUMMARY

The committee's findings point to the necessity of creating a joint research-to-operations transition office. The benefits of this approach, as described above, include these:

1. A dedicated, organized, and focused mechanism for transitioning research to operations;
2. A balanced and neutral office, reporting to high-level authorities in NASA and NOAA, charged with planning and coordinating the transitional process from research to operations, thereby strengthening the partnership between NASA and NOAA and supporting the missions of each;
3. A continuous, long-term planning mechanism connected to the budgetary planning processes in NASA and NOAA;
4. On-going review responsibility of all transitions;
5. Valuable input provided by an independent, external advisory council made up of individuals knowledgeable about both the research and operations; and
6. An equally balanced, high-level staff reporting to equally high-level authorities (within their respective agencies), charged with planning and coordinating the transitional process from research to operations.

While the committee believes that creation of the Interagency Transition Office would be a major step toward making transitions from research to operations faster and more effective, it realizes that the ITO by itself will not guarantee success. A strong and sustained commitment by NASA and NOAA leadership to the ITO in particular and to transitioning in general is required, and the ITO must be provided sufficient resources and authority to do its job. In addition, cultures in both agencies that favor technology transfer must be fostered, and appropriate reward systems need to be implemented to attract the high-quality people needed to make the ITO successful.

7

Findings and Recommendations

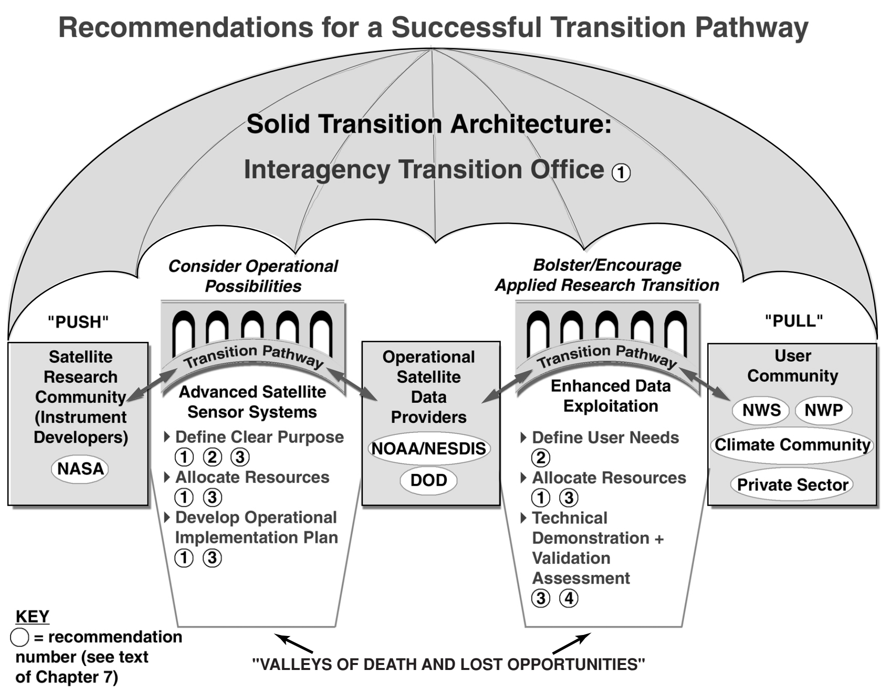

FIGURE 7.1 Idealized transition pathway summarizing the issues addressed and indicating the solutions recommended in this report.

BOX 7.1

Visualizing the Pathways for Transition

NASA-NOAA transitions are challenging because they must cross valleys of death and lost opportunities, a journey achieved by following a transition pathway that connects one side to the other (see Figure 7.1 in this chapter). To cross the valleys, each pathway must traverse bridges. Each bridge is composed of building blocks, which include a solid research foundation, laboratories, equipment, computers, algorithms, information technologies, and other necessary infrastructure to support the transition pathway. A weakness in any building block produces a rickety bridge and thus a poor pathway. The fundamental flaw in the present transition system is that NASA and NOAA own the "land at the valley edges," but nobody systematically designs, builds, and maintains the bridges. As a result, bridges are constructed ad hoc, and their underlying building blocks are of varying quality. The proposed solution is an Interagency Transition Office (ITO) that will develop a solid transition architecture that spans the entire pathway, connecting NASA with NOAA and then NOAA to the user community. The ITO would plan and coordinate the design of consistently reliable bridges built upon robust building blocks, but NASA and NOAA would retain responsibility for implementing the bridges and operating the pathways that cross them.

As discussed in earlier chapters, advances in the remote sensing of Earth's environment from space hold promise for realizing the vision of an Earth Information System. This system would consist of a four-dimensional gridded set of quantitative, geo-referenced digital data that describe the Earth system. These data would be increasingly valuable to a host of users in the public and private sectors and the academic community. Weather and climate services will benefit greatly from these advances, but it is necessary to improve the process of transitioning research results into operations in order to more quickly realize the return to society from the research investment. This chapter presents an overarching recommendation for an interagency planning and collaboration mechanism and follows up with supporting recommendations for more detailed program and mission design aspects to streamline and support the transition process. See Figure 7.1, which summarizes the issues and recommendations presented in this report, and Box 7.1, which describes how each of the key concepts in the report is related to the image of transition pathways.

INTERAGENCY TRANSITION OFFICE

Finding: As discussed in previous chapters, the current transition pathways for NASA research to NOAA operations include successful examples that represent strong models for other transition activities. In general, however, transitions have been ad hoc and are often complex and unstructured, at times working well and at other times not working as well as they could or even breaking down entirely. No organizational mechanism is available to ensure that the transition process in general is efficient and effective and that an overarching architecture for each transition is in place. The committee finds that more effective interagency planning, coordination, and collaboration are key to the rapid and effective transition of environmental measurements from research to operations. Further, a structured, consistent, and well-defined organizational approach to transitioning activities is needed.

Recommendation 1: A strong and effective Interagency Transition Office for the planning and coordination of activities of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) in support of transitioning research to operations should be established by and should report to the highest levels of NASA and NOAA.

The ITO should have broad responsibility (not specifically related to sensor capability) for ensuring that appropriate research is efficiently and effectively transitioned to operational uses. However, the ITO itself should not *implement* the transitioning activities. The implementation should be carried out by appropriate NASA or NOAA entities (such as the NPOESS Integrated Program Office, with its current charter for the acquisition of polar operational satellite systems) or by their partners in the academic community and private sector. The ITO is intended to support and simplify transitions by augmenting, enabling, and leveraging the existing infrastructure within NASA and NOAA rather than by introducing duplicative capability or bureaucracy.[1]

The products of the planning and coordination should include a formal evaluation of every new and improved sensor capability and mission. The evaluation should include an assessment of existing and potential users and uses of the new capability. The strategic plan for each mission should provide for flexibility in the mission as the scientific and technological capabilities evolve, as well as identify the financial and human resources necessary to carry out the plan.

The ITO should define measures of transition effectiveness and systematically monitor the progress of NASA and NOAA in implementing the agreed-upon

[1]The committee intends that the ITO be a flexible organization so that other agencies or foreign partners could join the process for specific missions by invitation from NASA and NOAA. The benefits of the ITO (described in Chapter 6, in the section entitled "The Recommended Approach: Establish an Interagency Transition Office") are still appropriate in any case, perhaps even more so when a partnership extends beyond NASA and NOAA.

transitions. It should also provide a forum for identifying weaknesses and other issues in the transitioning process and present candidate solutions for resolution to the highest levels of authority required at NASA and NOAA.

The ITO should have an independent, high-level advisory council consisting of representatives from the operational and research communities as well as from the public and private sectors. It should also serve as a forum for regular discussions between the leaders of the research and operational organizations.

An executive board, envisioned by the committee as including the NASA and NOAA administrators and the President's Science Advisor, at a minimum, should provide high-level oversight and review of the ITO. NASA and NOAA should consider including as executive board members representatives at an equivalent level from DOD (for example, the undersecretary of defense for acquisition and technology) and from other agencies when that would be appropriate to the mission of the ITO.

Implementation of the following recommendations is needed in order to support the mission of the proposed Interagency Transition Office. *However, these recommendations are not specifically tied to the establishment of the ITO. They stand on their own merit and would be necessary in order to strengthen any transitioning mechanism or pathway.*

IMPROVING COMMUNICATION AND COORDINATION

Finding: There has been no overarching formal mechanism for developing NOAA's operational requirements based on user needs, although the committee is aware of efforts in NOAA toward the development of such a mechanism and a formal strategic plan. Operational user needs and requirements are neither communicated well to NASA nor formally used by NASA in its priority-setting process.

Recommendation 2: NOAA and NASA should improve and formalize the process of developing and communicating operational requirements and priorities.

2.1 NOAA should continuously evaluate and define operational user needs and formally communicate them to NASA on a regular basis.

2.2 NASA should formally consider the requirements of NOAA and other operational agencies in establishing its priorities (the "pull" side of the transition process). NASA should establish appropriate programs and budgets as needed to respond to selected NOAA requirements.

THE EVALUATION OF MISSIONS FOR POTENTIAL TRANSITION OPPORTUNITIES AND THE NEED FOR TRANSITION PLANS

Finding: A major part of NASA's mission is, appropriately, to do exploratory Earth science research for which there are no immediate operational needs or requirements, but for which a large potential benefit to scientific understanding and eventually to operations might occur if a mission is successful.

The research and operational communities need to be more alert to new and unexpected applications of NASA's exploratory research and establish a process of assistance for discovering these applications. There is no formal NOAA process for identifying requirements for which NASA research would be beneficial. A formal process for evaluating all NASA missions for potential operational applications would provide a solid foundation for developing effective plans for transitioning activities. There is a need for transition plans, developed jointly by the research and operational community for all appropriate NASA missions (as determined by the mission evaluation process).

> **Recommendation 3: All NASA Earth science satellite missions should be formally evaluated in the early stages of the mission planning process for potential applications to operations in the short, medium, or long term, and resources should be planned for and secured to support appropriate mission transition activities.**

The evaluation process should include engaging in dialogue with the research and operational communities and obtaining input from possible users of the observations. For appropriate missions, as determined by the assessment, a flexible plan or architecture for a seamless transition pathway, including the necessary financial and human resources, should be developed, regularly reviewed, and updated as necessary. It is important to note that a transition plan may encompass an entire mission or sensor, or it may be limited to smaller mission elements. For example, a NASA research mission could develop a new calibration approach, algorithm, data-archiving system, component technology, or other mission element that has NOAA operational value. It is an appropriate role of the ITO to designate such a NASA mission as a transition candidate—in such cases the activities to be transitioned would be limited to the relevant elements of the total mission.

For a mission that is identified as having significant potential for providing data useful to operations, the following activities should be supported:

3.1 NASA and NOAA should work together to strengthen the planning, coordination, and management components of the mission. Teams of people with appropriate research and operational expertise should be assigned to the mission. A culture fostering aggressive and challenging approaches, risk taking, acceptance of outside ideas and technologies, flexibility, and a "can-do" attitude should be encouraged.

3.2 Adequate resources should be provided in order to support all aspects of the transitioning activities, as determined by the assessment and plans. Consideration should be given to establishing guidelines and mechanisms for encouraging transition efforts. For example, a small fraction (e.g., 5 to 10 percent) of each sensor or mission project budget might be allocated to transition activities. Principal investigators might be asked to submit plans or concepts for transitional activities, with significant points being allotted in scoring this aspect of the proposals.

3.3 Research into how to use new types of observations should be supported well in advance of the launch of the research or operational mission that acquires the observations. In parallel with the acquisition program, this research should include developing and testing algorithms to convert sensor data to environmental products (including environmental data records) and data-assimilation methods, as appropriate to the mission. The research may be carried out in a variety of institutions, including universities, national laboratories, cooperative institutes, and test bed facilities. The institutional mechanism(s) to conduct the research should be identified early in the mission.

3.4 Each research mission should have a comprehensive data-management plan. The plan should include the identification of potential users and approaches for processing the data, converting the raw data to information, creating metadata, distributing data and information to users in real time, and archiving and the subsequent accessing of data by users.

3.5 NASA and NOAA, through the ITO as defined in Recommendation 1, should develop a plan to include the use of NPOESS and GOES-R sensor data by the appropriate government agencies. A collaborative arrangement and at least one demonstration/pilot or benchmark project should be developed with each primary user agency (e.g., the U.S. Geological Survey, the U.S. Department of Agriculture, and the Environmental Protection Agency) using NPOESS and GOES-R products.

3.6 Each research mission should have an associated education and training plan. This plan should be addressed to the operational, research, and academic communities, including students. It could include, for example, scientific visitor exchange programs, support for collaborative research, workshops, and a plan for the timely flow of research data to operational and academic institutions.

3.7 The evaluation process and resulting transition plans should consider potential roles in the research-to-operations transition process for the academic community (including principal-investigator-led projects) and the private sector, both of which have relevant capabilities and knowledge not available within NASA and NOAA.

BUILDING A FLEXIBLE OPERATIONAL SATELLITE SYSTEM THAT CAN ADJUST MORE QUICKLY TO NEW SCIENCE AND TECHNOLOGIES

Finding: The current operational satellite system is inflexible and slow to adjust to opportunities presented by new scientific and technological advances. A more flexible system, including closer connections between the operational and research communities and the use of both research and operational data by both communities, would be beneficial.

While important differences and sometimes conflicts between research and operations exist, there are often synergies between the two that can be better exploited. Research missions can provide data that are useful for operations, even if only for a limited time. The experience gained in real time from the use of research observations is invaluable and can lead to definition and justification of future operational missions. The operational users of research observations can provide very useful information back to the researchers on the quality of the observations.

Recommendation 4: NASA and NOAA should jointly work toward and should budget for an *adaptive* and *flexible* operational system in order to support the rapid infusion of new satellite observational technologies, the validation of new capabilities, and the implementation of new operational applications.

4.1 Operational satellite programs should provide for the capability of validating advanced instruments in space and of cross-calibrating them with existing instruments, in parallel to the operational mission, by the most efficient means possible (e.g., by reserving approximately 25 percent of the payload power, volume, and mass capability; through "bridge" missions; and so on).

4.2 To the extent possible, observations from research missions should be provided in real time or near real time to researchers and potential users. Operational centers or associated test beds should use and evaluate the research observations in developing their products and should provide feedback to researchers. Test beds such as the Joint Center for Satellite Data Assimilation and the Joint Hurricane Testbed should be supported as a way to bridge the final steps in the gap between research and operations. The primary mission of such test beds should not be to conduct basic research or operations, but rather to develop and test new real-time modeling and data-assimilation systems to use the new observations. The test beds should include participation by the academic research community and should be quasi-independent from the operational agencies.

4.3 Senior personnel responsible for transition activities should be located at major operational centers of NOAA and at the major research segments of NASA.

In summary, to cross the valleys of death and lost opportunities successfully, a means of bringing NASA and NOAA together—as partners—to design and navigate the transition pathways between research and operations must be created. The Interagency Transition Office plan has the necessary underpinnings to span these valleys and facilitate smooth transitions from research to operations and then to end users.

References

Anthes, R.A., C. Rocken, and Y.-H. Kuo. 2000. Applications of COSMIC to meteorology and climate. Journal of Terrestrial, Atmospheric and Oceanic Sciences 11:115-156.

Changnon, S.A., ed. 2000. El Niño 1997-98: The Climate Event of the Century. Oxford University Press, New York.

Colgan, C.S., and R. Weiher. 2003. Linking Economic and Environmental Goals in NOAA's Strategic Planning. Draft NOAA report. NOAA, Washington, D.C.

Dutton, J.A. 2002. Opportunities and priorities in a new era for weather and climate services. Bulletin of the American Meteorological Society 83:1303-1311.

Ehlers, V. 2002. Statement to Subcommittee on Environment, Technology, and Standards, Committee on Science, U.S. House of Representatives. Hearing on Satellite Data Management at NOAA, July 24, 2002.

ESA (European Space Agency). 2000. Toward the Implementation of an Operational European Earth Observation Capability. ESA/C(2000)44. ESA, Paris, France.

GAO (General Accounting Office). 1997. Weather Satellites: Planning for the Geostationary Satellite Program Needs More Attention. GAO/AIMD-97-37. U.S. Government Printing Office, Washington, D.C.

GAO. 2002. Polar-Orbiting Environmental Satellites: Status, Plans, and Future Data Management Challenges. Testimony of Linda D. Koontz, Subcommittee on Environment, Technology, and Standards, Committee on Science, U.S. House of Representatives, July 24, 2002. U.S. Government Printing Office, Washington, D.C.

Goldin, Daniel S. 2000. Remarks of National Aeronautics and Space Administration Administrator at NASA Continual Improvement and Reinvention Conference on Quality Management, April 27, 2000, Alexandria, Va.

Hertzfeld, H.R., and R.A. Williamson. 2002. Socioeconomic benefits of earth science research. Paper IAF-02-B.5.01 presented at 53rd International Astronomical Congress, World Space Congress 2002, October 10-19, 2002, Houston, Tex.

Kelly, J.J. 2001. Opportunities for 21st century meteorology: New markets for weather, water and climate information. Presentation at First AMS Presidential Policy Forum, American Meteorological Society (AMS) Annual Meeting, Albuquerque, N. Mex., January 17, 2001. Available online at <http://www.ametsoc.org/AMS/atmospolicy/presforums/albq2001/>. Accessed March 12, 2003.

Kennel, C., E. Frieman, B. Moore, and L. Shaffer. 1998. Report of the Workshop on NASA Earth Science Enterprise Post-2002 Missions. NASA Headquarters, Washington, D.C., November 12, 1998. [Referred to as Easton Workshop Report and frequently as Kennel Report.] Available online at <http://www.earth.nasa.gov/visions/Easton/index.html>. Accessed March 12, 2003.

Kramer, H.J. 2001. Observation of the Earth and Its Environment—Survey of Missions and Sensors. Springer, Berlin, Germany.

NASA (National Aeronautics and Space Administration). 2000. Exploring Our Home Planet: Earth Science Enterprise Strategic Plan. NASA Headquarters, Washington, D.C.

NOAA (National Oceanic and Atmospheric Administration). 2001a. The Nation's Environmental Data: Treasures at Risk. Report to Congress on the Status and Challenges for NOAA's Environmental Data Systems. U.S. Department of Commerce, NOAA, Washington, D.C.

NOAA. 2001b. Weather impact on USA economy. NOAA Magazine Online, November 1, 2001. <www.noaanews.noaa.gov/magazine/stories/mag4.htm>. Accessed March 5, 2003.

NOAA. 2001c. NOAA's NESDIS: Economic Value for the Nation. U.S. Department of Commerce, NOAA, Washington, D.C.

NOAA. 2001d. A Strategic Plan for NOAA's National Environmental Satellite, Data, and Information Service (NESDIS). U.S. Department of Commerce, NOAA/NESDIS, Washington, D.C.

NRC (National Research Council). 1983. Low-Altitude Wind Shear and Its Hazard to Aviation. National Academy Press, Washington, D.C.

NRC. 1991. Assessment of Satellite Earth Observation Programs 1991. National Academy Press, Washington, D.C.

NRC. 1997. Toward a New National Weather Service, Continuity of NOAA Satellites. National Academy Press, Washington, D.C.

NRC. 1998a. The Atmospheric Sciences Entering the Twenty-First Century. National Academy Press, Washington, D.C.

NRC. 1998b. "On Climate Change Research Measurements from NPOESS," letter from Space Studies Board Chair Claude R. Canizares and Committee on Earth Studies Chair Mark Abbott to Dr. Ghassem Asar, associate administrator for NASA's Office of Earth Science, and Mr. Robert S. Winokur, NOAA, director of the National Environmental Satellite, Data, and Information Service (May 27). Space Studies Board, NRC, Washington, D.C.

NRC. 1999. A Vision for the National Weather Services: Road Map for the Future. National Academy Press, Washington, D.C.

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

NRC. 2000b. The Role of Small Satellites in NASA and NOAA Earth Observation Programs. National Academy Press, Washington, D.C.

NRC. 2000c. Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design. National Academy Press, Washington, D.C.

NRC. 2000d. Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites. National Academy Press, Washington, D.C.

NRC. 2001a. A Climate Services Vision: First Steps Toward the Future. National Academy Press, Washington, D.C.

NRC. 2001b. Transforming Remote Sensing Data into Information and Applications. National Academy Press, Washington, D.C.

NRC. 2001c. Improving the Effectiveness of U.S. Climate Modeling. National Academy Press, Washington, D.C.

NRC. 2001d. The Science of Regional and Global Change. National Academy Press, Washington, D.C.

NRC. 2001e. Issues in the Integration of Research and Operational Satellite Systems for Climate Research: II. Implementation. National Academy Press, Washington, D.C.

NRC. 2003. The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics. National Academies Press, Washington, D.C., in press.

Obermann, R.M., and R.A. Williamson. 2002. International cooperation and the transition from experimental research to operational sensors. Paper IAF-02-B.1.07 presented at 53rd International Astronomical Congress, World Space Congress 2002, October 10, 2002, Houston, Tex.

OTA (Office of Technology Assessment). 1993. The Future of Remote Sensing from Space: Civilian Satellite Systems and Applications. OTA-ISC-558. U.S. Government Printing Office, Washington, D.C.

Pagano, T., H. Aumann, S. Gaiser, and D. Gregorich. 2002. Early calibration results from the Atmospheric Infrared Sounder (AIRS) on Aqua, SPIE (International Society for Optical Engineering) Paper 4891-09, pp. 23-27 in Remote Sensing of the Atmosphere, Ocean, Environment, and Space. Third International Asia-Pacific Environmental Remote Sensing Symposium, Hangzhou, China.

Pielke, Jr., R.A., and J. Kimpel. 1997. Societal aspects of weather, Report of the Sixth Prospectus Development Team of the U.S. Weather Research Program to NOAA and NSF. Bulletin of the American Meteorological Society 78:867-876.

Pielke, Jr., R.A., and R. Carbone. 2002. Weather forecasts, impacts and policy: An integrated perspective. Bulletin of the American Meteorological Society 83:393-403.

Presidential Decision Directive/National Science and Technology Council-2. 1994. Convergence of U.S. Polar Orbiting Operational Environmental Satellite Systems. May 10, 1994.

Rosenfeld, J. 2001. Betting on the weather. Weatherwise 54(1):14-21.

Serafin, R.J., A.E. MacDonald, and R.L. Gall. 2002. Transition of weather research to operations: Opportunities and challenges. Bulletin of the American Meteorological Society 83:377-391.

Smith, W.L., F.W. Harrison, H.E. Revercomb, G.E. Bingham, J. Miller, D.E. Hinton, R. Petersen, and J.C. Dodge. 2002. Geostationary Fourier Transform Spectrometer (GIFTS): The Precursor Geostationary Satellite Component of the Future Earth Observing System. Proceedings of the International Geoscience and Remote Sensing Symposium, June 24-26, 2002, Toronto, Canada.

Udall, M. 2002. Statement to Subcommittee on Environment, Technology, and Standards, Committee on Science, U.S. House of Representatives. Hearing on Satellite Data Management at NOAA, July 24, 2002.

Ware, R., M. Exner, D. Feng, M. Gorbunov, K. Hardy, B. Herman, Y. Kuo, T. Meehan, W. Melbourne, C. Rocken, W. Schreiner, S. Sokolovskiy, F. Solheim, X. Zou, R. Anthes, S. Businger, and K. Trenberth. 1996. GPS sounding of the atmosphere from low Earth orbit: Preliminary results. Bulletin of the American Meteorological Society 77:19-40.

Zeng, L. 2000. Weather derivatives and weather insurance: Concept, application, and analysis. Bulletin of the American Meteorological Society 81(9):2075-2082.

Appendixes

A

Previous NRC Recommendations on Transitioning Research to Operations

TABLE A.1 Previous National Research Council Recommendations

Category	Recommendation	Report[a]
Research to operations	"NASA and NOAA should implement a replacement to the Operational Satellite Improvement Program (OSIP) having the following characteristics • A planned path for the transition of instruments from research to operations • A commitment to algorithm development commensurate with hardware development • Calibration and validation of derived geophysical parameters • Close linkage to the development, testing, and integration facility at NOAA's EMC." (p. 8) "NOAA should form a team at the start of sensor development, consisting of NOAA and non-NOAA scientists, as well as those representing the end user of forecast information to, (1) plan the full scope of the data research utilization effort as part of sensor design with a budget to support the activity, and (2) assist NCEP in developing the archiving requirements for the EMC user communities." (p. 8) "NOAA should adopt the philosophy in which new sensor development would incorporate plans for the inclusion of funds for the transition of the data into operational products at the appropriate stage of the development process." (p. 10)	*From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (NRC, 2000a)

continues

TABLE A.1 Continued

Category	Recommendation	Report[a]
Research to operations (cont'd)	"NOAA [should] study the balance of its efforts in weather and climate with the goal of establishing an organization that efficiently balances the task of performing research and transferring this research into operations." (p. 10)	NRC, 2000a (cont'd)
	"Climate research and monitoring capabilities should be balanced with the requirements for operational weather observation and forecasting within an overall U.S. strategy for future satellite observing systems. . . . • The Executive Branch should establish a panel within the federal government that will assess the U.S. remote sensing programs and their ability to meet the science and policy needs for climate research and monitoring and the requirements for operational weather observation and forecasting. —The panel should be convened under the auspices of the National Science and Technology Council and draw upon input from agency representatives, climate researchers, and operational users. —The panel should convene a series of open workshops with broad participation by the remote sensing and climate research communities, and by operational users, to begin the development of a national climate observing strategy that would leverage existing satellite-based and ground-based components." (p. 5)	*Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design* (NRC, 2000c)
	"The NASA Earth Science Enterprise [ESE] should continue to play an active role in the acquisition and analysis of systematic measurements for climate research as well as in the provision of new technology for NPOESS. . . . • [ESE] should develop specific technology programs aimed at the development of sustainable instrumentation for NPOESS. • [ESE] should ensure that systematic measurements that are integrated into operational systems continue to meet science requirements. • [ESE] should continue satellite missions for many measurements that are critical for climate research and monitoring." (p. 6)	
	"Joint research and operational opportunities such as the NPOESS Preparatory Project [NPP] should become a permanent part of the U.S. Earth observing remote sensing strategy. . . . • The [NPP] concept should be made a permanent part of the U.S. climate observing strategy as a joint NASA-IPO activity. • Some space should be reserved on the NPOESS platforms for research sensors and technology demonstrations as well as to provide adequate data downlink and ground segment capability. • NPP and NPOESS resources should be developed and allocated with the full participation of the Earth science community." (p. 6)	

TABLE A.1 Continued

Category	Recommendation	Report[a]
Research to operations (cont'd)	"Improve the capability to serve the climate information needs of the nation. • Ensure a strong and healthy transition of the U.S. research accomplishments into predictive capabilities that serve the nation. . . . • Expand the breadth and quality of climate products through the development of new instrumentation and technology. • Address climate service product needs derived from long-term projections through an increase in the nation's modeling and analysis capabilities. . . . • Develop better climate service products based on ensemble climate simulations." (p. 5)	*A Climate Services Vision: First Steps Toward the Future* (NRC, 2001a)
	"NOAA (in cooperation with NASA) should develop a long-range plan for the federal role in operational Earth remote sensing. To the maximum degree possible, this plan should facilitate common use of spacecraft and data-handling systems by institutions (public and private) that mount Earth remote sensing programs. . . ." (p. 45) "The system plan should center around the needs of operational programs. . . . Whenever possible, space should be made available for research sensors on vehicles that are used primarily for operational purposes. The potentialities of the Earth orbiting platforms (to be launched as part of the space station program) should be fully exploited. . . ." (p. 45)	*Assessment of Satellite Earth Observation Programs 1991* (NRC, 1991)
	"NOAA and DOD, in consultation with the research community, should lead in an effort by all involved agencies to jointly assess instrument facilities that contribute key data to public and private space weather models and to operational programs. They should then determine a strategy to maintain the needed facilities and/or work to establish new facilities. The results of this effort should be available for public dissemination." (pp. 13-14) "NOAA should assume responsibility for the continuance of space-based measurements such as solar wind data from the L1 location as well as near Earth and for distribution of the data for operational use." (p. 14) "NASA and NOAA should initiate the necessary planning to transition solar and geospace imaging instrumentation into operational programs for the public and private sectors." (p. 14) "The relevant federal agencies should establish an overall verification and validation program for all publicly funded models and system-impact products before they become operational." (p. 14)	*The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (NRC, 2003)

continues

TABLE A.1 Continued

Category	Recommendation	Report[a]
Research to operations (cont'd)	"The operational federal agencies, NOAA and DOD, should establish procedures to identify and prioritize operational needs, and these needs should determine which model types are selected for transitioning via the Community Coordinated Modeling Center and Rapid Prototyping Centers. After the needs have been prioritized, procedures should be established to determine which of the competing scientific and/or commercial models is best suited for a particular operational requirement." (p. 14)	NRC, 2003 (cont'd)
Technology—hardware	"NOAA and NASA should begin to explore the potential of integrating in situ and satellite observation networks in support of both research and operational needs." (p. 9)	*From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (NRC, 2000a)
	"The insertion of technology raises issues of hardware and software capability and capacity. Once a major system has been finalized, it is increasingly difficult to accommodate change. Hence, advance planning that anticipates change and technology insertion over the life of the program is essential. Such planning should be part of system definition and risk reduction (SDRR) phase and continue into the subsequent stages of design." (p. 39) "Competitive selection of instrument science teams should be adopted to follow the progress of the instrument from design and fabrication through integration, launch, operation, and finally, data archiving, thereby promoting more thorough instrument characterization." (p. 3)	*Issues in the Integration of Research and Operational Satellite Systems for Climate Research: II. Implementation* (NRC, 2001e)
	"Adaptability and flexibility are essential for any information system if it is to survive in a world of rapidly changing technical capabilities and science requirements. The system should not just react to change but instead should continually track technology and system performance so that it can respond proactively." (p. 23)	*Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites* (NRC, 2000d)
	"Flexibility in the NPOESS program: Current plans include weight and power growth allowances to enable testing of new sensor concepts and designs on the NPOESS platforms. The committee strongly supports this approach as it will provide opportunities for new measurements as well as a mechanism for cross-validation between different sensor designs. Other approaches to enhance flexibility might be the use of sensor designs that can be easily upgraded, or the use of small satellites as part of the operational observing system, or for technology demonstration." (p. 3)	"On Climate Change Research Measurements from NPOESS" (NRC, 1998b)

TABLE A.1 Continued

Category	Recommendation	Report[a]
Technology—hardware (cont'd)	"Instrument/platform design: The present plan is to use on-board propellant to maintain fixed orbit equator-crossing times for the NPOESS satellites. This is a significant improvement for the application of NPOESS measurements to climate research. However, in addition, an overall system architecture failure analysis of the sensors and satellite bus should be performed to identify whether there are small changes that might be made to increase system redundancy and reliability." (p. 3)	NRC, 1998b (cont'd)
	"The design of an overall mission architecture, whether for operational or research needs, is a complex process and requires a complete risk-benefit assessment for each particular mission. . . . [A] mixed fleet of small satellite and larger multi-sensor platforms may provide the best combination of flexibility and robustness." (p. 5)	*The Role of Small Satellites in NASA and NOAA Earth Observation Programs* (NRC, 2000b)
	"In planning for future missions . . . NASA and NOAA [should] consider the merits of small, medium, and larger satellites without prejudice, seeking the most appropriate system architecture based on mission requirements and success criteria." (p. 63)	
	"Special attention should be devoted to improving the cost-effectiveness of the federal effort in civil remote sensing (for example, by flying both operational and research instruments on the same platforms)." (p. 43)	*Assessment of Satellite Earth Observation Programs 1991* (NRC, 1991)
	"Researchers should have improved access to modern, high-end computing facilities connected with centralized operational activities. . . . These facilities should be sufficiently capable to enable comprehensive study of the climate system and help develop models and techniques to address relevant high-end climate modeling problems." (p. 6)	*Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001c)
Technology—software and data	"A long-term archiving system is needed that provides easy and affordable access for a large number of scientists in many different fields. . . . The system should have the ability to reprocess large data sets as understanding of sensor performance, algorithms, and Earth science improves. Examples of sources of new information that would warrant data reprocessing include the discovery of processing errors, the detection of sensor calibration drift, the availability of better ancillary data sets, and better geophysical models." (p. 4)	*Issues in the Integration of Research and Operational Satellite Systems for Climate Research: I. Science and Design* (NRC, 2000c)

continues

TABLE A.1 Continued

Category	Recommendation	Report[a]
Technology—software and data (cont'd)	"The use of internationally recognized [data] formats, standards, and protocols should be encouraged for remote sensing data and information. . . . [E]ntities pursuing common remote sensing data formats and standards should consult with the sensor and software vendors to ensure that data acquired from the use of new technologies for data acquisition, analysis, and storage and distribution are consistent with other data sets." (p. 6)	*Transforming Remote Sensing Data into Information and Applications* (NRC, 2001b)
	"In order to maximize the effectiveness of different operational climate modeling efforts, these efforts should be linked to each other and to the research community by a common modeling and data infrastructure. Furthermore, operational modeling should maintain links to the latest advances in computer science and information technology." (p. 7)	*Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001c)
	"NOAA, in cooperation with NASA, should invest in early, limited capability prototypes for both long-term archiving and the NPP data system." (p. 6)	*Ensuring the Climate Data Record from the NPP and NPOESS Meteorological Satellites* (NRC, 2000d)
	"Data preservation should be addressed by all data providers as a routine part of the data production process to ensure continuity of the data record and to avoid inadvertent loss of usable data." (p. 6)	*Transforming Remote Sensing Data into Information and Applications* (NRC, 2001b)
Applications and users	"NASA and NOAA should work together to ensure that the continuity of critical climate and weather observations is maintained." (p. 10) "NASA and NOAA should evaluate the potential savings that would result from an interagency commitment to archive NPOESS satellite data through EOSDIS." (p. 9) "It is critical that NPOESS develop a coherent and credible plan for the archiving of NPOESS data so that the data are readily available to the community, including the research, operational, and private sectors. This data should extend from raw satellite data to gridded geophysical variables to address the range of potential users." (p. 9)	*From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (NRC, 2000a)
	"NASA, in cooperation with NOAA, should support the development and evaluation of climate data records, as well as their refinement through data reprocessing." (p. 4) "NOAA and NASA should define and develop a basic set of user services and tools to meet specific functions for the science community, with NOAA assuming increasing responsibility for this activity as data migrates to the long-term archive." (p. 5)	*Ensuring the Climate Data Record from the NPP and NPOESS Meteorological Satellites* (NRC, 2000d)

TABLE A.1 Continued

Category	Recommendation	Report[a]
Applications and users (cont'd)	"NASA and NOAA should develop and support activities that will enable a blend of distributed and centralized data and information services for climate research." (p. 6)	NRC, 2000d (cont'd)
	"NASA's Office of Earth Science, Applications Division, in consultation with other stakeholders . . . should mount a study to identify and analyze the full range of short- and long-term costs and benefits of developing remote sensing applications and the full costs of their implementation by public, non-governmental, and other noncommercial users. In addition, NASA should support economic analyses to reduce the start-up costs of developing new remote sensing applications." (pp. 3-4)	*Transforming Remote Sensing Data into Information and Applications* (NRC, 2001b)
	"The Land Grant, Sea Grant, and Agricultural Extension programs should be expanded to include graduate fellowships and associateships to permit students to work at agencies that use remote sensing data. Such programs could help to improve communication and understanding among scientists and engineers who develop applications for remote sensing data and the agencies that use them." (p. 5)	
	"NASA's Space Grant program could be extended to include these training activities, much as the Land Grant program has fostered the development of agricultural extension agents." (p. 5)	
	"Federal agencies, including those that produce remote sensing images and those that use them, should consider creating 'extern' programs with the purpose of fostering the exchange of staff among user and producer agencies for training purposes." (p. 4)	
	"For example, NASA, NOAA, and USGS should create an extern program in collaboration with potential user agencies, such as the Environmental Protection Agency . . . and in so doing could produce trained staff to serve as brokers for information and further training." (pp. 4-5)	
	"Both public and private sector data providers should develop mechanisms to obtain regular advice and feedback on applications requirements for use in their planning processes. Advisory bodies that are consulted for input to these decisions should routinely include applications users." (p. 6)	

continues

TABLE A.1 Continued

Category	Recommendation	Report[a]
Applications and users (cont'd)	"Research studies on the socioeconomic aspects of climate and climate modeling should be undertaken at appropriate institutions to design the institutional and governmental structures required to provide effective climate services. The assessment should include: 1. an examination of present and future societal needs for climate information; 2. a diagnosis of existing institutional capabilities for providing climate services; 3. an analysis of institutional and governmental constraints for sustaining a climate observing system, modeling the climate system, communicating with the research community, and delivering useful climate information; 4. an analysis of the human resources available and needed to accomplish these tasks; 5. an analysis of costs and required solutions to remove the constraints in accomplishing the above tasks; 6. recommendations on the most effective form of institutional and governmental organization to produce and deliver climate information for the public and private sectors." (pp. 7-8)	*Improving the Effectiveness of U.S. Climate Modeling* (NRC, 2001c)
	"Promote more effective use of the nation's weather and climate observation systems. • Inventory existing observing systems and data holdings. . . . • Promote efficiency by seeking out opportunities to combine the efforts of existing observation networks to serve multiple purposes in a more cost-effective manner. . . . • Create user centric functions within agencies. . . . • Perform user-oriented experiments. . . . • Create incentives to develop and promote observation systems that serve the nation." (pp. 4-5)	*A Climate Services Vision: First Steps Toward the Future* (NRC, 2001a)
	"Interdisciplinary studies and capabilities are needed to address societal needs. • Develop regional enterprises designed to expand the nature and scope of climate services. . . . • Increase support for interdisciplinary climate studies, applications, and education. . . . • Foster climate policy education. . . . • Enhance the understanding of climate through public education." (p. 6)	

[a]The National Research Council (NRC) reports cited were all published by the National Academy Press (as of mid-2002 The National Academies Press), Washington, D.C., in the year indicated. They are also listed on p. 89.

B

Case Studies of Transitions from Research to Operations

INFRARED SOUNDERS

Infrared sounders provide information on the vertical structure of temperature and water vapor. These soundings have become a routine and essential part of day-to-day numerical atmospheric modeling around the world. This case study outlines the *unplanned and long pathway* of infrared sounders from research to operations.

Research Origin/Heritage

Temperature soundings have been obtained from weather satellites since the late 1960s when the NASA environmental research satellite Nimbus, the Defense Meteorological Satellite Program (DMSP) satellite, and the Improved TIROS Operational Satellite (ITOS) flew early research versions of infrared spectrometers and microwave radiometers. They were flown by NASA, the U.S. Air Force, and NOAA because the climate and weather research community wanted to find a way to observe temperature and humidity profiles over data-sparse regions. The missions were flown as research and development (R&D) efforts, but with the objective of having their data used in operational weather forecasting. In the case of the DMSP, the Air Force used operational systems to fly R&D sensors such as the sounder. In the case of the civil satellites, NASA flew the R&D sensors on its satellites (Nimbus) and made their research sensor data available to the ESSA (Environmental Science Services Administration)—the predecessor to NOAA—for operational use. The

TABLE B.1 Chronology of Early Satellite Sounders Flown on NASA and NOAA Satellites

Instrument	Satellite	Primary Period of Operation
SIRS-A	Nimbus-3	1969-1971
SIRS-B	Nimbus-4	1970-1972
ITPR, NEMS, SCR	Nimbus-5	1972-1975
VTPR	ITOS series	1972-1979
HIRS, SCAMS, PMR	Nimbus-6	1975-1979
HIRS-2, MSU, PMR	NOAA series	1978-1998
VAS	GOES series	1980-1996
HIRS-3, AMSU	NOAA series	1998-present

NOTE: The acronyms are spelled out in Appendix E.
SOURCE: Kalnay et al. (1996).

willingness to use the data in operational forecasts, however, involved negotiations between the data providers (NOAA) and the data users (the National Meteorological Center [NMC]). In 1969, the NMC director told a NOAA scientist, referring to satellite soundings, "If you can make them look like radiosonde data we can use them."[1] It would be many years involving much study before the satellite-derived soundings would be fully employed in operational numerical weather prediction. It is worth noting that NMC began to experiment with the operational sounding data from the very first sounder, the SIRS (Solar Infrared Radiation Station)-A, flown on the Nimbus-3 satellite, less than 2 months after its launch. Data used for the National Center for Atmospheric Research/National Centers for Environmental Prediction (NCAR/NCEP) Reanalysis Project reflect sensors flown on NASA and NOAA satellites as indicated in Table B.1 (Kalnay et al., 1996).

The first infrared High-resolution Infrared Radiation Sounder (HIRS-2) and Pressure-Modulator Radiometer (PMR) and Microwave Sounding Unit (MSU) sounding system flown together on an operational satellite was the Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder (TOVS), which began flying on TIROS-N in October 1978. TOVS data were made available to the global numerical modeling community in 1979, with the launch of NOAA-6. One of two different types of algorithms was used to transform the sounder radiance observations into temperature and moisture values at given levels. One of these algorithms was based on statistical regression relations between the temperature and moisture values at specific vertical levels of the atmosphere and the radiances observed within all the spectral channels of the sounding radiometers. This was the method used with SIRS-A, Nimbus-6, and the early NOAA TOVS data. Alternatively, a

[1]Personal communication from Ronald McPherson, Executive Director, American Meteorological Society, to committee member George L. Frederick.

nonstatistical matrix inverse method (i.e., a one-dimensional variational analysis method), which used the forecast as a first guess in the retrieval, was used throughout various periods of the satellite data processing, beginning with SIRS-B in 1970. In either case, these "retrievals," as they were called, of temperature and moisture values were used in numerical model runs without consistent positive impact, except in the data-sparse Southern Hemisphere, until the mid-1990s, at which time researchers discovered a better way to use the observations. Rather than trying to assimilate the temperature retrievals derived from the radiances, they assimilated the radiances themselves using a new three-dimensional variational analysis technique. The resulting improvement was dramatic, as reflected in Figures B.1 and B.2. Figure B.2 shows root-mean-square (RMS) observational increments (differences between

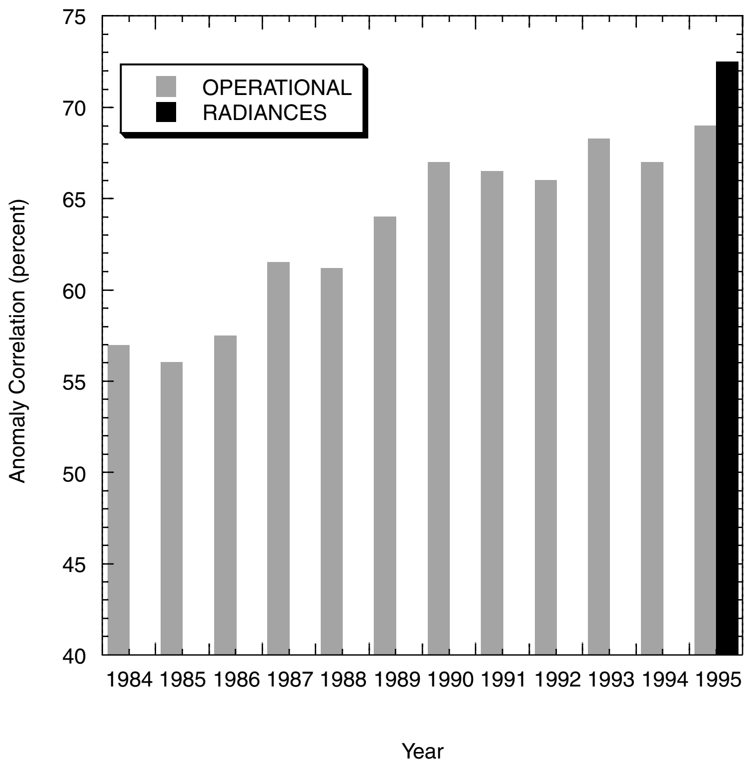

FIGURE B.1 Impact of the direct assimilation of radiances on the 5-day forecast 500-hPa anomaly correlations in the Northern Hemisphere, June through August. The improvement in 1995 was due to the assimilation of radiances from infrared sounders. SOURCES: Steve Lilly, National Centers for Environmental Prediction; Kalnay et al. (1998). Reprinted with permission.

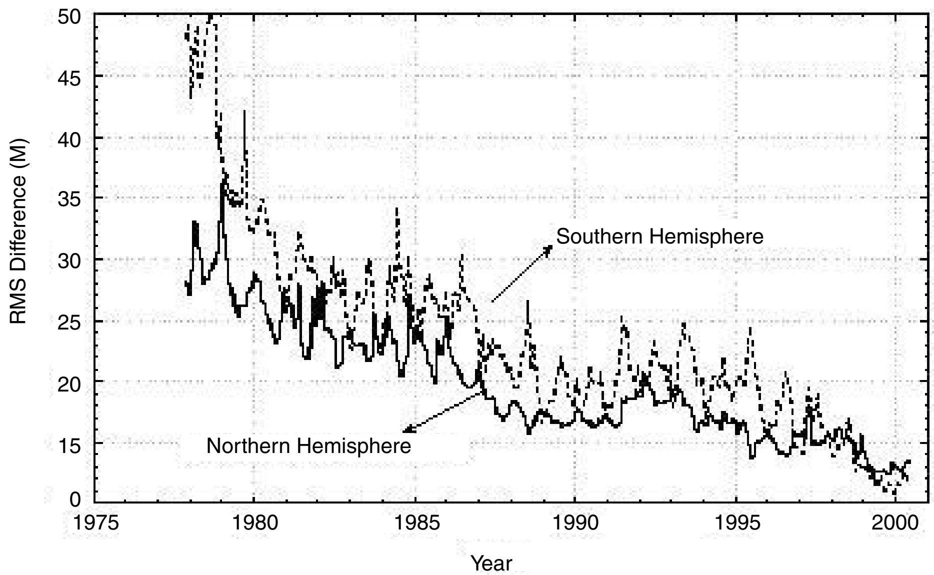

FIGURE B.2 RMS difference (M) between 6-hour forecasts of 500-hPa heights and radiosonde observations. SOURCES: Steve Lilly, National Centers for Environmental Prediction; Kalnay et al. (1998). Reprinted with permission.

6-hour forecasts and rawinsonde observations) for 500-hPa heights. The large improvements in 1995 are associated with the direct assimilation of radiances.

The reason why the satellite soundings had little impact on the forecast was that the satellite retrievals were treated as poor-quality radiosondes (i.e., point measurements) rather than as high-quality volume measurements (i.e., what the radiances represent). By assimilating the radiances rather than the retrievals, the proper spatial resolution of the data was necessarily represented in the model, thereby avoiding the prior aliasing of smaller-scale features with low spatial resolution data (i.e., the satellite soundings). It was not until the data user fully understood the characteristics of the satellite observations that a technique was devised for the proper assimilation of these data in their analysis/forecast operation.

Transition Process

There was no clear starting point for the transition from research on infrared sounders to their use in operational service and numerical weather prediction models. Early attempts by NMC to use the retrieved soundings occurred immediately after the first observations were made, and the impact on the forecasts was slight, or even negative, over data-rich regions. Eventually, by the mid-1990s, researchers found a much better way of using the observations—assimilating the radiances directly in the models—and for the first time the infrared sounding observations showed a consistent positive impact in the Northern Hemisphere (Kalnay et al., 1998).

Operational Status

Infrared sounders have become a valuable part of the global observing system, and the observations from the NOAA polar orbiters are now being used by all major weather-forecasting centers in the world. Using the radiances directly in models through three-dimensional and four-dimensional variational analyses has been so successful that the accuracy of forecasts in the Southern Hemisphere has approached that of forecasts in the Northern Hemisphere (Figure B.2). Plans are under way to incorporate data from infrared sounding sensors on geostationary satellites, thus increasing the temporal frequency of data over the region scanned. The assimilation of satellite soundings over Northern Hemisphere land areas, not done now so as to avoid a potential conflict with radiosonde information, should also improve forecasts as a result of enhanced spatial and temporal resolution of the analyses used to initialize the prediction process. Advanced infrared sounders to be placed on future geostationary satellites (e.g., Geosynchronous Imaging Fourier Transform Spectrometer [GIFTS]) will be able to vertically resolve the wind field, as well as provide temperature and moisture profiles with high spatial and temporal resolution, thereby providing improved observations of atmospheric dynamics as needed in order to improve the forecast operation.

Lessons Learned

The extended period between the first flight of an infrared sounder and the full operational use of soundings in numerical models can be attributed to a number of factors:

1. *Inadequate scientific research to determine an appropriate way of using the observations.* The discovery of how to use the radiance values rather than the retrieved profiles in numerical modeling took about 25 years.
2. *Resistance to change.* A major potential user insisted that the data look like radiosonde data.
3. *Lack of a technology transition plan or process.* The operational centers were not prepared to use the data when they first became available.

VERY HIGH RESOLUTION RADIOMETER/ ADVANCED VERY HIGH RESOLUTION RADIOMETER

Imaging radiometers used by NASA and NOAA are commonly designed to produce calibrated multichannel images of Earth and the atmosphere in the visible and infrared portions of the spectrum. These radiometers measure reflected solar radiation in the visible and near-infrared wavelengths and emitted radiation in the shortwave and thermal wavelengths from Earth's surface and the atmosphere. Radiometer data have become a mainstay for remotely sensing sea surface temperature and atmospheric temperature and moisture profiles. This case study captures the *successful transition* of research data from the Very High Resolution Radiometer (VHRR) into operational service. The early involvement of both research and operational managers at NOAA, as well as the development of a plan to "market" the benefits of the data to users, fostered the widespread use of the data.

Research Origin/Heritage

As part of the Operational Satellite Improvement Program, the Improved TIROS Operational Satellite (ITOS-1), the first three-axis stabilized polar-orbiting weather satellite, was launched on January 23, 1970. This satellite, developed and launched under NASA funding, carried both the older-generation vidicon instruments for real-time Automatic Picture Transmission and a new, two-channel scanning radiometer for both day and night imaging.

An upgraded version of the ITOS, ITOS-D (later renamed NOAA-2), was launched in October 1972. For this satellite, NASA replaced the vidicon cameras with the redundant SRs and added a new instrument, the two-channel VHRR, which was to provide high-resolution day and night imaging. There was close cooperation between NASA and NOAA. For example, because of budget difficulties at NASA, NOAA agreed to support some of the costs of developing these new instruments. Also, NASA developed the ground-based processing software for the VHRR data, and NOAA supplied the computers.

Transition Process

Although satellite data were becoming more widely accepted by users in the early 1970s, the ad hoc way during the early years of moving a new remote sensing capability into operations was recognized as inadequate. NOAA's National Environmental Satellite Service (NESS) created a project management arrangement within NESS, with the project manager selected from research and the project coordinator from the operations area. The project manager was to assure that the goals of ability to calibrate, accuracy, and so on, were being met, while the project coordinator was to assure that VHRR data could be processed and delivered in a timely manner. Since the existing operational activities were saturated with meeting the needs of the operational weather community, NESS established an Environmental Products Branch to respond to the needs of users outside the operational weather community—primarily oceanographers, hydrologists, and others—for products not being developed by the operational community. This research community of users was small at the time, and focused on using the data from the recently launched Earth Resources Technology Satellite (later renamed Landsat 1). Since VHRR data were of significantly lower spatial and spectral quality than Landsat data, they did not compete well for the attention of these users. However, VHRR data had one attribute not offered by Landsat—near-real-time availability to users.

To remedy the fact that there were few nonoperational users of VHRR data, the Environmental Products Branch set about to develop products that would take advantage of the near-real-time availability of VHRR data and then went out to the user communities to "sell" this capability. Some products—such as Polar Ice Charts, which depict the coverage and estimate the age and thickness of the polar ice sheet—were quickly accepted by the Navy Ice Center (which was located in the same building as NESS). Other products—such as Gulf Stream Analysis, which offered information on the location of the Gulf Stream and its eddies; West Coast Upwelling Charts, which provided details on the position and extent of the upwelling cold water along the coast; and Snow Cover Charts, which were important for managing the water resources of the western United States—had to be brought to potential users and marketed as supporting their needs. Soon these nonoperational users became accustomed to the products, and an operation was born.

As part of the meteorological upgrade process, the two-channel VHRR became a four-channel advanced VHRR (AVHRR/1), with the addition of a near-infrared (IR) channel to separate clouds from snow and ice and another IR channel to aid in determining sea surface temperature. The splitting of the original IR channel into two nonoverlapping intervals for further improvement in determining sea surface temperatures was designated as AVHRR/2, a five-channel instrument.

Operational Status

Currently, the six-channel AVHRR/3 is the operational instrument on the NOAA-15 and the subsequent POES (Polar-orbiting Operational Environmental Satellite) series; it is providing real-time data for sea surface temperature, vegetation index, snow and ice cover, fire detection, aerosols, and volcanic ash detection and tracking.

Lessons Learned

The lessons learned on transitioning research to operations from this case study on VHRR/AVHRR are these:

1. The operational agency (in this case NOAA) cared enough about the potential utility of the instruments to partially fund their development.
2. It is important to involve the research and operations community early in a mission. The researchers communicated with potential users, educated them about the observations and their potential use, and "marketed" the mission.
3. Near-real-time availability of research data to users is a valuable part of the transitioning process.

DEFENSE METEOROLOGICAL SATELLITE PROGRAM

The Defense Meteorological Satellite Program (DMSP)[2] has served the meteorological needs of the armed services for some 40 years, enabling the military to receive timely weather data in support of planning for both routine and mission-critical operations such as the Cuban missile crisis and the Vietnam War. While not a typical research program but an operational development program, DMSP developed and flew research instruments that were intended to provide operational capabilities, and it did so in an efficient and cost-effective way. This case study illustrates the key role that people play in the successful management and development of a satellite program. The impressive results of DMSP and the satellites that it produced proved beneficial for a series of research satellites and further DMSP satellite developments that were continued as "heritage" throughout the history of the program.

Research Origin/Heritage

In the mid-1950s, the Rand Corporation warned the U.S. Air Force (USAF) that successful operation of overhead photoreconnaissance satellites depended upon accurate and timely meteorological forecasts of the Sino-Soviet landmass. An interdepartmental study in April 1961 revealed that NASA held the U.S. franchise to establish requirements and develop meteorological satellites for both the Department of Commerce and the Department of Defense. A single National Operational Meteorological Satellite System (NOMSS) for both departments was intended to

[2]This section is based mostly on verbatim transcripts and summaries of the history of DMSP written by R. Cargill Hall. Those interested in more detail on the history of DMSP are referred to the original document, *A History of the Military Polar Orbiting Meteorological Satellite Program* (Hall, 1985).

avoid duplication, produce a less costly national capability, and meet all of the forecasting needs of the civil and military sectors.

The television camera of NASA's first experimental "wheel-mode" TIROS weather satellite, spin stabilized to inertial space, was launched on April 1, 1960. It viewed an oblique swath of Earth's surface occasionally in each orbit, instead of once each time it revolved. In 1962, NASA officials did not believe that a spin-stabilized satellite which would keep its spin axis perpendicular to its orbit plane could be developed in time to meet the need for strategic meteorological forecasts for reconnaissance operations over the Sino-Soviet block. The undersecretary of the Air Force therefore created an "interim" meteorological weather satellite program for the National Reconnaissance Office (NRO). On June 21, 1961, he asked the director of the Office of the Secretary of the Air Force Special Projects in El Segundo, California, for a minimum proposal for four Earth-referenced weather satellites to be launched on NASA Scout boosters. A proposal was provided for a small fixed budget and first launch in 10 months. The proposal was approved, and a program director for the new DMSP was appointed. The new program director, who was a meteorologist and an electrical engineer, accepted the assignment on condition that he would not have to use the resident Systems Engineering and Technical Direction (SE&TD) contractor, that he could select a small number of his own staff, and that he could use fixed-price, fixed-delivery contracts throughout the program. He believed that a SE&TD contractor could only justify its existence by introducing changes. Since changes involved time and money, SE&TD support was incompatible with fixed-price, fixed-delivery contracting.

Transition Process

DMSP incorporated two management approaches that proved decisive in the program's success and that may provide a model approach for the transition from research to operations in other endeavors of similar size and complexity: (1) a slim management team and (2) the use of a firm fixed-price contract.

The fixed-price, fixed-delivery contract proved valuable in December 1961 when a major structural component of the weather satellite, the base plate, failed during tests, and Radio Corporation of America (RCA) officials requested a 3-month delay for redesign. RCA was advised that it had 10 days to produce a fix or the contract would be terminated, at no cost to the government. The RCA program manager appeared 3 days later with revised internal schedules that met the original launch date.

The Air Force "blue suit" program team met its 10-month schedule, although, as the high-risk aspects of the effort suggested, without immediate success. Two Scout vehicles, one with the first NRO weather satellite onboard, failed in rapid succession in April and May 1962. However, on August 23, 1962, the first successful DMSP satellite was launched from Vandenberg Air Force Base in California. Although the ground control team had tracking problems early in the operational period of the satellite, each day at high noon the vehicle took pictures as it passed over the Soviet Union. Weather pictures of the Caribbean returned by this vehicle 2 months later, in October 1962, proved crucial during the Cuban missile crisis, permitting effective aerial reconnaissance missions over the region.

The nimble management structure and the fixed-price contract enabled flexibility and responsiveness from both the internal program team and the contractor. Although the team encountered significant challenges with the launch vehicle, DMSP's success in achieving a rapid and clean program with few technical problems cemented the nation's approach toward a two-pronged military and civil meteorological satellite system. The first DMSP satellite ceased operation on March 23, 1963, but by then the program had received a new life. NASA had delayed the planned Nimbus series of the NOMSS, and the NRO authorized the DMSP director to extend his interim program by at least a year. Flight number four was launched on February 19, 1963, with many more to follow.

In addition to the management and contract mechanisms used for the DMSP, the program benefited from the transition of research sensors into the DMSP program. The manager of the TIROS weather satellite program in NOAA's Weather Bureau, who was one of the few persons in NOAA cleared to know about DMSP, referred various experiments to the NRO-Air Force program, including a novel one conceived at the University of Wisconsin. The Wisconsin instrument weighed about 6 ounces and produced useful data on the radiated heat of cloud cover, from which the heat balance of Earth could be determined. Many other research sensors were incorporated on DMSP satellites, leading to improved meteorological capability and forecasting in the defense community.

When the first DMSP director stepped down in April 1965, DMSP had eclipsed all other overhead meteorological endeavors. Initial NASA skepticism notwithstanding, DMSP had pioneered the space technology so well, so quickly, and so inexpensively that the space agency (prodded firmly by the Department of Commerce) now embraced a carbon copy of the DMSP wheel-mode Block 1 satellite, called the TIROS Operational System (TOS), as an interim, polar-orbiting weather satellite. The first TOS, renamed ESSA-1, was launched in February 1966—4 years after DMSP proved the concept. Nine TOS civil satellites were launched between 1966 and 1969. A Nimbus first launch scheduled for June 1962 slipped to 1964; the Nimbus satellites were eventually directed to research purposes, never to become part of the NOMSS.

DSMP sped through four blocks of satellite platforms in the 1960s. By the late 1960s, Block 5 was on the drawing boards. The USAF Air Weather Service (AWS) was largely responsible for a payload design that made Block 5 especially user-friendly—for example, by formatting the imagery to standard AWS weather chart scales.

The decision to develop a user-friendly design for the Block 5 series of satellites was a strategy that contributed significantly to the transition from research to operations. The Block 5 spacecraft departed entirely from the TIROS technology and took the form of an integrated system in which the space and ground segments were designed together. The AWS representative and his engineering partner visited meteorologists at work and then examined what the industry could produce. Instead of starting with a sensor and determining what it might tell the user about the weather, these two individuals based the Block 5 design on the users' wish to receive a product in a form that approached as closely as possible the weather charts and maps that they, the meteorologists, employed—an example of "pull" transitioning.

The DSMP case study also teaches some important lessons about the value of involving university researchers and students in satellite missions.[3] During the mid-1960s, the university–USAF collaboration with DSMP was greatly aided by a team from the Electrical Engineering Department at the University of Wisconsin (UW), Madison, working with Professor Vern Suomi. Several of Suomi's meteorology graduate students and some USAF officers spent considerable time on the project at the Air Force Global Weather Central (Offutt Air Force Base, Omaha, Nebraska) and probably as much time in the electrical engineering and space astronomy laboratories as they did in the meteorology department. Their experiments onboard the early DMSP satellites were (1) those of USAF (primary) and (2) joint USAF/UW and sole UW (secondary). The graduate students helped with all of the experiments (design, calibration, data processing, algorithms, and so on). One experiment on the Earth radiation budget flew on several of the satellites from 1964 to 1967. Using black and white flat-plate radiometers, the experiment resulted in the first *global* Earth radiation budget measurements. The experiment revealed a warmer and darker planet Earth with a lower albedo in tropical regions than had been estimated in pre-satellite papers. This discovery had major ramifications in future global energetics and circulation studies.

Operational Status

Over time, DMSP was declassified, and program management was moved into the mainstream like other Air Force programs. This change led to an increase in the

[3]Personal communications of Thomas Vonder Haar, Colorado State University, with committee member George L. Frederick, May-August 2002.

number of staff and a lengthening of satellite development schedules and allowed other, attendant artifacts to creep into what had once been an efficient operation. Increasing complexity and a lack of strong systems engineering support and of independent verification and validation (IV&V) led to early failure of Block 5D satellites. In the early 1980s, a situation arose during which no DMSP spacecraft were fully operational. Military forecasters had to rely on NOAA satellites during this period. The adverse operational impacts of relying on civil satellites that DSMP supporters had been warning against over the years did not materialize. Subsequently, systems engineering and IV&V processes were strengthened, and the DMSP satellite constellation was healthy again by the mid-1980s. Ultimately, in the early 1990s, convergence of the military and civil weather satellite programs became a reality, and the integrated DMSP and NOAA program—the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program—was born. DMSP will continue to operate until 2008, with the launch of NPOESS.

Lessons Learned

The lessons learned from this case study are as follows:

1. The novel management scheme was made possible by a small program office, consisting of a few key energetic people with strong ties to the user (USAF Air Weather Service) and the research community (University of Wisconsin, Madison, primarily), that exercised technical direction. It could make decisions and act quickly. The office achieved an excellent success record at low cost.
2. Incorporating the needs of the user (the "pull" side of transitioning) into early instrument design and data-processing systems pays big dividends in transitioning systems from research to operational use.
3. Joint teams of scientists and engineers within universities bring more strength to university–government collaborations. This lesson is still in practice today at the University of Wisconsin, Colorado State University, and the National Center for Atmospheric Research, among others. Furthermore, military officers assigned to graduate studies at major research universities can further enhance collaborations in high-tech areas.
4. Multiagency and university collaborations in new high-tech areas can lead to early science breakthroughs and can help infuse new ideas and concepts in our science.
5. Government and university collaborations in space programs are important in educating and training the next generation of space scientists and engineers.

LIGHTNING DETECTION FROM SPACE

Lightning is often the earliest indication of thunderstorm development and may precede the first radar echoes by as much as 15 minutes. Many studies have shown lightning to be associated with significant events such as heavy rainfall, severe weather, winter weather, and hurricanes. Observations of lightning are therefore clearly useful for operational forecasting (Orville, 1987).

Within the continental United States, there is a National Lightning Detection Network, operated by Global Atmospherics, Inc., which provides cloud-to-ground lightning data to the National Weather Service (NWS) in support of its forecasting activities in the United States. Space-based sensors can provide significantly more lightning data than ground-based sensors can, and they can provide these data on a global basis. For example, most ground-based sensors are only capable of detecting cloud-to-ground lightning over land, which makes up only about 25 percent of total lighting activity. Space-based sensors can detect all forms of lightning activity over land and sea, 24 hours a day.[4] Thus, over land, the detection of cloud-to-cloud lightning as provided by a spaceborne sensor could provide earlier detection of the development of severe convective storms, and over the sea the space-based sensor could serve as a surrogate for radar and surface lightning detectors. However, the operational utility of the space-based data has not been demonstrated to the point at which it is viewed as a requirement for the Geostationary Operational Environmental Satellite (GOES) program.

This case illustrates the *lack of a successful pathway* for transitioning proven space-based lightning detection sensors into operational use.

Research Origin/Heritage

The analysis of global lighting activity from space began in the late 1970s with the use of data products developed for the DMSP Operational Linescan System (OLS). The OLS is a DMSP instrument dedicated to monitoring the distribution of clouds and cloud-top temperatures on a global scale twice each day[5] (Turman, 1978). Further research took place at NASA's Marshall Space Flight Center. An Optical Transient Detector (OTD), developed at Marshall and launched in 1995 on the Micro-Lab-1 satellite from a Pegasus rocket into a 70-degree inclination orbit, was able to survey virtually all areas of the globe where lightning normally occurs, for a period of several years (Christian et al., 1996).

---

[4]See the Web site <http://thunder.msfc.nasa.gov/research.html>. Accessed March 4, 2003.

[5]See the Web site <http://www.ngdc.noaa.gov/dmsp/descriptions/doc_ols.html>. Accessed March 4, 2003.

Another instrument developed at Marshall, the Lightning Imaging Sensor (LIS), is a staring imager that is optimized to locate and detect lightning with storm-scale resolution (4 to 7 km) and to detect the distribution and variability of total lightning (cloud-to-cloud, intracloud, and cloud-to-ground) during the day and night. The LIS was launched aboard the Japanese-U.S. Tropical Rainfall Measuring Mission (TRMM) satellite in 1997 and is still in orbit (Christian et al., 1999). The Lightning Mapper Sensor (LMS) program, which is also under development at Marshall, will be capable of continuously mapping lightning during both day and night. The LMS has been proposed for launch into geostationary orbit as part of the GOES system.

Transition Process

Although lightning-detection technology had been successfully demonstrated by the DMSP OLS and the Marshall instruments (OLS, OTD, and LIS), there is so far no pathway for transitioning the technology into operational service. This gap separating the demonstration of sensor capability from the use of satellite lightning data in operational weather prediction has resulted, in large part, because there appears to be no stated requirement—or "pull"—other than for cloud-to-ground lightning, from the operational weather and climate organizations. With no operational requirement for either global or regional coverage of total lightning, the National Environmental Satellite, Data, and Information Service (NESDIS) is not able to consider a lightning sensor as a high priority. In this "push-only" situation, there has not been a successful effort to develop a documented NWS and/or DOD requirement for the space-based lightning measurement. Either there is an insufficient demonstration of the cost-effective value of the space-based lightning observations by the research community or insufficient funding for applied research and operational demonstrations of the added value of the observations.

Operational Status

To date, satellite lightning-detection sensors have remained a research and experimental technology. The technology, with its potential benefits, has not been transitioned into operations.

Lessons Learned

The following are lessons learned from this case study:

1. No transition pathway was established, in part because there was insufficient "push" from the research community and "pull" from the operational community.

2. As a technology advances past a proof-of-concept demonstration, there should be a parallel investment in the demonstration of an operational data product for use by either direct or intermediate operational users to push the development of an operational requirement for the proven technology. The result of the proof-of-concept demonstration must be a documented user requirement for the new observation capability in order to create the pull needed to transition the experimental capability into an operational measurement system.

OCEAN ALTIMETRY

Ocean altimetry provides measurements on sea surface height. These measurements are important data for understanding ocean circulation on a wide range of time and space scales. Ocean altimetry data are also valuable for operational missions, including naval applications such as ship routing, search and rescue, and antisubmarine warfare, and for civilian applications such as tidal information for navigation, pollutant spill dispersion, and fisheries forecasting. This case study describes *a successful example* of how NASA, NOAA, and international partners came together in the interest of planning for continuity in ocean altimetry data and to improve sampling capabilities in existing systems.

Research Origin/Heritage

Measurements of ocean topography from space using radar altimeters were conceived in the 1960s, with proof-of-concept missions in the 1970s, including one altimeter that was flown aboard Skylab in 1973. This stage culminated with the Seasat altimeter in 1978, followed by the first operational use of radar altimetry by the U.S. Navy that was launched aboard Geosat in 1985. The focus of the first 18 months of this mission was to develop a high-resolution map of the global marine geoid. These data were classified for many years but have now been released. After the completion of its 18-month primary operational mission, Geosat was maneuvered into the Seasat orbit, and the data were made available to the research community.

The operational Geosat mission and its orbit requirements were not compatible with many of the research community's requirements for studies of ocean topography. Moreover, the altimeter system design lacked many key elements (e.g., a water vapor radiometer, a dual frequency altimeter for ionospheric corrections, and an active attitude control system), which further compromised data quality (Chelton et al., 2001). Nevertheless, Geosat provided valuable data for some research purposes (Fu et al., 1990).

Additional radar altimeters were flown onboard the European Space Agency's (ESA's) series of research satellites, ERS-1 and ERS-2. This program has continued with a radar altimeter on the ESA Environmental Satellite (ENVISAT) that was launched early in 2002. However, these missions accommodated other research sensors, and thus the orbits were constrained to be Sun-synchronous, which is not optimal for studies of ocean topography because of aliasing of solar ocean tides into the signals of interest. In addition, the atmospheric drag at the 800-km altitude of the ERS and ENVISAT satellites resulted in orbit errors that are too large for some research applications.

The first dedicated mission for ocean topography was TOPEX/Poseidon, a joint NASA-CNES (Centre National d'Etudes Spatiales) program. Launched in 1992, TOPEX/Poseidon was designed for a 3-year mission, with sufficient contingency to be extended to 5 years. However, TOPEX/Poseidon continues to operate nearly flawlessly, and a new joint NASA/CNES mission, Jason-1, was launched in late 2001. Both of these missions were designed specifically to meet the science requirements for studies of ocean topography. A vigorous research program has improved the overall accuracy of the measurements to 4 cm (Chelton et al., 2001), significantly better than any previous altimeters. Moreover, the research community has expanded its observing requirements to resolve smaller time and space scales in order to study the mesoscale variability of ocean circulation. To meet these requirements, new approaches will be needed, such as constellations of altimeters and wide-swath altimeters (Chelton, 2001).

Transition Process

A radar altimeter will be flown as part of NPOESS, but given the operational constraints of the other sensors onboard, the NPOESS satellites will be in a Sun-synchronous orbit. Many of the continuing science requirements for studies of ocean circulation will thus not be met by the altimeter on the planned NPOESS platforms. However, NOAA/NESDIS has begun to explore other options with NASA to meet the requirements of the research community as well as the operational requirements of the NPOESS system. These needs have led NASA and NOAA to discuss a closer relationship between the two agencies regarding the Jason follow-on mission (sometimes referred to as Jason-2) as part of the overarching Ocean Surface Topography Mission (OSTM).

In early 2001, NASA and NOAA reached a preliminary agreement on the distribution of responsibilities for the Jason follow-on, with NOAA taking the lead operational responsibility for the mission. NOAA would be responsible for ground systems, mission operations (after commissioning), and data archive and distribution, and it would participate in calibration/validation and scientific research. NASA would provide the launch vehicle and some of the supporting sensors, system engineering, and project management, and would fully participate in calibration/validation and lead the scientific research aspects of the mission. CNES would also do system engineering, and in addition would provide the primary altimeter and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking, the satellite bus, integration, orbit determination, and data processing. The European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) would acquire data through a purchase agreement.

By spring 2001, the NASA-NOAA understanding had expanded to become a quadrilateral program between CNES, EUMETSAT, NASA, and NOAA for the OSTM, with a defined set of responsibilities for each agency, a steering group, and a project plan. This new OSTM plan also includes the opportunity for NASA to explore the feasibility of a Wide Swath Ocean Altimeter (WSOA) as part of the Jason-2 package, a prospect made possible by cost savings generated by NOAA participation in Jason-2. By late 2001, letters had been exchanged by all parties, and OSTM was moving forward as part of the Fiscal Year 2002 federal budget request.

In late spring 2002, it had been determined by CNES that there were no “showstoppers” to including the WSOA on the Jason-2 satellite bus. The four partners are strongly supportive of the flight of the WSOA on Jason-2 and are proceeding through the formal approval process. They are also working out the details of the OSTM and the technical and programmatic structures necessary for its success. The OSTM partners planned to have a complete set of program baseline assumptions by the fall of 2002, with a program confirmation review in early 2003. This will be followed by the start of a phase C/D contract for the satellite.

Lessons Learned

The lessons learned from this case study are these:

1. Conflicting science and operational requirements can be overcome through communication and leadership at all levels, including administration and the research community.

2. Positive synergy can occur between the research and operational communities. For example, the dedication of the research community continued to show the value of ocean altimetry and how continuous improvement can lead to new insights. The highly visible success of TOPEX/Poseidon encouraged senior management to take risks and seek new initiatives for follow-on missions. The operational community recognized the value of these measurements and was willing to examine how the new technologies such as wide-swath altimetry could be used in their operations.

SPACEBORNE SCATTEROMETRY: A NEARLY COMPLETE TRANSITION FROM RESEARCH TO OPERATIONS

Scatterometers are microwave radar instruments designed to measure global radar backscatter cross-section and wind velocity over the oceans under nearly all weather conditions. The data can be used in weather and ice-edge prediction, as well as for research in oceanography, meteorology, and large-scale air-sea interaction. Scatterometers have been flown on NASA and ESA research missions continuously since 1991. These missions have provided near-real-time data that have been used in operational numerical weather prediction and marine forecasting. The United States and Europe have taken different approaches to involving operational agencies in research scatterometry missions. However, notwithstanding the successful operational use of scatterometer data supplied by research missions, neither ESA/EUMETSAT (in Europe) nor NASA/NOAA/DOD (in the United States) have yet flown instruments to measure ocean vector winds as part of their operational observing systems.

Research Origin/Heritage

The recognition that the oceanic microwave backscatter cross section at moderate incidence angles contained information on near-surface wind speed and direction arose from radar research conducted after World War II in both the defense and civilian sectors (Moore and Fung, 1979; Barrick and Swift, 1980; Pierson, 1983). The first spaceborne instrument useful for demonstrating scatterometry was flown on the NASA Skylab missions in 1973 to 1974, but it was not until the NASA Seasat mission in 1978 that a microwave scatterometer instrument that focused specifically on wind observations (SASS, the Seasat-A Satellite Scatterometer) was flown in space (Grantham et al., 1977; Freilich, 1985). The Seasat spacecraft suffered a catastrophic power failure in October 1978 (only 100 days after launch), and it was not until the early 1980s that credible geophysical processing algorithms were developed and comprehensive data validation was performed. Nonetheless, SASS demonstrated that accurate measurements of wind velocity could be obtained from spaceborne scatterometers and allowed construction of the first accurate, basin-scale, 100-km-resolution maps of synoptic surface winds over the ocean.

The SASS data were never used for operational numerical weather prediction or marine forecasting, since near-real-time telemetry was not available, and geophysical processing algorithms were not in place at launch. Investigations into the operational utility of future scatterometer data were initiated as soon as SASS wind velocity data became available. Atlas et al. (2001) reviewed studies assessing the impact of assimilating SASS data into operational numerical weather prediction systems.

Several studies evaluated the use of spaceborne microwave scatterometer data for subjective tropical and extratropical marine forecasting and storm prediction (Black et al., 1985; Hawkins and Black, 1982; Stoffelen and Cats, 1991), capitalizing on the extensive coverage, high spatial resolution, and generally uniform accuracy of the measurements.

Following the demise of Seasat, NASA and the ESA pursued parallel initiatives to design and fly scatterometers. Each agency recognized the potential operational utility of the scatterometer wind measurements, yet neither agency committed to missions that fully addressed operational requirements. The programmatic approaches chosen by NASA and ESA differed substantially, and while both programs achieved comparable success, the foundations for operational transition were quite different.

ESA and the European Remote Sensing Satellite Program

ESA established its Optional Remote-Sensing Preparatory Programme in 1979 to develop technologies for future microwave remote sensing missions. The program had both scientific and economic objectives focusing on ocean and ice monitoring. Studies for the first of these missions, the ERS-1, were conducted from 1982 to 1983, and the mission, which included a scatterometer, moved into implementation in 1984. ERS-1 was designed to be an "experimental/pre-operational system" that would lead eventually to a fully operational microwave-based Earth observation capability. It was justified on grounds of producing services and products with direct economic benefit (ESA, 1995). Although the primary objectives of the missions focused on increasing scientific understanding (research) and developing commercial and economic applications of the measurements, it was recognized on the basis of the Seasat analyses that the scatterometer wind data could contribute to operational weather forecasting.

ESA contracted with a variety of European national and multinational operational meteorological agencies to perform pre-launch technical studies related to the processing and exploitation of the scatterometer wind data. These interactions established a technical dialogue between the space and operational agencies and fostered a detailed technical understanding of the data formats and their expected characteristics at the user agencies prior to launch. ESA set the overall ERS-1 wind data accuracy requirements to conform with World Meteorological Organization and user agency requirements (Offiler, 1994). The satellite telemetry and ground processing systems were designed to allow data to be processed and distributed to national operational meteorological agencies within 3 hours of receipt from the spacecraft (Burger, 1991; Fea, 1991). ESA supported a number of meteorological centers, including the European Centre for Medium-Range Weather Forecasts

(ECMWF), the U.K. Met Office, the Dutch meteorology office, and MeteoFrance, to characterize, validate, perform quality control, and refine aspects of the processing algorithms for the scatterometer data following launch (e.g., Stoffelen and Anderson, 1995, 1997; Stoffelen, 1998; Offiler, 1994).

The ERS-1 mission was launched on July 17, 1991, and operated until October 3, 2000. The essentially identical follow-on ERS-2 mission was launched April 21, 1995, and scatterometer operations continued until January 2001. Although initially the ERS-1 wind products did not meet the pre-launch specifications (Stoffelen and Anderson, 1995), algorithm and processing refinements led by investigators at ECMWF yielded accurate vector wind products within about 18 months after launch. ECMWF began routine assimilation of ERS wind products in May 1996.

Through international agreements and competitive proposals, U.S. operational meteorological agencies and NASA-sponsored researchers received ERS data beginning early in the ERS-1 mission. The operational agencies received the data in near real time from ECMWF, while the research scientists obtained science-quality data routinely from the ESA IFREMER (French Research Institute for Exploitation of the Sea)/CERSAT (French ERS Processing and Archiving Facility) and, using NASA algorithms and model functions, through the Jet Propulsion Laboratory. Assimilation of ERS scatterometer data into U.S. numerical weather prediction models was investigated both at the National Centers for Environmental Prediction (NCEP) and in the research community (principally at Goddard Space Flight Center; Atlas et al., 2001). However, ERS scatterometer data were never operationally assimilated in the NCEP models. Graphical, Web-based imagery with ERS wind measurements were routinely produced in the NOAA/NESDIS Office of Research and Applications and used by NOAA marine forecasters.

The NASA NSCAT, QuikSCAT, and SeaWinds Projects

Seasat's successful demonstration of the utility of scatterometer wind measurements led NASA to form a Satellite Surface Stress (S^3) Working Group in September 1981, to "identify scientific problem areas in which significant science advances might be expected if a new scatterometer were to be flown" (O'Brien et al., 1982). The S^3 panel was composed of 20 scientific and technical experts from academia, industry, NASA centers, and DOD, most of them researchers. Identification of operational and commercial uses for surface wind measurements was a distinctly secondary S^3 objective; potential scatterometer contributions to operational weather forecasting were outlined only briefly in the report's Chapter IV, "Other Applications for Satellite Wind Stress."

On the basis of the SASS results and the S^3 recommendations and science requirements, NASA initiated the NASA Scatterometer (NSCAT) project for designing and building a dual-swath, Ku-band scatterometer instrument and an associated NASA ground data processing and distribution system to service the research community.

In contrast with other efforts such as the TOPEX/Poseidon altimeter, NASA's scatterometer plans did not include funding for a spacecraft and launch vehicle. Rather, NASA initially planned to provide the scatterometer instrument as part of the measurement suite on the proposed DOD Navy Remote Ocean Sensing System (NROSS). Navy requirements and objectives for NROSS were focused on acquiring measurements and generating and distributing near-real-time analyses and forecasts to the fleet, with particular emphasis on extreme weather conditions. Navy surface wind measurement requirements were identical to those established years earlier in the Operational Requirement for Satellite Measurement of Oceanographic Parameters (SMOP OR WO5270S, February 10, 1977). These wind accuracy requirements were comparable with, and in some areas more stringent than, the NASA (S^3) research requirements. However, as the Navy retained the responsibility for developing the near-real-time processing algorithms and data-distribution system, NASA focused on designing a scatterometer flight instrument that could provide sufficiently accurate backscatter measurements and a ground processing system to provide geophysical products to the scientific research community.

The NROSS budget was cut and the schedule was delayed, eventually leading to cancellation of the program in 1988 (NRC, 1995, Figure 2.3, p. 42). By that time, NASA had built a significant fraction of the NSCAT flight hardware, invested substantial resources in development of the ground processing system, and selected and funded a broad-based scatterometer science team to conduct research using scatterometer data (NASA, 1985; Freilich, 1985).

Following the cancellation of NROSS, NASA searched extensively for a funded mission and spacecraft that could accommodate the NSCAT instrument. An international collaboration was eventually arranged to fly NSCAT as a U.S. contribution to the Japanese National Space Development Agency's (NASDA's) Advanced Earth Observation Satellite (ADEOS-I) research mission (Naderi et al., 1991; Graf et al., 1998).

Although NASA's primary responsibility was to provide wind data to the oceanographic and meteorological research communities, the operational potential for scatterometry was recognized. Since the Navy (which had responsibility for the operational aspects of NROSS) no longer participated in the NSCAT program, NASA and NOAA/NESDIS developed a substantive collaboration that, with NASDA help, allowed global NSCAT data to be downloaded and processed within 3 hours of acquisition. During the pre-launch period, the Jet Propulsion Laboratory developed and supported NSCAT algorithms and processing code to run on NESDIS operational computers, NESDIS provided ground tracking and telemetry capability to allow downloading of ADEOS-I data on nearly an orbit-by-orbit basis, and NASDA modified its original spacecraft operation plans both to provide for early turn-on of the NSCAT instrument after launch and for routine downloading at the NOAA stations during the mission (Graf et al., 1998).

ADEOS-I was launched on August 17, 1996, and NSCAT measurements were available nearly continuously from mid-September 1996 until the abrupt failure of the spacecraft's solar panel on June 30, 1997. Validated near-real-time data were made available by NOAA/NESDIS starting in February 1997. Assimilation of NSCAT vector wind data into the Goddard Earth Observing System (GEOS-2) resulted in a 24-hour extension of useful forecast skill in the Southern Hemisphere extratropics, with more modest impacts in the Northern Hemisphere extratropics (Atlas et al., 2001).

While the increased coverage of NSCAT relative to ERS-1 yielded significantly larger forecast impacts in numerical weather prediction, its largest contribution came in operational subjective marine forecasting. Graphical depictions of NSCAT data were distributed rapidly by NOAA/NESDIS and were used extensively and routinely by marine forecasters at line stations and at the Marine Prediction Center.

Even before the launch of NSCAT, NASA began the development of a new generation of Ku-band scatterometer instruments using scanning pencil beams rather than fan beam antennas (Freilich et al., 1994; Spencer et al., 1997). This "SeaWinds" scatterometer could be accommodated far more easily that the fan-beam designs, and featured an 1,800-km-wide swath for exceptional coverage from polar orbit. Originally selected for flight on the AM NASA Earth Observing System spacecraft, the decision was made to continue collaboration with Japan and fly SeaWinds as a NASA contribution to the ADEOS-II mission.

Following the premature failure of ADEOS-I and the loss of NSCAT data, NASA initiated the rapid-development QuikSCAT mission to minimize the gap in broad-swath scatterometer data between NSCAT and SeaWinds/ADEOS-II. QuikSCAT utilized an off-the-shelf satellite bus and existing flight hardware and spares prepared for SeaWinds/ADEOS-II; the mission was ready to launch approximately 18 months after the demise of ADEOS-I, although the actual launch was delayed, owing to launch vehicle problems, until June 1999. Scatterometer data were obtained starting in July 1999, and validated near-real-time data were produced routinely by NOAA/NESDIS (using NASA-provided software) starting in early 2000. As with NSCAT, these data are provided to marine forecast offices in graphical form and to major national and international forecast centers for assimilation into numerical weather prediction systems (Box B.1).

BOX B.1

National Weather Service Advisory, August 26, 2000, 2100 UTC

REMARKS:
262100Z1 POSITION NEAR 21.4N7 130.6E0.
TROPICAL STORM (TS) 20W (PRAPIROON), LOCATED APPROXIMATELY 375 NM SOUTH-SOUTHEAST OF OKINAWA HAS TRACKED NORTH NORTHWESTWARD AT 20 KNOTS OVER THE PAST 6 HOURS. THE WARNING POSITION IS BASED ON 261730Z9 INFRARED SATELLITE IMAGERY. THE WARNING INTENSITY IS BASED ON SATELLITE CURRENT INTENSITY ESTIMATES OF 30 AND 35 KNOTS AND A SHIP REPORT OF 35 KNOTS.
ANIMATED ENHANCED INFRARED SATELLITE IMAGERY DEPICTS CONVECTION IS SHEARED 15 NM TO THE NORTH AND EAST OF A PARTIALLY EXPOSED LOW LEVEL CIRCULATION CENTER (LLCC). IMAGERY ALSO INDICATES CONVECTION HAS INCREASED IN INTENSITY OVER THE PAST 06 HOURS.
UW-CIMSS ANALYSIS AND THE 200 MB ANALYSIS INDICATE OUTFLOW ALOFT CONTINUES TO IMPROVE AS THE TROPICAL UPPER-TROPOSPHERIC TROUGH (TUTT) TO THE WEST CONTINUES TO FILL. **A 260916Z4 QUIKSCAT PASS INDICATED A WELL DEFINED LLCC WITH LIGHTER WINDS AROUND THE CENTER AND STRONGER WINDS ON THE PERIPHERY.** THE SYSTEM IS FORECAST TO TRACK NORTHWESTWARD THROUGH 24 HOURS, THEN INCREASINGLY WEST-NORTHWESTWARD AS THE SUB-TROPICAL RIDGE BUILDS IN NORTH OF THE SYSTEM. **THE 35 KNOT WIND RADII HAVE BEEN INCREASED BASED ON THE 260916Z4 QUIKSCAT PASS.**

Transition/Operational Status

The U.S. and European space agencies have each flown scatterometers on multiple research missions. Scatterometer data from many of these research missions have been made available in near real time and have been used operationally for subjective regional marine forecasting, global numerical weather prediction, and ice-edge tracking. Backscatter and ocean surface vector wind data from the NASA QuikSCAT mission are presently being used operationally by a number of operational agencies, including ECMWF, NCEP, the U.S. National Weather Service, and the U.S. Joint Ice Center at the National Snow and Ice Data Center. However, scatterometers have not yet been flown as part of either the U.S. or European operational observing systems.

A SeaWinds instrument is planned for launch in November 2002 onboard the Japanese NASDA ADEOS-II research mission. NESDIS will receive ADEOS-II scatterometer data in near real time and will use NASA-supplied software to process the measurements to geophysical units. The SeaWinds data will also be distributed in near real time by NESDIS to international meteorological agencies. Plans call for overlap between the QuikSCAT/SeaWinds and SeaWinds/ADEOS-II missions to allow cross-calibration of the instruments and a seamless effective operational transition.

EUMETSAT and ESA will fly Advanced Scatterometers (ASCATs) on the Meteorological Operational Polar (METOP) satellite missions. The first METOP mission will launch in October 2005, with a 5-year lifetime. Two additional METOP missions are planned for launch at 4- to 5-year intervals, leading to a continuous 14-year time series. Consistent with the operational nature of METOP, the ASCAT data will be available to European and international meteorological agencies in near real time.

The baseline U.S. operational NPOESS constellation (to be launched starting in about 2008 to 2010) does not include scatterometer instruments, nor are there firm NPOESS requirements for all-weather surface wind velocity measurements. Surface wind velocity measurements in NPOESS will be acquired by the Conical Microwave Imager/Sounder (CMIS), a multifrequency polarimetric microwave radiometer. Although limited aircraft flights of polarimetric microwave radiometers have indicated the presence of a measurable wind directional signal (Yueh et al., 2002), the technique has not been demonstrated from space, nor have the error characteristics been quantified as has been the case for scatterometer data. The first spaceborne test of the technique is planned for early 2003 with the flight of the Naval Research Lab Windsat/Coriolis mission (Gaiser, 1999). Recently, NOAA management has made public statements of its willingness to examine the possibility of adding scatterometers to the operational observing system in the NPOESS time frame (Taverna, 2002).

Lessons Learned

Several conclusions regarding the transition from research to operations can be drawn from the similarities and differences between the U.S. and European scatterometer programs:

1. Near-real-time data delivery from research missions is required in order to gain the interest of operational numerical weather prediction agencies.
2. Although graphical products from research missions can be produced rapidly for subjective forecasting use, the assimilation of new observations into regional and global numerical weather prediction forecast/analysis systems requires detailed knowledge of the measurement error characteristics and extensive testing in the operational setting. This knowledge is generally not achieved for at least 1 or 2 years after calibrated geophysical data become available from new instruments.
3. The NASA-NOAA Joint Center for Satellite Data Assimilation played a strong and positive role in transferring knowledge of the data and assimilation techniques

that had been developed in research mode for NSCAT and ERS-1/2 to NCEP. Thus, although NCEP had not assimilated ERS-1/2 or NSCAT data whereas ECMWF had several years of ERS assimilation experience, operational assimilation of QuikSCAT data at NCEP actually began about 10 days earlier than at ECMWF.

4. Notwithstanding successful exploitation of scatterometer data by meteorological researchers and operational use of scatterometer measurements acquired by both U.S. and international missions, the incorporation of all-weather surface vector wind measurements into the operational observing constellations has taken 10 to 15 years and is not yet a reality.

SPECIAL SENSOR MICROWAVE/IMAGER

The Special Sensor Microwave/Imager (SSM/I) is an instrument carried on the satellites of the Defense Meteorological Satellite Program (DMSP). SSM/I data are used to develop products on ocean surface wind speed, ice coverage and age, precipitation over water, soil moisture, land surface temperature, snow cover, and sea surface temperature. These products are useful in weather and ocean prediction as well as for climate monitoring and research, including studies of interannual and seasonal variations, regional climate variations, and the El Niño Southern Oscillation. The SSM/I case study illustrates the importance of funding data-processing and algorithm development as a critical component of the space sensor acquisition process in order to provide for a rapid transition from research to operations.

Research Origin/Heritage

The SSM/I drew significantly on the heritage of the Scanning Multichannel Microwave Radiometer, an imaging five-frequency radiometer launched in 1978 on the Seasat and Nimbus-7 satellites (the radiometer on the Seasat provided data for only a few months; that on Nimbus-7 provided 10 years of data). The Navy provided strong support for the development and launch of the seven-frequency SSM/I on the DMSP satellites.

Transition Process

The transition of the SSM/I data into operational service required extensive data-processing and algorithm development, specifically, the translation of sensor data records (SDRs) into environmental data records (EDRs). Without sufficient research and resources for this process, the SSM/I data would have been in a form that was useless to users (operational meteorologists). The slowness in using the data from the infrared sounders was well known (see the infrared sounder case study, above).

Both the space- and ground-segment management organizations (DMSP System Program Office [SPO] and AWS/AFGWC) recognized this weakness and sought to improve the ground-support processing for SSM/I.[6] What with the failure, due to inadequate research on how to use the data, of the past series of DMSP satellites to deliver operationally useful data, considerable emphasis was placed on ensuring the needed research prior to launch of the SSM/I.[7]

The method of converting SDRs to EDRs was by algorithms that average or difference channel brightness temperatures. Therefore, a series of retrieval algorithms would have to be developed before the launch, followed by a calibration/validation process after launch, to determine the accuracy of the algorithms. As part of its effort to ensure that SSM/I data were used, the DMSP SPO took on the responsibility for developing and funding SSM/I sensor products and for funding an accompanying validation program for the EDR algorithms. The sensor contractor (Hughes) then developed about six algorithms prior to SSM/I's launch. The U.S. Naval Research Laboratory was supported for a 1-year validation program. This new process was successful; there was essentially immediate use of the SSM/I data by a number of users after launch, and a process was in place for developing improvements to the algorithms on the basis of the validation effort. An additional, unplanned benefit followed from the decision to release the SSM/I data stream and make it available to the wider, non-DOD research community. The result was a much broader validation process for the data and processing algorithms, which increased the usefulness of the data for the operational community significantly. This open availability of the data also led to the extensive use of the data by the international climate research community, most notably in the development of global water vapor and precipitation long-term analyses by the Global Energy and Water Cycle Experiment through such projects as the Global Precipitation Climatology Project.

---

[6]There had been previous examples of significant difficulties in providing the ground processing of raw data record data into SDR and EDR data owing to priorities and funding that pointed to a serious problem with respect to the assignment of responsibility and the scale of resources. Basically, the space segment of the program operated on a budget on the order of 20 times the size of the operational user who was responsible for converting the SDRs into EDRs. In the early days, the usefulness of the satellite IR sounder data was considered questionable by the operational community and, therefore, the priority for resources for the processing of these data was too low to assure operational processing into EDRs by the time of launch. This developed into a situation in which, for all practical purposes, a sensor was launched and never processed for use by the operational users.

[7]Personal communications from Walter Meyer, General Dynamics Advanced Information, and Richard Savage, Hughes Aircraft Company, for additional background to committee member Paul Try, May 2002.

Operational Status

The SSM/I and related follow-on sensors continue to be operational as part of the DMSP system, and similar sensors will be carried on the NPOESS spacecraft. These sensors will provide environmental data from advanced retrieval algorithms. However, assimilation of imaging microwave sensor data into Numerical Weather Prediction models is just beginning to be addressed.

Lessons Learned

The lessons learned from this case study include the following:

1. It is important to consider how data will be used well in advance of a launch, and to develop algorithms that will process the raw data to generate useful products.
2. The responsibility and funding for delivering sensor data in a form useful for direct and intermediate operational users should be borne by the space segment of the process. The space segment cannot be allowed to have the limited responsibility for only acquiring the hardware, but also must have an integrated responsibility that includes *continuing calibration and validation* of SDRs and a baseline of EDRs.
3. The full and early release and open availability to the research community of new operational data in both SDR and EDR form provide significant benefit through the development and illustration of improved and new uses of the original data.

SOLAR X-RAY IMAGER

The Solar X-ray Imager (SXI)[8] is an instrument designed to collect images of the Sun in the x-ray region of the spectrum. Such images have proven valuable for predicting solar activity and its impact on the near-Earth environment as well as on space-based and ground-based systems. SXI, now flying on the GOES satellites, provides an example of a transition that was slowly, but eventually *successfully completed*, despite a number of difficulties encountered in making it happen.

Research Origin/Heritage

Flares and other activity on the Sun have a considerable impact on the near-Earth space environment, with major consequences such as satellite failures, com-

[8]This case study is condensed from materials provided through personal communication from Patricia L. Bornmann, Ball Aerospace and Technologies Corporation, to committee liaison William B. Gail, April 9, 2002.

munications blackouts, and power-grid failures. Observations of the solar disc in the x-ray portion of the spectrum provide critical information about solar activity, but they can only be made from space. In contrast to ground-based observations, x-ray images allow easy identification of solar regions called coronal holes, which are closely correlated with the sporadic production of high-energy particles. Full-disc x-ray observations thus provide an important tool for predicting the impact of solar activity on the near-Earth space environment.

The research value of regular x-ray solar observations was first demonstrated on Skylab in 1973. NOAA Space Environment Center (SEC) forecasters quickly recognized that an operational follow-on based on imaging the entire solar disc was a high priority. Over the next decade, additional x-ray instruments flew on research missions, but low data rates and the research focus on higher spatial resolution meant that full-disc images were rare. In 1991, the Japanese Yokhoh mission flew a full-disc x-ray imager, the Solar X-ray Telescope (SXT), which reconfirmed the value of daily full-disc images.

Transition Process

By the early 1980s, the NOAA/SEC interest in flying a full-disc operational x-ray monitor was becoming widely known. One impediment to transition was purely technical: a solar x-ray imager is best suited to a nonspinning platform, and the GOES spacecraft were spin-stabilized prior to the launch of GOES-8 in 1994. The largest impediment to transition, however, turned out to be an inadequate budget. Space weather instruments, such as particle detectors and magnetometers, had historically been small and relatively inexpensive. NOAA/NESDIS was willing to fly a solar x-ray imager on the GOES-NEXT satellites being designed at the time, but had no budget to do so. Because they were aware of similar solar-monitoring needs within the DOD, NOAA/SEC decided to seek the support of the Air Force. Personnel at NOAA/SEC and the Air Force's ground-based solar observatory in New Mexico started working toward a solar x-ray instrument on GOES. This advocacy process proceeded slowly because of limited human resources throughout the late 1980s, and GOES-NEXT design decisions were made without consideration of the needs for a solar x-ray imager.

With a demonstrated need for full-disc solar x-ray imagery but having no operational sensor, NOAA/SEC turned to the Japanese in the early 1990s for access to SXT data. After considerable negotiation, the Japanese agreed to provide access to SXT data with two provisions: (1) images were not to be shared (particularly with military users), and (2) new ideas or discoveries made using the data could not be made public for 1 year.

In 1990, the Air Force identified $18 million to apply to the project, but schedule constraints limited inclusion of the x-ray sensor to only the last of the five spacecraft within the original GOES-NEXT procurement. Because spacecraft design decisions had been frozen, it was discovered that about half of the Air Force budget of $18 million would be required for spacecraft modifications alone. To work within the available budget, it was decided that the instrument would be built by NASA at the Marshall Space Flight Center, where some of the costs could be absorbed by nonproject funds. Although the design was to be made available to industry to build follow-on instruments, budget constraints resulted in performance limitations that reduced the value of this instrument for future designs. The instrument was finally launched on GOES-12 in 2001. Two follow-on instruments are being built by industry through a contract initiated in 1996.

Operational Status

The first operational NOAA Solar X-ray Imager, SXI, was launched on GOES-12 in 2001, nearly 30 years after the research justification for the operational need was identified on Skylab. Following successful checkout, the spacecraft was placed in on-orbit storage, ready to replace one of the currently operating GOES.

Lessons Learned

The main lesson learned in the SXI experience is that inadequate financial and human resources can prolong the transition from research to operations for many years after a technology has been demonstrated and a need established:

1. Limited personnel left NOAA scientists overburdened during the development of SXI, requiring them to both do science and support the SXI development. These same human resource limitations resulted in use of NOAA personnel with primary expertise in data analysis as the technical advisers responsible for understanding and establishing the SXI instrument design and operational requirements.
2. Difficulties with establishing funding for SXI prolonged the transition process to nearly 30 years (NRC, 2003).

VOLCANIC ASH MAPPER

The Volcanic Ash Mapper (VOLCAM)[9] instrument was designed to conduct research on volcanic clouds and eruption precursors, providing measurements of

[9] This case study is condensed from materials provided through personal communications from Arlin J. Krueger, University of Maryland, Baltimore County, to committee liaison William B. Gail, April 4, 2002.

volcanic ash and sulfur dioxide (SO_2) clouds, SO_2, total ozone, smoke, and dust. The data to be collected by VOLCAM would assist in monitoring volcanic ash clouds and would provide valuable information for aviation safety.

VOLCAM is an example of a measurement that has demonstrated strong operational potential but, despite substantial effort and interest in both the research and operational communities, *has not successfully been transitioned* to operational status.

Research Origin/Heritage

In 1982, data from the NASA Total Ozone Mapping Spectrometer (TOMS) showed a surprising anomaly in the vicinity of the El Chichon volcano in southern Mexico. Investigation of the anomaly led to the first demonstration that SO_2 in volcanic eruption clouds can be detected with satellite sensors operating in the ultraviolet (UV) portion of the spectrum, and that the larger-than-expected quantity of SO_2, rather than ash, clearly is the driver of volcano-climate effects. At about the same time, the first incidents were being reported of commercial aircraft becoming disabled after encountering volcanic ash clouds. A British Airways 747 lost all power after flying through the ash cloud from the Gallunggung volcano in Indonesia; its engines restarting only after heroic measures, the airliner was forced to land with a windshield that had been rendered nearly opaque by the ash. A KLM 747 also had all four engines flame out when flying through the ash cloud of the Mt. Redoubt eruption in the Aleutian Islands. Again, after heroic measures the crew managed to restart the engines, after losing 10,000 feet of altitude. The aircraft landed safely at Anchorage, Alaska, with damage to the engines, flight surfaces, and windscreen. According to the U.S. Geological Survey (USGS, 1997), at least 15 aircraft were damaged from 1980 to 1997 while flying through volcanic ash clouds along North Pacific air routes. In addition, at least 80 ash cloud encounters occurred worldwide in the same time period, causing hundreds of millions of dollars in damage and lost revenue.

These incidents led to great interest in TOMS data by the U.S. Geological Survey (USGS), the Federal Aviation Administration (FAA), and NOAA. A fast turn-around system was developed by the principal investigator of TOMS to respond to requests about reported volcanic eruptions. It soon became clear that SO_2 was a unique discriminator between eruptions that produce large, dangerous clouds and smaller eruptions that represent little threat to aircraft. NASA continued to support this quasi-operational capability for a number of years on a best-efforts basis.

In the 1990s, theoretical developments indicated that the sensitivity of the TOMS UV technique could be greatly enhanced by a better selection of wavelengths. This meant that the scientific output could be extended to the monitoring of pre-eruptive gas emissions, which were predictive for eruptions. However, the value of this technique from polar orbiting satellites was limited, because the probability of seeing these low-altitude emissions depends on catching cloudfree moments. Thus, it became clear that geostationary satellites provide ideal platforms for volcano monitoring as well as for observing the drift of volcanic clouds.

Transition Process

Recognizing the operational value of the TOMS data, the FAA, NOAA, and NASA established a Memorandum of Understanding (MOU) to provide for the transfer of NASA technology to NOAA for processing TOMS data and for the provision of raw data to NOAA. The production software was incorporated into the NOAA/NESDIS near-real-time operational system. Special real-time processing codes were developed and delivered to the National Weather Service in Anchorage for immediate readout of the NASA Earth Probe TOMS instrument during satellite passes. The system was also planned for the QuikTOMS mission, but that satellite was destroyed in a launch failure in 2001.

Meanwhile, the Office of the Federal Coordinator for Meteorology (OFCM) set up a working group to coordinate the activities of the operational agencies for dealing with volcanic ash clouds in aviation safety. Participants included the FAA, NOAA, USGS, DOD, the Smithsonian Institution, NASA, and the airline industry, represented by the Air Line Pilots Association and Air Transport Association. The primary satellite tools for the detection of volcanic clouds were the NASA/TOMS and the NOAA POES/AVHRR and GOES/sounder instruments. In addition, visible satellite imagery was used to detect plumes by their shapes. One of the immediate concerns of the OFCM Volcanic Ash Working Group was a NOAA plan to change the GOES sounder wavelengths, with the consequence that an important technique for retrievals of ash would no longer be possible. A second concern was the growing risk to aircraft from the increased number of flights, especially in the North Pacific, with its high density of active volcanoes.

With this history, NASA made several attempts to develop new capabilities to detect volcanic eruptions. Two pertinent missions were proposed in the first Earth System Science Pathfinder Announcement of Opportunity (AO) in 1996, one by NASA Langley Research Center and one by the Jet Propulsion Laboratory. The proposal from Langley Research Center was selected in Step 1, with the plan to fly as a payload-of-opportunity on a commercial communications satellite, but it had to be withdrawn when the commitment with the satellite provider could not be completed.

Goddard Space Flight Center, with the principal investigator (PI) of TOMS as VOLCAM PI, decided to propose the VOLCAM mission to the second ESSP AO in 1998 when OFCM indicated that substantial support would be available if the UV sensor were augmented with an infrared (IR) sensor for nighttime detection. It was estimated at the time that this mission could be accomplished for a NASA cost of $45 million by flying on an existing spacecraft such as GOES. Part of the proposal strategy was to include other agencies as partners, contributing according to their means and capabilities. NASA would do mission development, flight hardware, software development, and scientific research; NOAA would do data ingest, processing, and analysis; FAA would do aviation control planning and education; and USGS would do eruption prediction and diagnosis. NESDIS agreed to contribute the processing costs, and the NWS endorsed the proposed concept, although reservations were expressed about the limited resolution of the IR camera. The FAA also endorsed the proposal, although attempts to elevate the level of commitment within the FAA failed. The FAA uses the NWS as its source of environmental data for air traffic control. The perceived lack of direct involvement in production of the data was a factor that limited the FAA's contribution to the in-kind training costs following successful launch of the mission. The USGS administrator strongly supported the proposal, but warned that direct funding and substantial commitments could not be provided owing to the Office of Management and Budget's concerns over "mission creep." However, the USGS offered in-kind support during the operational test phase of the mission.

NASA selected the VOLCAM proposal on the basis of its scientific merits, and asked for a full Step 2 proposal. During the Step 2 study, agreements were reached with the Tracking and Data Relay Satellite (TDRS) project for flight service on either TDRS I or J and with NOAA/NESDIS to carry VOLCAM on either GOES N or O. Two commercial satellite owners also indicated interest in working with NASA. At the end of the Step 2 studies, VOLCAM was one of two candidate missions selected to conduct extended assessment studies, with one of the two to be selected for flight based on the extended study. The strong science, low risk, and flight heritage were cited as the major strengths of VOLCAM. Weaknesses were cited in the data flow plan in the partner agencies, uncertainty in spacecraft integration costs, and lack of maturity in the IR camera design. The weaknesses were addressed in the extended study report. During the oral phase of the report, the question of the commitment of other agencies was raised, and it became apparent that in-kind contributions did not meet the expectations of the associate administrator of NASA's Earth Science Enterprise (ESE). However, none of the attendees from other agencies was able to commit resources to the instrument and mission development. The prime issue was a commitment for continued operational funding support beyond the scientific demonstration mission rather than support for the proposed ESSP mission.

VOLCAM was not selected for flight, but the ESE associate administrator expressed an intention to explore a cooperative program with NOAA for flight of the

UV sensor on a future GOES satellite. The cooperative program was later defined as a joint mission with a proposed NOAA instrument, the Special Events Imager (SEI), which had partial funding in the FY 2000 NOAA budget. Owing to the limited funding, both teams were asked to determine whether the functions of SEI and VOLCAM could be combined in a single instrument. Technical issues ended up eliminating this possibility, but a compromise plan was submitted to merge the electronics portions of the instruments. The joint project ultimately failed when Congress eliminated the SEI item from the NOAA budget. Without a NOAA contribution to the hardware costs, the joint mission was abandoned.

Operational Status

The VOLCAM instrument has not been successfully transitioned to operational status, although some of the VOLCAM eruption-monitoring algorithms developed for use with the TOMS sensor have been transitioned to NWS.

Lessons Learned

Lessons learned from the VOLCAM case study are largely related to a lack of sufficient agency commitment. In spite of relatively strong interest by a number of agencies, no one agency was sufficiently supportive to lead the transition.

1. VOLCAM was developed out of a long-standing interagency collaboration at the working level, a result of the NASA-led geophysical science and natural hazards program's having produced information of value to the operational agencies. An MOU was established between NASA and the operational agencies to cooperate in the area of volcanic hazard data. Nevertheless, neither the MOU nor the collaboration between agencies at the working level was sufficient to establish agency commitment for the VOLCAM transition.
2. NOAA has a very limited capacity or budget to evaluate new sensing concepts internally, so advancements in observational measurements are difficult to make unless they involve extending the capabilities of NOAA's few core instruments.
3. Other than the GIFTS mission, NASA has not funded any geostationary sensor proposals in recent years. Opportunities to evaluate new research sensors or measurements for geostationary operational use have thus been extremely limited.
4. The lack of an organizational transition mechanism between NASA and NOAA makes direct transfer of technologies between the agencies difficult.

TROPICAL RAINFALL MEASURING MISSION

The Tropical Rainfall Measuring Mission (TRMM) is a low-Earth-orbiting satellite with an orbit that oscillates about the equator between roughly 35°N and 35°S. A joint mission between the United States and Japan, TRMM's primary stated goals were (1) to improve the understanding of crucial links in climate variability that are due to the hydrological cycle, (2) to improve the large-scale numerical models of weather and climate through assimilation of TRMM data, and (3) to advance our understanding of cloud ensembles and their impacts on larger-scale circulations. Shortly after launch, scientists recognized that TRMM would also provide valuable new information on hurricanes in all stages of development.

Research Origin/Heritage

In 1987, the U.S. Department of Defense (DOD) became the first to fly a passive multifrequency microwave imager on a meteorological satellite. The Special Sensor Microwave/Imager (SSM/I) channels penetrate to Earth's surface unless the signal is attenuated by precipitation or large aerosols. One of the SSM/I channels senses at a frequency of 85 GHz, with a spatial resolution of 13 to 15 km. This channel is able to penetrate nonraining clouds. However, larger, frozen hydrometeors (e.g., hail, graupel) and raindrops associated with vigorous convection dramatically scatter radiation at this frequency. Thus, the sensor can detect intense rain associated with hurricane rainbands and the eyewall, owing to the lowered brightness temperatures created by the intense scattering. A time series of 85-GHz data can reveal a storm's internal convective structure and evolution by mapping the organization and vigor of the convection around the storm center.

Building on the success of the DOD program, NASA launched a special satellite for measuring meteorological quantities over the tropics using passive and active microwave sensors. The TRMM satellite completed 4 years of successful data collection in November 2001. The primary TRMM sensors include a precipitation radar, TRMM Microwave Imager (TMI), and Visible/Infrared Scanner. TRMM's precipitation radar is an active sensor and the first successfully deployed civilian rainfall-rate-monitoring radar to operate from space. The precipitation radar can provide three-dimensional profiles of precipitation through storm cloud patterns. (Kummerow et al. [2000] provide more detail on the TRMM instruments, algorithms, and a wide range of early results.) The TMI is a multichannel, dual-polarized, conically scanning passive microwave instrument similar to the SSM/I. The purpose of the visible/infrared instrument is to enable TRMM to be a "flying rain gauge." The TRMM satellite radar and radiometer combination is intended to obtain high-quality vertical profiles of precipitation as well as surface rainfall estimates. TRMM's rainfall-rate observations from the combined radar and passive microwave instruments allow the calibration of empirical rain estimates from the IR sensors. As a result, uncertainty in tropical rainfall has been greatly reduced from earlier space-based estimates. Currently, these techniques are being applied to estimate hurricane rainfall.

Transition Process

TRMM observations are also being used to provide better initial conditions for numerical models. Krishnamurti et al. (2000) have developed a complex modeling approach using TRMM data that is showing promise for improving 3-day hurricane forecasts of both track and intensity. The approach uses multiple analyses and multiple models to create a "super-ensemble" forecast.

TRMM data are being provided in near real time to hurricane forecasters. The high-resolution imagery is being used to help locate the centers of hurricanes and to assess convective organization trends. The value of TRMM to the forecast and research communities is evidenced by its wide usage in operational tracking and forecasting of tropical systems, along with its contribution to the increased understanding of the global water cycle. Figure B.3 shows TRMM-derived rainfall rates and surface winds obtained from QuikSCAT for Hurricane Floyd in 1999.

Operational Status

TRMM is not considered an operational satellite; however, TRMM observations are being used by operational forecast centers as noted above. The Global Precipitation Measurement mission, a joint Japan-U.S. mission scheduled for launch in 2007, is a follow-on to TRMM.[10]

Lessons Learned

The lessons learned from this case study are these:

1. The involvement of the operational community in preparing for TRMM observations before launch allowed for the rapid testing of TRMM data in operational models.
2. Satellites designed primarily for research or for proof of concepts can provide data that are useful for operations if the operational centers are prepared for the data and if the data are provided in real time.

[10] Additional information is available online at <http://gpm.gsfc.nasa.gov>. Accessed January 22, 2003.

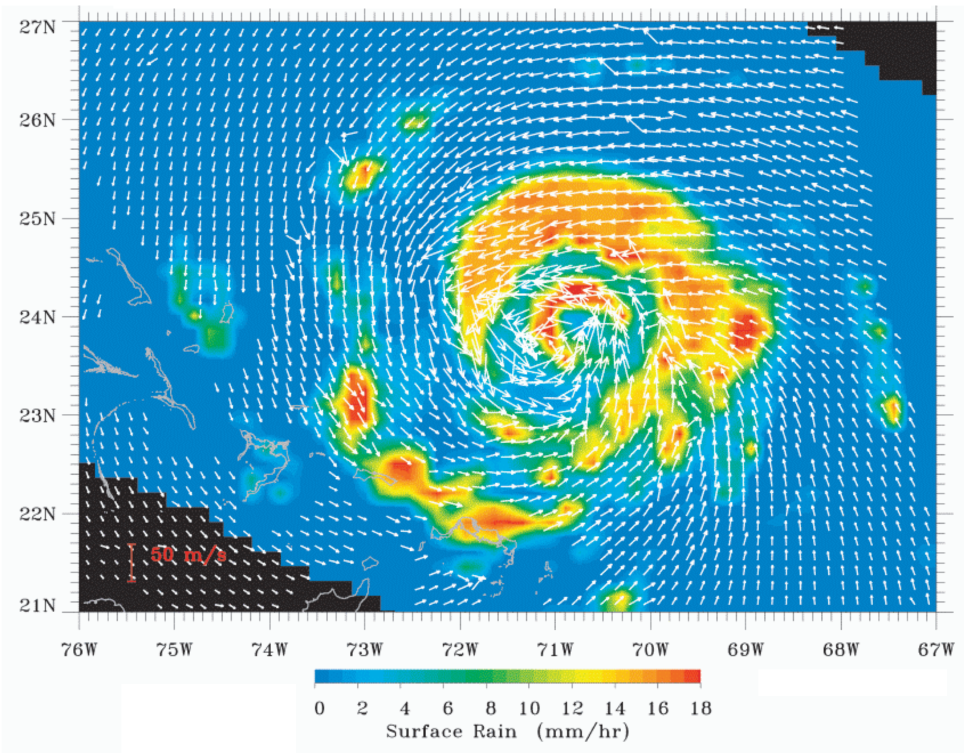

FIGURE B.3 Example of QuikSCAT surface wind data overlain on TRMM rainfall signatures during Hurricane Floyd in 1999. SOURCES: Liu et al., 2000 (Plate 12 in Simpson et al., 2003). Reprinted with permission.

REFERENCES

Atlas, R., R.N. Hoffman, S.M. Leidner, J. Sienkewicz, T.-W. Yu, S.C. Bloom, E. Brin, J. Ardizzone, J. Terry, D. Bungato, and J.C. Jusem. 2001. The effects of marine winds from scatterometer data on weather analysis and forecasting. Bull. Amer. Meteorol. Soc. 82:1965-1990.

Barrick, D.E., and C.T. Swift. 1980. The Seasat microwave instruments in historical perspective. IEEE J. Ocean. Eng. OE-5:74-79.

Black, P.G., R.C. Gentry, V.J. Cardone, and J. Hawkins. 1985. Seasat microwave wind and rain observations in severe tropical and midlatitude marine systems. Adv. Geophys. 27:197-277.

Burger, J.J. 1991. ERS-1 ready for launch. ESA Bull. No. 65:13-15.

Chelton, D.B. 2001. Report of the High-Resolution Ocean Topography Working Group. Ref. 2001-4. College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis.

Chelton, D.B., J.C.Rèis, B.J. Haynes, L.-L. Fu, and P.S. Callahan. 2001. Satellite altimetry. Satellite Altimetry and Earth Sciences, L.-L. Fu and A. Cazenave, eds. Academic Press, San Diego, Calif.

Christian, H.J., K.T. Driscoll, S.J. Goodman, R.J. Blakeslee, D.A. Mach, and D.E. Buechler. 1996. The Optical Transient Detector (OTD). Pp. 368-371 in Proceedings of the 10th International Conference on Atmospheric Electricity, Osaka, Japan, June 10-14, 1996.

Christian, H.J., R.J. Blakeslee, S.J. Goodman, D.A. Mach, M.F. Stewart, D.E. Buechler, W.J. Koshak, J.M. Hall, W.L. Boeck, K.T. Driscoll, and D.J. Bocippio. 1999. The Lightning Imaging Sensor. Pp. 746-749 in Proceedings of the 11th International Conference on Atmospheric Electricity, Guntersville, Ala., June 7-11, 1999.

ESA (European Space Agency). 1995. New Views of the Earth—Scientific Achievements of ERS-1. ESA SP-1176/1. ESA, Paris, France.

Fea, M. 1991. The ERS ground segment. ESA Bull. No. 65:49-61.

Freilich, M.H. 1985. Science Opportunities Using the NASA Scatterometer on N-ROSS. JPL Publication 84-57. Jet Propulsion Laboratory, Pasadena, Calif..

Freilich, M.H., D.G. Long, and M.W. Spencer. 1994. SeaWinds: A scanning scatterometer for ADEOS-II—Science overview. Pp. 960-963 in Proc. Int. Geosci. Rem. Sens. Symp., Pasadena, Calif., August 8-12, 1994.

Fu, L.-L., W.T. Liu, and M.R. Abbott. 1990. Satellite remote sensing of the ocean. The Sea: Ocean Engineering Science, Vol. 9, Pt. B, B. Le Méhauté and D.M. Hanes, eds. John Wiley & Sons, New York.

Gaiser, P.W. 1999. Windsat—Satellite-based polarimetric microwave radiometer. 1999 IEEE MTTS-Dig. 1:403-406.

Graf, J., C. Sasaki, C. Winn, T. Liu, W. Tsai, M. Freilich, and D. Long. 1998. NASA scatterometer experiment. Acta Astronautica 43:397-407.

Grantham, W.L., E.M. Bracalante, W.L. Jones, and J.W. Johnson. 1977. The SeaSat—A satellite scatterometer. IEEE J. Ocean. Eng. OE-2:200-206.

Hall, R. Cargill. 1985. A History of the Military Polar Orbiting Meteorological Satellite Program. National Reconnaissance Office History Program. Originally classified 1985 (declassified 2000). National Reconnaissance Office, Washington, D.C..

Hawkins, J.D., and P.G. Black. 1982. Seasat scatterometer detection of gale force winds near tropical cyclones. J. Geophys. Res. 88:1674-1682.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne, and D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77(3):437-431.

Kalnay, E., S.J. Lord, and R.D. McPherson. 1998. Maturity of operational numerical weather prediction: Medium range. Bull. Am. Meteorol. Soc. 79(12):2753-2769.

Krishnamurti, T.N., C.M. Kishtawal, Z. Zhang, T. LaRow, D. Bachiochi, E. Williford, S. Gadgil, and S. Surendran. 2000. Multimodel ensemble forecasts for weather and seasonal climate. Journal of Climate 13(23):4196-4216.

Kummerow, C., et al. 2000. The status of the tropical rainfall measuring mission (TRMM) after two years in orbit. J. Appl. Meteorol. 39(12):1965-1982.

Liu, W.T., H. Hu, and S. Yueh. 2000. Interplay between wind and rain observed in Hurricane Floyd. EOS Trans. 81:253-257.

Moore, R.K., and A.D. Fung. 1979. Radar determination of winds at sea. Proc. IEEE 67:1504-1521.

Naderi, F.M., M.H. Freilich, and D.G. Long. 1991. Spaceborne radar measurement of wind velocity over the ocean—An overview of the NSCAT scatterometer system. Proc. IEEE 79:850-866.

NASA (National Aeronautics and Space Administration). 1985. Scatterometer Research in Oceanography and Meteorology Announcement of Opportunity. A.O. OSSA-1-85, January 31, 1985. NASA, Washington, D.C.

NRC (National Research Council). 1995. Earth Observations from Space—History, Promise, and Reality. National Academy Press, Washington, D.C.

NRC. 2003. The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics. National Academies Press, Washington, D.C., in press.

O'Brien, J.J., and members of NASA Satellite Surface Stress Working Group. 1982. Scientific Opportunities Using Satellite Surface Stress Measurements Over the Ocean—Report of the Satellite Surface Stress Working Group. Nova University/N.Y.I.T. Press, Fort Lauderdale, Fla.

Offiler, D. 1994. The calibration of ERS-1 satellite scatterometer winds. J. Atmos. Ocean. Technol. 11:1002-1017.

Orville, R.E. 1987. Meteorological applications of lightning data. Rev. Geophys. 25:411-414.

Pierson, W.J. 1983. Highlights of the Seasat-SASS Program: A review. Pp. 69-86 in Satellite Microwave Remote Sensing (T.D. Allen, ed.). Halstead Press, New York.

Simpson, R.H., R.A. Anthes, M. Garstang, and J.M. Simpson, eds. 2003. Hurricane! Coping with Disaster: Progress and Challenges Since Galveston, 1900. American Geophysical Union, Washington, D.C..

Spencer, M.W., C. Wu, and D.G. Long. 1997. Tradeoffs in the design of a spaceborne scanning pencil beam scatterometer: Application to SeaWinds. IEEE Trans. Geosci. Rem. Sens. 35:115-126.

Stoffelen, A. 1998. Toward the true near-surface wind speed: Error modeling and calibration using triple collocation. J. Geophys. Res. 103:7755-7766.

Stoffelen, A., and D.L.T. Anderson. 1995. The ECMWF Contribution to the Characterization, Interpretation, Calibration and Validation of ERS-1 Backscatter Measurements and Winds, and Their Use in Numerical Weather Prediction Models. ESA Contractor Report. European Centre for Medium-Range Weather Forecasts, Reading, U.K.

Stoffelen, A., and D. Anderson. 1997. Ambiguity removal and assimilation of scatterometer data. Q. J. R. Meteorol. Soc. 123:491-518.

Stoffelen, A., and G.J. Cats. 1991. The impact of Seasat-A scatterometer data on high-resolution analysis and forecasts: The development of the QE-II storm. Mon. Wea. Rev. 119:2794-2802.

Taverna, M.A. 2002. U.S. seeks to regain edge in climate issue. Aviation Week 157(2):62-63.

Turman, B.N. 1978. Analysis of lightning data from the DMSP satellite. J. Geophys. Res. 83:5019.

USGS (U.S. Geological Survey). 1997. Volcanic Ash—Danger to Aircraft in the North Pacific. USGS Fact Sheet 030-97. USGS, Reston, Va.

Yueh, S.H., W.J. Wilson, and S. Dinardo. 2002. Polarimetric radar remote sensing of ocean surface wind. IEEE Trans. Geosci. Rem. Sens. 40:793-800.

C

Future Missions

RECENTLY LAUNCHED AND UPCOMING MISSIONS WITH U.S. INVOLVEMENT

Several missions in which the United States is or will be involved present opportunities for transition to operational service. The European Space Agency (ESA) is also planning Earth observation missions, discussed below, that may provide operational benefits. Table C.1 lists recently launched and upcoming U.S. and international cooperative research missions that can offer operational dividends.

FUTURE EUROPEAN SPACE AGENCY "CORE" MISSIONS

ESA "Core" missions are ESA-led missions devoted to long-term research goals. Three Mission Advisory Groups (MAG) have been established for these missions. The main objective of the groups is to support the European Space Agency in consolidating the science and mission requirements and to ensure that requirements are compatible with the system specifications. In late 2003, two of the three missions will be selected to go forward to Phase B (design and development). These missions will be eventually implemented (launched) in 2007-2010.

- EarthCARE (Earth Clouds, Aerosol and Radiation Explorer)—a joint European-Japanese mission, which is to address the need for a better understanding of the interactions between cloud, radiative, and aerosol processes that play a role in climate regulation.

• SPECTRA (Surface Processes and Ecosystem Changes Through Response Analysis)—a mission that will study the role of terrestrial vegetation in the global carbon cycle and its response to climate variability.

• WALES (Water vApour and Lidar Experiment in Space)—a mission to provide a better understanding of the distribution of atmospheric water vapor in the troposphere and lower stratosphere.

Additional information is available online:
<http://www.esa.int/export/esaLP/ASESMYNW9SC_earthcare_0.html>
<http://www.esa.int/export/esaLP/ASE12YNW9SC_spectra_0.html>
<http://www.esa.int/export/esaLP/ASE77YNW9SC_wales_0.html>

FUTURE EUROPEAN SPACE AGENCY "OPPORTUNITY" MISSIONS

"Opportunity" missions are not necessarily ESA-led and are on a smaller scale than "Core" missions. As part of the second cycle of Earth Explorers Opportunity Missions, three new candidate proposals were selected to enter Phase A (feasibility study) in May 2002. The three missions selected are ACE+, EGPM, and SWARM:

• ACE+ (Atmospheric and Climate Explorer)—a climatological mission that will measure variations and changes in global atmospheric temperature and water vapor.

• EGPM (European contribution to Global Precipitation Mission)—a mission element within an international initiative to measure precipitation (e.g., rain, snowfall) all over Earth every 3 hours.

• SWARM—a constellation of small satellites to study the dynamics of Earth's magnetic field and its interactions with the Earth system.

It is expected that the feasibility studies will be complete by mid-2004, after which two of the three missions will be selected for implementation. The launch of the first mission is envisaged for 2008.

Additional information is available online:
<http://www.esa.int/export/esaLP/ESAILYJE43D_ace_0.html>
<http://www.esa.int/export/esaLP/ESAGKZJE43D_egpm_0.html>
<http://www.esa.int/export/esaLP/ESA3QZJE43D_swarm_0.html>

TABLE C.1 Recently Launched and Upcoming Missions with U.S. Involvement

Mission	Instruments	Description[a]	Launch Date	Web Links
Advanced Earth Observation System II (ADEOS II)	The SeaWinds Radar Scatterometer Global Imager (GLI) Advanced Microwave Scanning Radiometer (AMSR) Improved Limb Atmospheric Spectrometer (ILAS II) Polarization and Directionality of the Earth's Reflectances (POLDER)	The SeaWinds scatterometer is a specialized microwave radar that measures near-surface wind velocity (both speed and direction) under all weather and cloud conditions over Earth's oceans. This is a twin sister to the QuikSCAT sensor and will fly on the Japanese ADEOS-II Spacecraft to provide similar observations beyond the QuikSCAT mission. The experiment is a follow-on mission and continues the data series initiated in 1996 by the NSCAT.	Launched November 2002	<http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index.php> <http://winds.jpl.nasa.gov/missions/seawinds/seaindex.html> <http://gaia.hq.nasa.gov/ese_missions/launch.cfm?lau_id=16>
The SOlar Radiation and Climate Experiment (SORCE)	Total Irradiance Monitor (TIM) Spectral Irradiance Monitor (SIM) Solar Stellar Irradiance Comparison Experiment (SOLSTICE) XUV Photometer System (XPS)	SORCE is a NASA-sponsored project that will provide Total Irradiance measurements and the full Spectral Irradiance measurements required by climate studies. The spectral measurements include ultraviolet, extreme ultraviolet, and the visible to near infrared. SORCE represents the merging of the EOS Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and the Total Solar Irradiance Mission (TSIM). SORCE observations provide understanding of the roles of Sun's variations on Earth's climate and potential impacts on public health.	Launched January 2003	<http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index.php> <http://lasp.colorado.edu/sorce/>

continues

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
Meteosat Second Generation (MSG)	Spinning Enhanced Visible and Infrared Imager (SEVIRI) The Geostationary Earth Radiation Budget (GERB) experiment	MSG is a joint project between ESA and EUMETSAT. ESA is developing and procuring the first satellite, MSG-1, and procuring MSG-2 and MSG-3 on behalf of EUMETSAT, which is developing the ground segment. EUMETSAT is also procuring the launchers and establishing user needs, and will run the system once it becomes operational. The first satellite, MSG-1 is due for launch on board an Ariane 5 launcher in August 2002. MSG-2 will follow on about 18 months later. MSG-3 will be built and put in storage until it is required to take over as MSG-1 nears the end of its life. Each satellite will have a nominal 7-year lifetime. A fourth MSG satellite of the same design is foreseen to ensure continuity of service until the end of the next decade.	Launched August 28, 2002	<http://www.esrin.esa.it/msg/> <http://www.esa.int/export/esaSA/GGGGEHCM8EC_earth_0.html>
Ice, Clouds, and Land Elevation Satellite (ICESat)	Geo-science Laser Altimeter System (GLAS)	ICESat provides a subset of the EOS measurements, primarily land, ice, and sea ice altimetry products with secondary products being cloud/aerosol lidar and land/vegetation altimetry. In particular the mission determines decadal variation of ice sheet thickness over Greenland and Antarctica, altitude and thickness of clouds, vegetation heights, land topography, and ocean surface and sea ice altimetry.	Launched January 2003	<http://icesat.gsfc.nasa.gov/> <http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index/php>

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
ICESat (cont'd)		The main scientific objective is to understand the role of polar regions in the Earth's climate and sea-level variations. Data can be used to measure the impact on coastal zone management from change in sea level, provide improved digital terrain for disaster management, measure invasive species management, aid in carbon management (biomass), and measure air quality.		
WindSat		WindSat is a polarimetric microwave radiometer developed by the U.S. Navy and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO) for measuring ocean surface wind speed and direction. WindSat will demonstrate the viability of using polarimetry to measure the wind vector from space and provide operationally usable tactical information to Navy units. The payload provides risk reduction data that the NPOESS IPO will use in the development of the Conical Microwave Imager Sounder (CMIS). WindSat is the primary payload on the DOD Space Test Program's Coriolis Mission.	Launched June 2003	<http://code8200.nrl.navy.mil/windsat.html>

continues

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
Meteorological Operational Polar Satellites of EUMETSAT (METOP)	Advanced Very High Resolution Radiometer (AVHRR/3) High Resolution Infrared Radiation Sounder (HIRS/4) Advanced Microwave Sounding Unit-4 (AMSU-4) Microwave Humidity Sounder (MHS) Infrared Atmospheric Sounding Interferometer (IASI) Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS)	METOP will gather essential global information by day and by night, about the atmosphere and the land and ocean surfaces. A primary task is to measure the temperature and the humidity of the global atmosphere, using instruments capable of sounding the atmosphere throughout its depth. A second important task is to obtain global images of clouds and weather systems, and information about the sea and land surfaces, including, in particular, ocean surface winds. Atmospheric ozone will also be monitored. In addition to these instruments, METOP will carry a data collection system to gather information from ground-based systems, support Search and Rescue services, and measure the local space environment. The responsibility for operations in polar orbit will be shared starting in 2005. This will establish the Initial Joint Polar System (IJPS) with NPOESS supporting the afternoon orbit and EUMETSAT responsible for the morning orbit.	2003 (estimated)	<http://www.eumetsat.de> <http://earth.esa.int/METOP.html>

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
Aura	Ozone Monitoring Instrument (OMI) Microwave Limb Sounder (MLS) Tropospheric Emission Spectrometer (TES) High Resolution Dynamics Limb Sounder (HIRDLS)	The Aura satellite hosts a suite of scientific instruments designed to make the most comprehensive measurements ever undertaken of atmospheric trace gases. Its objective is to study the chemistry and dynamics of the Earth's atmosphere with emphasis on the upper troposphere and lower stratosphere (0-30 km). The mission will measure ozone, aerosols, and several key atmospheric constituents that play an important role in atmospheric chemistry, air quality, and climate. United Kingdom and the Netherlands are providing instruments for this mission.	January 2004 (estimated)	<http://eos-chem.gsfc.nasa.gov/> <http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index/php>
CloudSAT	94 GHz Cloud Profiling Radar (CPR)	CloudSAT will use advanced radar to "slice" through clouds to see their vertical structure, providing a completely new observational capability from space. Current satellites can only image the uppermost layers of clouds. CloudSAT will be one of the first satellites to study clouds on a global basis. It will look at their structure, composition, and effects. This is a cooperative mission with Canada. Data from CloudSAT can be used for air quality determination, weather models, water management, aviation safety, and disaster management.	Spring 2004 (estimated)	<http://cloudsat.atmos.colostate.edu/> <http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index/php>

continues

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
CryoSat (Europe)	The SAR/ Interferometric Radar Altimeter (SIRAL)	CryoSat is a radar altimetry mission dedicated to the observation of the polar regions. Its aim is to study possible climate variability and trends by determining the variations in thickness of the Earth's continental ice sheets and marine sea ice cover.	2004 (estimated)	<http://www.esa.int/export/esaLP/ESAOMH1VMOC_cryosat_0.html>
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO)	High resolution wide field camera (WFC), covering 620-670-nm region 2-wavelength (532 nm and 1064 nm) polarization sensitive lidar Imaging Infrared Radiometer (IIR), at 8.7 micron, 10.5 micron, and 12.0 micron	CALIPSO will provide key measurements of aerosol and cloud properties needed to improve climate predictions. CALIPSO will fly a 3-channel lidar with a suite of passive instruments in formation with Aqua to obtain coincident observations of radiative fluxes and atmospheric conditions. CloudSat will also fly in formation with CALIPSO to provide a comprehensive characterization of the structure and composition of clouds and their effects on climate under all weather conditions. This comprehensive set of measurements is essential for accurate quantification of global aerosol and cloud radiative effects to understand their role in formation and variation of Earth's climate. This is a cooperative mission with France. Data from CALIPSO can aid in air quality determination, invasive species management, water management and conservation, early warning for homeland security, public health, and improved weather models.	Spring 2004 (estimated)	<http://www-calipso.larc.nasa.gov/> <http://eospso.gsfc.nasa.gov/eos_homepage/mission_profiles/index/php>

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
The Advanced Land Observing Satellite (ALOS) (NASDA)	Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) Phased Array type L-band Synthetic Aperture Radar (PALSAR)	ALOS is a Satellite following the Japanese Earth Resources Satellite-1 (JERS-1) and Advanced Earth Observing Satellite (ADEOS) which will utilize advanced land observing technology. The ALOS will be used for cartography, regional observation, disaster monitoring, and resource surveying.	2004 (estimated)	<http://www.nasda.go.jp/projects/sat/alos/index_e.html>
Stratospheric Aerosol and Gas Experiment III (SAGE III)		SAGE III is an improved extension of the successful Stratospheric Aerosol Measurement II (SAM II), SAGE I, and SAGE II experiments. The additional wavelengths and operation during both lunar and solar occultation that SAGE III provides will improve aerosol characterization; improve the gaseous retrievals of O_3, H_2O, and NO_2; add retrievals of temperature, pressure, NO_3 and OClO; extend the vertical range of measurements; provide a self-calibrating instrument independent of any external data needed for retrieval; and expand the sampling coverage. The SAGE III mission on the International Space Station seeks to enhance our understanding of natural and human-derived atmospheric processes by providing high latitude long-term measurements of the vertical structure of aerosols, ozone,	Launched 2001	<http://www-sage3.larc.nasa.gov>

continues

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
SAGE III (cont'd)		water vapor, and other important trace gases in the upper troposphere and stratosphere.		
New Millennium Program's Earth Observing 3 (NMP/EO3)	Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS)—Indian Ocean METOC Imager (IOMI)	GIFTS-IOMI incorporates the breakthrough technologies of an innovative atmospheric measuring concept developed at NASA's Langley Research Center. The GIFTS-IOMI objective is to demonstrate and flight qualify advanced technologies for application to future space missions and to provide better meteorological and atmospheric chemistry data products (results).	December 2005 (estimated)	<http://nmp.jpl.nasa.gov/eo3/about/about.html>
Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC)	GPS radio occultation receiver Tiny Ionospheric Photometer (TIP) Coherent Electromagnetic Radio Tomography (CERT) Tri-Band Beacon (TBB) transmitter	COSMIC is a joint Taiwan-U.S. space mission, with a plan to launch a constellation of six micro-satellites. Each satellite will carry three instruments: a Global Positioning System (GPS) radio occultation (RO) receiver, a Tiny Ionospheric Photometer (TIP), and a Tri-Band Beacon (TBB). The COSMIC constellation will provide up to 3,000 RO soundings that are distributed relatively uniformly around the Earth. The RO measurements can be used to derive the vertical profiles of temperature, moisture, and electron density. The TIP and TBB instruments will provide additional ionospheric measurements.	2005 (estimated)	<http://www.cosmic.ucar.edu> <http://www.nspo.gov.tw/e50/menu0304.html>

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
NPOESS Preparatory Project (NPP)		NPP will provide NASA with continuation of global change observations following Earth Observing System (EOS) TERRA and Aqua missions. These include measurements for the following: atmospheric and sea surface temperatures, humidity sounding, land and ocean biological productivity, and cloud and aerosol properties. In addition, NPP will provide the National Polar-orbiting Operational Environmental Satellite System (NPOESS) with risk reduction demonstration and validation for 3 of the 4 critical NPOESS sensors, algorithms, and processing (VIIRS, CrIS, and ATMS).	December 2005 (estimated)	<http://www.ipo.noaa.gov/Projects/npp.html>
Landsat Data Continuity Mission (LDCM)		LDCM is a joint NASA-United States Geological Survey (USGS) mission to extend the Landsat record of multispectral, 30-meter resolution, seasonal, global coverage of the Earth's land surface. However, neither NASA nor the USGS will produce, procure, or operate a spacecraft. Rather, science data will be procured from a vendor who fulfills the requirements of the LDCM Data Specification. The means or mechanism for acquiring those data are at the discretion of the vendor, subject to verification by the government that the proposed approach can produce the data and data products specified. Vendor selection is expected during the first half of calendar 2003.	2005 (estimated)	<http://ldcm.nasa.gov/> <http://ldcm.usgs.gov/>

continues

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
The Soil Moisture and Ocean Salinity (SMOS) Mission (Europe)	MIRAS (Microwave Imaging Radiometer using Aperture Synthesis) passive L-band 2D-interferometer	The overall objectives of the SMOS mission are to provide global observations of two crucial variables for modeling the weather and climate, Soil Moisture and Ocean Salinity. It will also monitor the vegetation water content, snow cover, and ice structure.	2007 (estimated)	<http://www.esa.int/export/esaLP/smos.html>
Global Precipitation Measurement (GPM)	Dual-frequency Precipitation Radar (DPR)—Primary Satellite GPM Microwave Imager (GMI) Various passive microwave radiometers	GPM is a joint mission with the National Space Development Agency (NASDA) of Japan and other international partners. Building upon the success of the Tropical Rainfall Measuring Mission (TRMM), it will initiate the measurement of global precipitation, a key climate factor. Its science objectives are: to improve ongoing efforts to predict climate by providing near-global measurement of precipitation, its distribution, and physical processes; to improve the accuracy of weather and precipitation forecasts through more accurate measurement of rain rates and latent heating; and to provide more frequent and complete sampling of Earth's precipitation.	2007 (estimated)	<http://gpm.gsfc.nasa.gov>
The Gravity Field and Steady-State Ocean Circulation Mission (GOCE) (Europe)		GOCE is intended to provide the unique data set required to formulate global and regional models of Earth's gravity field and the geoid (its reference equipotential surface) to high spatial resolution and accuracy. It will also advance research in the fields of steady-state ocean circulation, physics of Earth's interior and leveling systems (based on GPS).	2006 (estimated)	<http://www.esa.int/export/esaLP/ESAYEK1VMOC_goce_0.html>

TABLE C.1 Continued

Mission	Instruments	Description[a]	Launch Date	Web Links
Triana	Advanced Whole Earth Radiometer A suite of small, next-generation space weather monitoring instruments Scripps EPIC (Earth Polychromatic Imaging Camera)	Triana uses the Sun-Earth libration point (1,000,000 km away from Earth) to continuously observe the Earth. This is a cooperative project between the offices of Earth and Space science.	To be determined	<http://triana.gsfc.nasa.gov/home/>
Vegetation Canopy Lidar (VCL)	Multi-Beam Laser Altimeter (MBLA)	The principal goal of the Vegetation Canopy Lidar (VCL) mission is the characterization of the three-dimensional structure of the Earth. The two main science objectives are: (1) Land cover characterization for terrestrial ecosystem modeling, monitoring and prediction, and climate modeling and prediction, and (2) Global reference data set of topographic spot heights and transects.	2020	<http://www.geog.umd.edu/vcl>

[a]All mission descriptions are quoted from the Web sites listed in the “Web Links” column and accessed in May 2003.

D

Biographical Information for Committee Members

Richard A. Anthes (*Chair*), president of the University Corporation for Atmospheric Research, is an atmospheric scientist, author, educator, and administrator. His research interests include weather phenomena, such as tropical cyclones, and remote sensing using the Global Positioning System. Following a faculty position at Pennsylvania State University, he joined the National Center for Atmospheric Research (NCAR), first as director of the Atmospheric Analysis and Prediction Division, then as director of NCAR. Dr. Anthes has published more than 90 articles and books. He chaired the National Research Council (NRC) Committee on National Weather Service Modernization and has served on numerous other NRC committees and boards, including the Board on Atmospheric Sciences and Climate (1986-1989) and the Committee on Earth Studies (1982-1984).

Susan K. Avery (*Vice Chair*) is professor of electrical and computer engineering at the University of Colorado and director of the Cooperative Institute for Research in Environmental Sciences. Her research program utilizes ground-based Doppler radar techniques for observing the neutral atmosphere. Current research topics of her program include studies of wave dynamics and wave interactions between scales of motion; the coupling of energy and momentum from the lower to the upper atmosphere; and precipitation structure using combined radar measurements. Dr. Avery has served as chair of the U.S. National Committee for the International Union of Radio Science (USRI); chair of the National Science Foundation's Geosciences Advisory Committee; scientific discipline representative and URSI representative for the Scientific Committee on Solar-Terrestrial Physics; and commissioner of the American Meteorological Society (AMS). She is also a fellow of the AMS and of the Institute for Electrical and Electronics Engineers and a member of the National Research Council's Board on Atmospheric Sciences and Climate.

Mark R. Abbott is dean of the College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, where he has been a professor since 1988. His research, which focuses on the interaction of biological and physical processes in the upper ocean, relies on both remote sensing and field observations. Dr. Abbott deployed the first array of bio-optical moorings in the Southern Ocean as part of the U.S. Joint Global Ocean Flux Study (JGOFS). He chairs the U.S. JGOFS Science Steering Committee and is also a member of the Moderate-resolution Imaging Spectrometer (MODIS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) science teams. He was a member of the Space Studies Board and chaired its Committee on Earth Studies.

Grant C. Aufderhaar is principal director and distinguished engineer at The Aerospace Corporation, where he directs aerospace research and development in support of national security space programs. His technical expertise lies in the areas of environmental effects, satellite-based and in situ remote sensing technology, and the application of space systems data to user needs. During his tenure in the Air Force, Dr. Aufderhaar served as the Department of Defense (DOD) representative on the National Research Council's (NRC's) Board on Atmospheric Sciences and Climate and was a member of the Interdepartmental Committee for Meteorological Services and Supporting Research. While at The Aerospace Corporation, he has served as chair of the R&D Panel of the NRC Committee on National Aviation Weather, was a member of the Air Force Scientific Advisory Board (AFSAB) Space Review Vehicles Panel, was a member of the AFSAB Commercial Space Services Panel, and served as chair of the DOD Battlespace Environments Technology Area Review and Assessment Panel.

George L. Frederick is general manager, Windprofiler Business Unit, Vaisala Meteorological Systems, Inc. He manages a strategic business unit of Vaisala involved with atmospheric projects that include design, installation, and data processing of atmospheric measurement systems employing both in situ and remote sensing techniques. He is working with government, state, and private industry to better employ remote sensing technology for the enhanced monitoring of atmospheric pollutants, aviation safety, and mesoscale weather forecasting. Mr. Frederick a fellow and past president (1999-2000) of the American Meteorological Society.

Russell Koffler provides consultant services to clients in the area of Earth observations. He formerly served as deputy assistant administrator for Satellites and Information Services, the chief operating officer of NOAA's National Environmental Satellite, Data, and Information Service. In this position, Mr. Koffler managed the federal government's civil operational Earth-observing satellite systems and the principal national environmental data centers. As Very High Resolution Radiometer project coordinator, he was responsible for developing and implementing the ground data processing system for NOAA's first high-resolution visible and infrared satellite instrument. Mr. Koffler is a recipient of the Department of Commerce 1986 Silver Medal and is a senior member of the American Institute of Aeronautics and Astronautics. He is a member of the American Meteorological Society, the Association for Computing Machinery, and the American Society for Photogrammetry and Remote Sensing.

Peter R. Leavitt is president of Weather Information, Inc. Previously, he was chief executive officer of Weather Services Corporation and held several other positions with the company. He is active in several professional associations and has served on various National Research Council committees, including the National Weather Service Modernization and Transition Committee (chair), the Committee on Modernization of the National Weather Service, and the Committee on Aviation Weather Services. Mr. Leavitt has served as president of the Boston chapter of the American Meteorological Society (AMS) and has participated in numerous AMS committees. He is the recipient of the AMS Award for Outstanding Contribution to the Advance of Applied Meteorology.

William L. Smith is chief scientist for atmospheric sciences at NASA Langley Research Center where he plans, directs, and coordinates research, technology, and science programs dealing with the problems of Earth's atmosphere. Previously, Dr. Smith was a principal investigator of several satellite programs for NOAA and was professor of atmospheric and oceanic sciences at the University of Wisconsin, Madison. Currently, he is lead scientist for the Geosynchronous Imaging Fourier Transform Spectrometer, which will fly on NASA's Earth Observing-3 mission in 2005. Dr. Smith is past president of the International Radiation Commission of the International Association for Meteorology and Atmospheric Physics, and he has received the American Meteorological Society's Clarence Leroy Meissinger Award. He served on the Panel on Mesoscale Research of the National Research Council's Board on Atmospheric Sciences and Climate.

Richard W. Spinrad is technical director of the Office of the Oceanographer of the Navy, and his supervisor sits as the naval deputy to NOAA. As the technical director, Dr. Spinrad is the senior civilian technical adviser to the Navy's meteorological and oceanographic (METOC) organization, ensuring that the technical elements of naval oceanography programs are adequate, realistic, and consistent with established policy. He is also the Oceanographer's principal adviser on scientific and technical issues and is a key liaison to the military and civilian METOC communities.

Paul D. Try is senior vice president and program manager at Science and Technology Corporation and director of the International Global Energy and Water Cycle Experiment Project Office. Dr. Try served in the U.S. Air Force from 1960 through 1988, during which time he rose to the position of chief of staff of Air Weather Service headquarters. He has more than 30 years of federal and private sector experience in operational meteorological services and supporting research and has provided direct support to several federal organizations in technical program planning and requirements definition. His special expertise is in meteorological in situ and remote sensors (satellite and radar), as well as in national and international data collection, processing, exchange, and archival activities. In addition, Dr. Try served as president of the American Meteorological Society and received the Bronze Star, Defense Superior Service Medal, and the Legion of Merit.

Christopher S. Velden is a physical science senior researcher in the Space Science and Engineering Center at the University of Wisconsin, Madison. His current research interests include hurricanes and tropical cyclones and satellite data applications. Mr. Velden is also leader of the Tropical Cyclones Group at University of Wisconsin, Madison, and NOAA's Cooperative Institute for Meteorological Satellite Studies and chair of the International Satellite Winds Working Group. He served as a member of the U.S. Weather Research Project Science Steering Committee (1996-1999), the GOES Science Team (1996-1998), and the Geostationary Microwave Sounder Working Group (1995-1996). Mr. Velden was the recipient of the American Meteorological Society's Banner Miller Award in 2000 for "an outstanding contribution to the science of hurricane and tropical weather forecasting."

Committee on Earth Studies Liaisons

Michael H. Freilich is a professor in the College of Oceanic and Atmospheric Sciences at Oregon State University. His research interests include microwave ocean remote sensing, especially surface wind measurement and analysis techniques; surface wave modeling; and nearshore processes. His current research focuses on development of empirical models relating radar backscatter to near-surface winds; characterization of centimetric ocean surface roughness and atmospheric mesoscale phenomena using satellite measurements; and development and application of advanced statistical validation techniques. Dr. Freilich heads the Ocean Vector Wind Science Team on NASA's QuikSCAT mission. (QuikSCAT is a "quick recovery" mission—accomplished in 11 months—that is filling the gap created by the loss of data from the NASA Scatterometer [NSCAT]). Dr. Freilich served on the National Research Council's Ocean Studies Board (1992-1995). He was also a member of the Panel on the NOAA Coastal Ocean Program (1993-1994).

William B. Gail is director, Advanced Programs for Earth Science, Ball Aerospace and Technologies Corporation. Dr. Gail is responsible for business development and proposal activities for NASA, NOAA, and international customers covering instruments, spacecraft, and space systems in the areas of earth sciences.

Staff

Carmela J. Chamberlain is a senior project assistant for the Space Studies Board. She began working for the National Research Council in 1974 as a senior project assistant in the Institute for Laboratory Animals for Research, which is now a board in the Division on Earth and Life Studies. In 1977 she transferred to the Space Science Board, which is now the Space Studies Board.

Catherine A. Gruber has been a senior project assistant with the National Research Council's Space Studies Board since 1995, working part-time for the past 5 years on report preparation and archiving. Ms. Gruber came to the NRC in 1988, working first as a senior secretary for the Computer Science and Telecommunications Board and then as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. Previously, she was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology. She received a B.A. in natural science from St. Mary's College of Maryland.

Richard Leshner is a research associate for the Space Studies Board and a Ph.D. candidate in science and technology policy at the George Washington University in Washington, D.C. Mr. Leshner worked as a space systems engineer focusing on the integration of power, heating, and propulsion systems before coming to the National Research Council. In addition to a general interest in space policy, Mr. Leshner's research interests include the history and progress of satellite programs in the Earth sciences, international cooperation in space, export control policy and the politics of defense trade controls, the theory and practice of technology transfer, and the role of interest groups in the policy-making process.

Pamela L. Whitney is a senior program officer at the Space Studies Board, where she has directed studies and workshops on international cooperation in space, remote sensing from space and its applications, and several other space research, technology, and policy topics. Ms. Whitney also serves as the executive secretary of the U.S. national committee to the Committee on Space Research (COSPAR), an interdisciplinary committee of the International Council for Science (ICSU). Previously, she held positions as an analyst at CSP Associates, Inc., an aerospace consulting firm; as a researcher and writer for Time-Life Books, Inc.; and as a contractor for the National Geographic Society, the World Bank, and the Office of Technology Assessment. Ms. Whitney holds an A.B. in economics from Smith College and an M.A. in international communication from American University. She is a member of Women in Aerospace and the International Academy of Astronautics.

E

Acronyms

ADEOS	Advanced Earth Observation Satellite
ADM	Atmospheric Dynamics Mission
AFGWC	Air Force Global Weather Center
AIRS	Atmospheric Infrared Radiation Sounder
ALADIN	Atmospheric Laser Doppler Instrument
AMSU	Advanced Microwave Sounder Unit
AO	Announcement of Opportunity
APS	Aerosol Polarimetry Sensor
ASCAT	Advanced Scatterometer
ASOS	Automated Surface Observing System
ATMS	Advanced Technology Microwave Sounder
AWS	Air Weather Service
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CERSAT	Centre ERS d'Archivage et de Traitement
CMIS	Conical Microwave Imager/Sounder
CNES	Centre National d'Etudes Spatiales
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CRD	Capstone Requirements Document
CrIS	Cross-track Infrared Sounder

DIAL	Differential Absorption Lidar
DMSP	Defense Meteorological Satellite Program
DMSP (SPO)	DMSP Systems Program Office
DOD	Department of Defense
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EADM	European Atmospheric Dynamics Mission
ECMWF	European Centre for Medium-Range Weather Forecasts
EDR	environmental data record
EIS	Earth Information System
EMC	Environmental Modeling Center
ENVISAT	Environmental Satellite
EOS	Earth Observing System
EPA	Environmental Protection Agency
ERS	European Remote Sensing satellite
ESA	European Space Agency
ESE	Earth Science Enterprise
ESSA	Environmental Science Services Administration
ESSP	Earth System Science Pathfinder
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
EXCOM	Executive Committee
FAA	Federal Aviation Administration
GAO	General Accounting Office
GEOS	Goddard Earth Observing System
GIFTS	Geosynchronous Imaging Fourier Transform Spectrometer
GIFTS-IOMI	GIFTS Indian Ocean METOC (Meteorology and Oceanography) Imager
GMES	Global Monitoring for Environmental Security
GOES	Geostationary Operational Environmental Satellite
GOES-NEXT	Geostationary Operational Environmental Satellite–Next Generation
GPM	Global Precipitation Measurement
GPS	Global Positioning System
GPS/MET	Global Positioning System/Meteorology
GPSOS	Global Positioning System Occultation Sensor
GRACE	Gravity and Climate Experiment
GSFC	Goddard Space Flight Center

HIRS	High-resolution Infrared Radiation Sounder
IASI	Interferometer Atmospheric Sounding Instrument
ICESat	Ice, Clouds, and Land Elevation Satellite
IFREMER	French Research Institute for Exploitation of the Sea
IORD	Integrated Operational Requirements Document
IPO	Integrated Program Office
IR	infrared
ITO	Interagency Transition Office
ITOS	Improved TIROS Operational Satellite
IV&V	Independent Verification and Validation
JCSDA	Joint Center for Satellite Data Assimilation
JHT	Joint Hurricane Testbed
lidar	light detection and ranging
LIS	Lightning Imaging Sensor
LLWAS	Low-Level Wind Shear Alert System
LMS	Lightning Mapper Sensor
METOP	Meteorological Operational Polar satellites of EUMETSAT
MHS	Microwave Humidity Sounder
MNS	Mission Needs Statement
MODIS	Moderate-resolution Imaging Spectroradiometer
MOU	Memorandum of Understanding
MSU	Microwave Sounding Unit
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NCAR	National Center for Atmospheric Research
NCDC	National Climate Data Center
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service (NOAA)
NESS	National Environmental Satellite Service
NHC	National Hurricane Center
Nimbus	NASA environmental research satellite series
NMC	National Meteorological Center
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration

NOAA SEC	NOAA Space Environment Center
NOMSS	National Operational Meteorological Satellite System
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NRO	National Reconnaissance Office
NROSS	Navy Remote Ocean Sensing System
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NWP	Numerical Weather Prediction
NWS	National Weather Service
OFCM	Office of the Federal Coordinator for Meteorology
OLS	Operational Linescan System
OMB	Office of Management and Budget
OMPS	Ozone Mapping and Profiler Suite
ORD	Operational Requirements Document
OSE	Observing System Experiment
OSIP	Operational Satellite Improvement Program
OSTM	Ocean Surface Topography Mission
OTA	Office of Technology Assessment
OTD	Optical Transient Detector
PI	principal investigator
PMR	Pressure-Modulator Radiometer
POES	Polar-orbiting Operational Environmental Satellite
QuikSCAT	Quick Scatterometer
QuikTOMS	Quick Total Ozone Mapping Spectrometer
R&D	research and development
RCA	Radio Corporation of America
RMS	root mean square
RO	radio occultation
S^3	Satellite Surface Stress
SAR	synthetic aperture radar
SASS	Seasat-A Satellite Scatterometer
SCAMS	Scanning Microwave Spectrometer

SDR	sensor data record
SDRR	System Definition and Risk Reduction
SE&TD	Systems Engineering and Technical Direction
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SEC	Space Environment Center
SEI	Special Events Imager
SESS	Space Environment Sensor Suite
SIRS	Solar Infrared Radiation Station
SMOP OR	Operational Requirement for Satellite Measurement of Oceanographic Parameters
SPO	System Program Office
SSM/I	Special Sensor Microwave/Imager
SXI	Solar X-ray Imager
SXT	Solar X-ray Telescope
TDRS	Tracking and Data Relay Satellite
TDWR	Terminal Doppler Weather Radar
TIROS	Television Infrared Observation Satellite
TMI	TRMM Microwave Imager
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TOS	TIROS Operational System
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USWRP	U.S. Weather Research Program
UW	University of Wisconsin
UV	ultraviolet
VAS	VISSR Atmospheric Sounder
VHRR/AVHRR	Very High Resolution Radiometer/Advanced VHRR
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIRS	Visible Infrared Scanner
VISSR	Visible and Infrared Spin Scan Radiometer
VOLCAM	Volcanic Ash Mapper
VTPR	Vertical Temperature Profile Radiometer

WSOA	Wide Swath Ocean Altimeter
WSR88-D	Weather Surveillance Radar-1988 Doppler