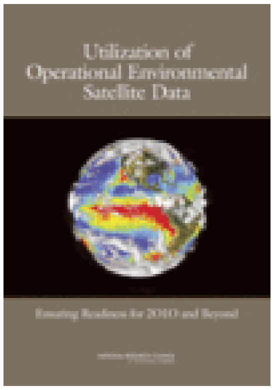

Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond

Committee on Environmental Satellite Data Utilization,
National Research Council

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Utilization of Operational Environmental Satellite Data

Ensuring Readiness for 2010 and Beyond

Committee on Environmental Satellite Data Utilization

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Foreword

One of the principal functions of the Space Studies Board and the Aeronautics and Space Engineering Board is to anticipate problems and offer advice on how the relevant federal agencies can position themselves to avoid or mitigate particular issues. This report, *Utilization of Operational Environmental Satellite Data: Ensuring Readiness for 2010 and Beyond*, is very much in that spirit.

The issue addressed by this report is threefold. We are ever more in need of being good stewards of our planetary home. We have as a potential resource the increasing availability of useful and important environmental data, particularly from space. We have an ever-broadening community of users who, armed with the knowledge of our environmental past and present, can effectively apply this knowledge to improve their own lives and advance the public good. The question is how to link the need, the availability of data that can offer solutions, and the users who can apply these data.

This report offers useful advice particularly to the National Oceanic and Atmospheric Administration, which has an increasingly important role in acquiring, but also in processing and archiving, environmental data and making it available to the broad and growing community of diverse users.

Lennard A. Fisk, *Chair*
Space Studies Board

Preface

In 2001, following a National Research Council (NRC)-National Oceanic and Atmospheric Administration (NOAA) workshop on opportunities for NOAA's environmental satellite program, then Space Studies Board Chair John H. McElroy sent a letter to Gregory W. Withee, Assistant Administrator for NOAA's Satellite and Information Services, outlining three potential studies (see Appendix A).

After discussions with NOAA and NASA the Committee on Environmental Satellite Data Utilization was established to address the following tasks (see Appendix B):

1. Review the likely multiplicity of uses of environmental data collected by the nation's operational environmental satellites, both in terms of the disciplinary applications of the data (e.g., research, operations, meteorology, hydrology, oceanography, rivers, coasts, fisheries, hydrology, agriculture, space weather) and in terms of the institutional or organizational origins of the users (e.g., intra-governmental (at all levels), international, regional, researchers, for-profit, non-profit, and educational entities).

2. Characterize the likely interfaces between NOAA as a data provider and the range of data users, as well as third-party "added-value" commercial and non-profit users who broker applications by converting the data to a more usable form.

3. Assess the implications of these multidirectional interfaces in terms of needs for (a) data accessibility and quality, (b) compatibility and cross-accessibility with data from other government sources, (c) data volume, (d) information technology, (e) user education, and (f) user participation in planning and performance feedback.

4. Identify critical factors that may drive the evolution of data management responsibilities in areas such as real-time processing; data stream transparency, traceability, access, and characterization; data archiving and retrieval; and reprocessing.

5. Recommend appropriate approaches to secure the engagement of the science and applications community in successfully dealing with the challenges identified in the tasks above and in enhancing the utilization of both active short-term and long-term NOAA data archives.

This report presents the conclusions and recommendations developed by the committee in response to these tasks.

For their help in making its study possible, the committee acknowledges the many individuals who provided briefings and background material. They include:

Richard Anthes, Chair of the NRC Committee on NASA-NOAA Transition from Research to Operations and President of the University Corporation for Atmospheric Research;
Ghassem Asrar, Associate Administrator, NASA;
John J. Bates, Chief, Remote Sensing Applications Division, National Climatic Data Center;
William Belton, Assistant Remote Sensing Program Manager, USDA Forest Service;
Robert “Buzz” Bernstein, SeaSpace, Inc;
Marie Colton, Director, Office of Research and Applications, NOAA/NESDIS;
Stanley Cutler, NOAA Consultant/Mitretek;
Gerald Dittberner, Chief, Advanced System Planning Division, NOAA Satellite and Information Service;
James Dodge, Research Division, Earth Science Enterprise, NASA;
Bradley Doorn, Remote Sensing Specialist, Production Estimates and Crop Assessment Division, Foreign Agricultural Service, USDA;
Robert Feden, Chief of Staff, Office of the Special Assistant, Office of the Assistant Secretary of Defense (Networks and Information Integration)/Department of Defense, Chief Information Officer;
Mitch Goldberg, Chief, Satellite Meteorology and Climatology Division, Office of Research and Applications, NOAA;
Geoffrey Goodrum, NOAA/NESDIS;
Tony Hollingsworth, Head of Research, ECMWF;
David Jones, President and CEO, StormCenter Communications, Inc.;
Thomas R. Karl, Satellite and Information Services Director, National Climatic Data Center, NOAA;
Christopher Lynnes, Systems Engineer, Goddard Earth Sciences Distributed Active Archive Center;

Stephen Mango, Chief Scientist, NPOESS Integrated Project Office, NOAA;
Ronald McPherson, Executive Director, American Meteorological Society;
Paul Menzel, NESDIS/NOAA;
Michael Moore, Dawn Lowe, Curt Schroeder, and Steve Fox, Raytheon;
Michael Mussetto, NPOESS SSPR Project Scientist;
H.K. Ramapriyan, R. Ullman, and K. McDonald, NASA Goddard Space Flight Center;
Richard G. Reynolds, Chief, Ground Systems Division, Office of Systems Development, NOAA/NESDIS;
Hans-Peter Roesli, Swiss Federal Office of Meteorology and Climatology (MeteoSvizzera);
Gary Route, NPOESS IDPS Chief Engineer;
Stanley Schneider, IPO/NASA;
Edward Sheffner, Applications Division, Earth Science Enterprise, NASA;
James Silva, Manager, NPOESS Data Exploitation Project and NPOESS Implementation Manager, Office of Systems Development;
Howard J. Singer, Chief, Research and Development Division, NOAA Space Environment Center;
Gurindar Sohi, University of Wisconsin;
John Townshend, Chair, Geology Department, University of Maryland, College Park;
Jeffrey Tu, NPOESS System Architecture Lead;
Louis Uccellini, Director, National Centers for Environmental Prediction, National Weather Service, NOAA;
Eric Webster, Majority Staff Director, Subcommittee on Environment, Technology, and Standards, House Science Committee;
David Williams, Head of Strategic Planning and International Relations, EUMETSAT;
Gregory Williams, Senior Policy Analyst, Earth Science Enterprise, NASA;
Gregory W. Withee, Associate Administrator for Satellite and Information Services, NOAA; and
Helen M. Wood, Director, Office of Satellite Data Processing and Distribution, NOAA Satellite and Information Service.

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the 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 participation in the review of this report:

Grant C. Aufderhaar, The Aerospace Corporation,
Ana P. Barros, Duke University,
Jim Gray, Microsoft Bay Area Research Center,
Bruce D. Marcus, TRW (retired),
John H. McElroy, University of Texas, Arlington (retired),
J. Bernard Minster, University of California, San Diego, and
Robert J. Serafin, National Center for Atmospheric Research.

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 Roberta Balstad, CIESIN, Columbia University, and

William G. Agnew, General Motors Corporation (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.

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APPENDIXES

Executive Summary

There is no doubt that environmental satellite data have grown to be the most important source of information for daily global weather forecasting. In addition, these data are now also used by innumerable professionals and laypersons in pursuits as varied as oceanic, atmospheric, terrestrial, and climate research; environmental monitoring; aviation safety; precollege science education; and rapid-response decision support for homeland security, to name just a few. Compounding the pressure put on NOAA and NASA by expanding user communities to provide high-quality data products around the clock is the precarious state of the underfunded satellite data utilization program, which is struggling to keep up with demand for currently available data and the rapidly increasing sophistication of user requirements. The planned next-generation operational satellite systems, comprising both polar-orbiting and geostationary platforms, are designed to meet the needs of user communities whose complex applications are rapidly evolving.

Although the focus of this report is the use of satellite data for civilian rather than defense or national security purposes, a dual-use approach is expected as military and civilian satellite systems converge. The new systems will continue the record of climate-quality observations, but the increase in raw data will be unprecedented—perhaps an order-of-magnitude increase every 2 to 3 years. Expected to develop as a result of this expanded Earth-observing capability are novel ways of using satellite data that will have an increasing impact on citizens' daily lives. Thus satellite data providers will have to continuously evolve, revise, and in some cases radically redefine their role as well as plan for increased research, operations, and infrastructure. The high-level training required by such personnel and the continuing education of users are equally important and also must be planned and provided for.

Meeting the challenges posed by the imminent and unprecedented exponential increase in the volume of satellite-system data requires an end-to-end review of current practice, including characterization of process weaknesses, an assessment of resources and needs, and identification of critical factors that limit the optimal management of data, plus a strategic analysis of the optimal utilization of environmental satellite data.

In this report, the Committee on Environmental Satellite Data Utilization (CESDU) offers findings and recommendations aimed at defining specific approaches to resolving the potential overload faced by the two agencies—NOAA and NASA—responsible for satellite data (see the preface for the committee's statement of task). The committee has focused on the end-to-end utilization of environmental satellite data by characterizing the links from the sources of raw data to the end requirements of various user groups, although, given its limited scope, the committee could not thoroughly examine every link in the chain. CESDU's goal is to characterize and provide sensible recommendations in three areas, namely, (1) the value of and need for environmental satellite data, (2) the distribution of environmental satellite data, and (3) data access and utilization. The committee's findings are based on its members' knowledge of trends in technology; past lessons learned; users' stated requirements; and other supporting information. The committee hopes that this report will help NOAA and NASA identify and avoid impediments to optimal utilization of environmental satellite data.

Over the course of meetings held to collect information for this report, the committee heard presentations from several key agencies and organizations reflecting a broad range of professional perspectives. From these it distilled four consistent and recurring themes that significantly shaped its final findings and recommendations:

- A growing and diverse spectrum of individuals, companies, and agencies routinely utilize and depend on environmental satellite data and information;
- Products that best serve the public, together with effective use of public funds, create an ongoing evolution of requirements for data imposed on and by operational users;
- Improvements in available flight and ground technologies are being made that meet these new requirements—as demonstrated by research satellite missions and aircraft flights; and
- NOAA is committed to the collection of data with improved quality, reliability, latency, and information content.

The value of environmental satellite data derives from the unique, near-real-time, continuous global coverage from space of Earth's land and ocean surfaces and its atmosphere—value that increases significantly as we accumulate satellite records that provide a historical perspective. In addition, the committee believes that, in the near future, environmental satellite data will be employed by a much wider spectrum of users—from individuals with real-time weather data displays in their home, car, truck, boat, plane, business, or campsite, to a wide range of companies with value-added products developed from those data, to farmers, mariners, truckers, and aviators dependent on weather, to numerical modeling centers that provide weather, crop, fire, drought, flood, health, climate, and other predictions and alerts. Indeed, evidence presented to the committee strongly suggests that we should look to and prepare for a future in which cable TV, wireless networks, personal digital assistants, direct satellite broadcast, and the Internet enable continuous, uninterrupted access to environmental satellite data, information, and knowledge as an essential element of commerce, recreation, and the conduct of everyday life for the majority of people.

Thus it will not be sufficient merely to collect greater amounts of environmental satellite data, although the expected orders-of-magnitude increase in the volume of collected data will in itself pose special challenges. The committee heard testimony about increasing requirements to recover more of the information content in the data, and also about an anticipated increase in the number and diversity of environmental satellite data users who will demand instantaneous access to the particular data and information they want. To achieve improved utilization of environmental satellite data will therefore require that as much effort and planning be devoted to the ground systems serving this user community as to the flight systems that originally collect the data. To successfully realize the future outlined above, the agencies responsible for archiving and distributing environmental satellite data must develop the essential visions, plans, and systems. The following findings of the committee and the recommendations based on them are offered to help NASA and NOAA in that process.

THE VALUE OF AND NEED FOR ENVIRONMENTAL SATELLITE DATA

Finding: Improved and continuous access to environmental satellite data is of the highest priority for an increasingly broad and diverse range of users. Their needs include real-time imagery for decision making in response to events such as forest fires, floods, and storms; real-time data for assimilation into numerical weather prediction models; recent imagery for assessment of crops and determination of impacts on the environment resulting from diverse human activities such as marine and land transportation; and data coverage spanning many

years that allows assessment of patterns and long-term trends in variables, such as sea-surface temperature, land use, urbanization, and soil moisture. Users of environmental satellite data include individuals; federal government agencies; state and local managers, planners, and governments; commercial producers of added-value products; and Web, print, and TV/radio broadcasters.

Recommendation 1: To best serve the diverse user communities and to meet growing demand, the committee recommends that, as soon as is practical, agencies providing environmental satellite data and products collaborate, with NASA and NOAA taking the lead, to develop an explicit strategy and implementation plan for data distribution systems, user interfaces, and increased user engagement and education. The goals of this plan should be to facilitate access to current, historical, and future environmental satellite data and products in ways that acknowledge the range of skills and evolving needs of the user communities and to support these users by providing appropriate supporting information and educational material.

Finding: The national and individual user requirements for multiyear climate system data sets from operational environmental satellites, as currently delineated in the Climate Change Science Program strategic plan,[1] are placing special demands on current and future data archiving and utilization systems. These demands include more stringent requirements for accurate cross-platform radiometric calibration, new combinations of multiple satellite and instrument data, and algorithms for generating advanced biophysical variables. Detecting climate change trends often involves evaluating data at the limits of measurement precision, and so periodic, absolutely consistent reprocessing of climate data records is a fundamental requirement.

Recommendation 2: Creating climate data records (CDRs),[2] which quantify subtle but important global change trends, is not a task that can be accom-

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[1] U.S. Climate Change Science Program, *Strategic Plan for the U.S. Climate Change Science Program: A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*, available at http://www.climatescience.gov/Library/stratplan2003/default.htm, accessed July 12, 2004.

[2] A preliminary report by the NRC's Board on Atmospheric Sciences and Climate (*Climate Data Records from Environmental Satellites: Interim Report*, National Academies Press, Washington, D.C., 2004, page 1) defines a climate data record as "a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change." The report adds, "In addition we further segment satellite based CDRs into Fundamental CDRs (FCDRs) which are calibrated and quality controlled sensor data that have been improved over time, and Thematic CDRs (TCDRs), which are geophysical variables derived from the FCDRs, such as sea surface cloud temperature and cloud fraction."

plished solely in routine operational environments (such as with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and Geostationary Operational Environmental Satellite (GOES)). The committee recommends that NASA, along with NOAA, select multidisciplinary, research-oriented, end-to-end science teams that will select those NPOESS, GOES, and other systems' data products and variables that are scientifically important and technologically feasible for long-term CDR development. These science teams will design and maintain a proactive strategy for the stewardship and multidecadal production of the selected CDRs.

Finding: NOAA has limited experience with land data sets because historically its mission has focused on the oceans and atmosphere. Major advances in land remote sensing have occurred in the last decade, fostered primarily by the Earth Observing System developed by NASA, that are not reflected in NPOESS planning. The committee found that NOAA has so far not effectively utilized current satellite technologies and data sets for vegetation science, management, or applications. For example, of 58 environmental data records (EDRs) defined for NPOESS, only 6 are specifically for land, and of these only 2 are vegetation oriented. For the 2012 flight of GOES-R, only 20 of the approximately 170 environmental observation requirements (EORs) are land-surface related; of these, only 4 are vegetation related.

Recommendation 3: NOAA should convene an intergovernmental committee with NASA, the U.S. Department of Agriculture, the Department of the Interior, the Environmental Protection Agency, and other interested parties to select the variables for land vegetation data for generation from NPOESS, GOES, and other operational systems that will have high utility for both land management and the hydroecological sciences.

THE DISTRIBUTION OF ENVIRONMENTAL SATELLITE DATA

Finding: The constellations of satellites now in space and planned for the future include platforms launched by several nations, and more complete and comprehensive coverage of environmental data fields can be achieved by combining the data from these different national efforts.

Recommendation 4: The U.S. Environmental Satellite Data Program should work to facilitate user access to data from other nations' satellites as well as its

own and to facilitate synthesis of data across platforms by providing supporting metadata.

Finding: The Comprehensive Large Array-data Stewardship System is being designed by NOAA to catalog, archive, and disseminate all NOAA environmental satellite data produced after 2006. Given the magnitude of this effort—and considering the growing volume, types, and complexity of environmental satellite data; the increasingly large and diverse user base; and expectations for wider and more effective use of the data—the committee emphasizes the importance of NOAA's (1) having a comprehensive understanding of the full scope of the technical requirements for data cataloging, archiving, and dissemination and (2) ensuring implementation based on that knowledge. Key to successful implementation of a strong system that will serve operational users and the nation well are detailed planning, proactive follow-through, and NOAA's incorporation of lessons learned from previously developed, similarly scaled initiatives with similar systems requirements.

Recommendation 5:

a. NOAA should conduct an immediate review of the entire Comprehensive Large Array-data Stewardship System (CLASS) program. This review should aggressively solicit and incorporate recommendations from the designers, builders, operators, and users of similar systems, particularly those systems comprised by the Earth Observing System Data and Information System.

b. CLASS should be designated and developed as NOAA's primary data archive system for environmental satellite data and other related data sets. NOAA should ensure that CLASS is designed to adequately serve the full spectrum of potential environmental satellite data users. In addition to end users, CLASS should be designed to disseminate data to the broadest possible community of data brokers and value-added providers. The CLASS architecture should explicitly include the public programmatic (e.g., Web services) interfaces that these third parties require.

c. NOAA should plan for and identify resources required for an increased CLASS effort to fulfill the needs outlined in a and b above.

Finding: NOAA does not appear to be effectively leveraging the substantial and growing third-party resources available for creating, archiving, and distributing environmental satellite data products. In particular, the current CLASS effort appears to include end-user services (such as Web ordering, e-commerce, and product customization) that could just as easily be provided by

third parties, while ignoring the lower-level programmatic interfaces that value-added providers require.

Recommendation 6:

a. NOAA should consider both centralized and decentralized approaches to managing the generation and distribution of environmental satellite data products to ensure cost-effective and efficient utilization of existing human and institutional expertise and resources. Centralized handling should be provided for operationally critical core products and should include the acquisition, processing, distribution, archiving, and management of calibrated, navigated radiances and reflectances at the top and bottom (atmospherically corrected) of the atmosphere, as well as for selected key products and metadata. Specialized higher-level environmental data products could be handled (processed, reprocessed, and distributed) in a physically and organizationally distributed (and diverse) manner.

b. NOAA should take maximum advantage of the exponentially decreasing costs of computing resources and allow for distributed implementations by third parties.

c. NOAA should consider mutually beneficial partnerships and partnering models with the private sector (e.g., commercial value-added data and product services providers) that have the twin objectives of ensuring user-oriented open access to the data and providing the best value to end users.

Finding: Over the life of a project the cost of ownership of online (disk) storage is competitive with, and decreasing more rapidly than, that of offline (tape or optical) storage. The ability to store and process large volumes of satellite data online will thus become ubiquitous. More than any physical medium, Internet connections to these online data sources will prove a stable, economical, and widely available mechanism for data transfer.

Recommendation 7:

a. NOAA's default policy should be to maintain all public satellite data online, in archives that can be accessed (partitioned) to maximize throughput and replicated (mirrored) to ensure survivability.

b. NOAA should transition to exclusively online access to satellite data. Distribution on physical media should be provided as a custom service by third parties.

c. NOAA should plan for and identify resources to support handling of the anticipated increase in archival and dissemination requirements beyond 2010.

DATA ACCESS AND UTILIZATION

Finding: Data from diverse satellite platforms and for different environmental variables must often be retrieved from different sources, and these retrievals often yield data sets in different formats with different resolution and gridding. The multiple steps currently required to retrieve and manipulate environmental satellite data sets are an impediment to their use.

Recommendation 8: Data access and distribution should be designed, and associated products tailored, to be compatible with users' processing, storage, distribution, and communications resources and their information requirements.

a. NOAA should improve access to its data by allowing users to focus searches by geographic region, dates, or environmental variables, thus helping provide the means to search from one user interface across all environmental satellite data held by U.S. agencies. Tailored subsets of data products should be made available for routine distribution and/or in response to a specific request.

b. Further, NOAA's user interfaces should allow stored environmental satellite data sets and/or images to be retrieved in a common data format and with geolocated gridding selected from a list of options by the user. Subsetting and subsampling should be combined to provide a continuum of data products from broad-area, low/moderate-resolution products to regional, high-resolution products.

c. NOAA should concentrate on ensuring the commonality, ease, and transparency of access to environmental satellite data and providing no-cost data streams in a few standardized, user-friendly formats selected primarily to maximize ease of translation into community-specific formats.

d. NOAA should support the development of third-party format translation services and the adaptation of existing community-standard tools to NOAA-standard formats.

e. The data that NOAA provides to users should be accompanied by metadata that documents data quality, discusses possible sources of error, and includes a complete product "pedigree" (algorithm theoretical basis, sensor and calibration, ancillary data, processing path, and validation status and component uncertainties).

Finding: Some major segments of the user community currently do not have the resources to fully utilize all of the environmental satellite data available to

them. The principal obstacles to expanded use have been inadequate and/or discontinuous funding for applied research as a part of data utilization programs, the lack of support for education and outreach programs, and the lack of trained professional brokers and facilitators available to work with the various bidirectional interfaces between users and providers within the environmental satellite data utilization system.

Recommendation 9: A continuous level of adequate resources, especially for applied research and education of the work force in the use of environmental satellite data, is needed to exploit the huge investments already made in the satellite system. Satellite data providers and the scientific research community should also take a leading role in facilitating collaboration with their end-user partners. These efforts should include outreach, training, and technical assistance for the more sophisticated user communities as well as for the rapidly emerging nonscientific, nongovernmental user groups, with the ultimate goal being to enable straightforward and effortless user access to environmental satellite data and data products.

Finding: Early and ongoing cooperation with dialogue among users, developers of satellite remote sensing hardware and software, and U.S. and international research and operational satellite data providers is essential for the rapid and successful utilization of environmental satellite data. Active research and development is required to achieve operational sustainability—today's research anticipates and underpins the satisfaction of tomorrow's operational requirements. Many of the greatest environmental satellite data utilization success stories (see, e.g., the case study on the European Centre for Medium-range Weather Forecasts in Appendix D) have a common theme: the treatment of research and operations as a continuum, with a relentless team focus on excellence with the freedom to continuously improve and evolve.

Recommendation 10: To ensure the ongoing development of future operational environmental satellite data products that have high quality and value requires an ongoing evaluation of the U.S. effort to collect and provide environmental satellite data. An integrated, sustainable basis for the stewardship of future operational systems, sensors, and algorithms should be fostered by establishing close cooperation between the research and operational agencies responsible for the utilization of environmental satellite data (including their development, collection, processing and reprocessing, validation, distribution, and exploitation), with research and operations viewed as a continuum and

not as two independent areas of effort. To meet evolving customer requirements, this cooperation between research and operational agencies should be coordinated in close partnership with the user community. Only a fully funded, end-to-end system, from satellite/sensor design to data assimilation/utilization, can fully optimize the investments that have been made.

1

Elements in a Dynamic System for Data Utilization

The Committee on Environmental Satellite Data Utilization (CESDU) was formed at the request of NOAA and NASA to provide special input on and a vision for the use of environmental satellite data in 2010 and beyond. Environmental satellite data has been acquired for more than 40 years. Today, the volume of data is increasing dramatically, as is its use.

To successfully achieve comprehensive environmental satellite data utilization in the 2010-2020 era will require, in addition to data continuity, three foundational elements:

1. Advanced environmental geostationary and polar satellite, airborne, NEXRAD, and in situ sensor systems for excellence in data collection;
2. Integrated, seamless ground systems whose excellence supports enhanced and tailored data utilization, exploitation, and discovery; and
3. Knowledgeable utilization brokers who work among the groups involved—essentially, trained practitioners who develop effective linkages, connecting people with people throughout the end-to-end process of satellite data utilization (Figure 1.1).

THE DATA TSUNAMI

The increasing data rates and volumes of global observations from satellites that have presented major challenges over the past four decades will continue to drive planning for environmental data utilization during the coming decades. The number

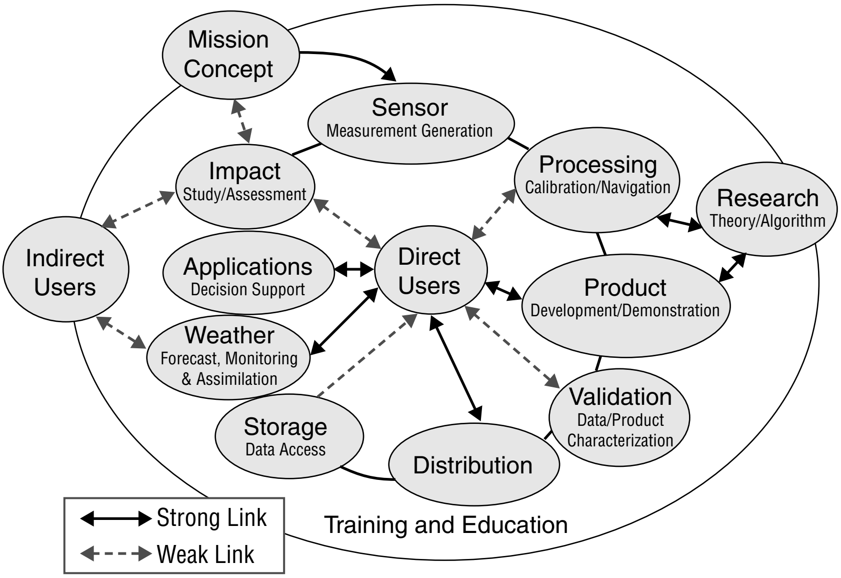

FIGURE 1.1 The complex end-to-end process of environmental satellite data utilization has many functional links and presents many opportunities for feedback between the processing steps in the overall system. SOURCE: Courtesy of Hung-Lung Allen Huang, University of Wisconsin-Madison.

of environmental satellites (see Box 1.1) will increase—up to 100 are to be launched between 2004 and 2014—as will their sensing capabilities. New user demands for cross-sensor and cross-satellite data products will bring additional new challenges that will have to be addressed not only at the system level, but also often by new national and international partnerships. The development of a large new segment of public and private sector service providers brings special challenges and opportunities. Advances in computing and storage technologies have enabled activities that were only dreamed of a few years ago. Now, NOAA must plan to deal with the ever-increasing wealth of environmental satellite data, as well as the growing number and sophistication of end users, while maintaining current operations. The challenges faced by those planning for environmental satellite data collection and management include not only handling this volume but also achieving the full potential of these data by educating more and increasingly diverse users and by providing for data archiving and retrieval that facilitate user access.

BOX 1.1

Environmental Satellites

In 1957 the first satellite, Sputnik, was launched. Environmental data acquisition from space began with the launch on April 1, 1960, of the first TIROS (Television Infrared Observations Satellite), a polar-orbiting platform that returned infrared images of clouds. By July 1965, 10 TIROS satellites had been launched. These were followed by 9 ESSA (Environmental Satellite Services Administration) satellites launched between 1966 and 1969, and then 5 ITOS (Improved TIROS) satellites, called NOAA-1 through NOAA-5, that were launched into polar orbits between 1970 and 1976. NASA and NOAA collaborated on the NIMBUS 1 through 7 satellite series (launched from 1964 to 1978). This program provided a test bed for many weather and climate observations. The TIROS-N operational satellites included NOAA-6 and NOAA-7, which carried the AVHRR (Advanced Very High Resolution Radiometer) and TOVS (TIROS Operational Vertical Sounder) and were launched between 1978 and 1981; these platforms provided a significant step forward by returning atmospheric profiles and improved surface temperatures. The current series of polar-orbiting satellites, the ATN (Advanced TIROS-N), began to fly in 1983 with the launch of NOAA-8.

Polar-orbiting satellites also have provided the ability to obtain high-resolution imagery of the land surface; NASA launched the ERTS (Earth Resources Technology Satellite) in 1972 using the pioneering, Earth-oriented NIMBUS-type spacecraft. Its instrumentation provided imagery with a spatial resolution on the ground of 10 meters. The Landsat program employed this technology; with improvements it reached a resolution of several meters. The French developed a similar capability in their SPOT satellite and the Japanese in MOS-1 and JERS-1.

Geostationary satellites were launched beginning in 1966, initially to test the feasibility of maintaining a stationary orbit. The ATS (Applications Technology Satellite) series launched by NASA up through 1974 returned color images of Earth from space and allowed regular cloud observations. Collection of meteorological data to support improved weather forecasts was a goal of the Synchronous Meteorological Satellites (SMS-1 and SMS-2) launched by NASA in 1974 and 1975. NOAA followed with the operational geostationary satellites of the Geostationary Operational Environmental Satellite (GOES) series beginning in 1975. In 1994 new three-axis stabilized satellites came into service in the GOES series that provided full-time coverage of Earth's surface, allowing visual and infrared images and soundings that looked at severe storms, clouds, winds, ocean currents, fog, snow cover, and other environmental variables as well as providing data relay services. Because of the high value of land and ocean coverage for weather forecasting, the United States operates two GOES satellites, one covering the East Coast and one the West Coast, with an overlap between.

Beginning in the 1980s NOAA began dialogues with other nations for coordination of satellite resources to work toward the best possible global coverage. Partnerships are now in place with EUMETSAT (European Organization for the Exploitation of Meteorological Satellites) and other nations. The international coordination is part of the World Meteorological Organization's World Weather Watch (WWW) program, and anticipates the International Earth Observation System.

In the mid-1990s the United States embarked on planning for the integration of civilian and defense meteorological satellite systems. This effort by NOAA, NASA, and DOD has led to the development of the National Polar-orbiting Operational Environmental Satellite System (NPOESS). The launch of the first NPOESS satellite is expected in 2009, with a bridge mission—the NPOESS Preparatory Project (NPP) scheduled to fly in late 2006—that will provide spectroradiometric continuity between NPOESS and the research sensors flying on NASA's Earth Observing System (EOS). To date, EOS has demonstrated the merits of

continues

BOX 1.1 continued

NPOESS's multispectral (36-channel) moderate-resolution imagery and hyperspectral temperature and moisture sounding capabilities.

At present, a diverse set of environmental observations are being made, with routine satellite coverage of the land and ocean surfaces, as well as the atmosphere. Included among the phenomena observed are precipitation, flood extent, storm events, dust clouds, fires and smoke, topography, ecosystems, volcanic ash, winds, sea-surface currents, sea-surface temperatures, sea ice, ocean color, atmospheric water vapor and temperature profiles, and so on. The diversity of environmental satellite data is exemplified in two images of Hurricane Isabel: Plate 1 shows Isabel on September 13, 2003, when it was a Category 5 storm threatening the Caribbean and the southern United States; Plate 2 shows Isabel as it approached landfall on the outer banks of North Carolina on September 18. The image is a "true-color" (red-green-blue) NASA image taken by the Moderate-resolution Imaging Spectroradiometer (MODIS)—the research equivalent of the Visible and Infrared Imager/Radiometer Suite (VIIRS) to be flown on NPP and operationally by NPOESS in three orbit planes (with global coverage every 4 hours) beginning in 2009.

Plate 3 anticipates a future capability to be delivered with the Hyperspectral Environmental Suite (HES) on GOES-R in 2012: four-dimensional water vapor structure and wind profiling, in this case water-vapor tracer winds (the tracking of moisture features on constant-altitude surfaces determined by retrieval analyses) for Hurricane Bonnie (August 26, 1998). This simulation demonstrates the power of hyperspectral atmospheric profiling of temperature, moisture, and winds. Compared with the current operational system, the new capability will provide greatly improved spatial resolution, more rapid temporal refresh, and finer vertical resolution through increased spectral information content.

This future, populated by advanced flight instruments yielding higher-quality measurements, will bring further downstream ground system expansion, with the estimated increase in data volume over the next 10 years equivalent to the increase seen over the last 20 to 30 years. The universe of potential operational environmental data beyond 2010 will include data collected by a large portion of the estimated 30 to 40 such satellites being operated each year for research, operations, and technology demonstrations by U.S. agencies as well as by those of other nations. A number of satellite systems and constellations will operate under international partnerships.

As shown in Plate 4, during the 1990s the NOAA archives grew from a little over 100 terabytes to more than 760 terabytes. This growth is not a one-time perturbation. Instead it represents a significant trend that is expected to continue for the next few decades. The second chart in Plate 4 shows the projected growth in archive requirements over the 15-year period from 2000 to 2015. By 2015 the archive requirements are projected to be approximately 15,000 terabytes, an increase of about 20 times the 2000 volume.

Plate 5 shows the archive growth from 2000 to 2015 based on major NOAA systems. Much of the growth is due to new systems such as NPOESS and GOES-R becoming operational. These new systems offer NOAA the opportunity to significantly enhance its operational capabilities and provide important data to support NOAA's mission. However, the resulting data tsunami requires NOAA to plan accordingly for the archiving and distribution of the data.

BIDIRECTIONAL INTERFACES IN AN END-TO-END SYSTEM TO MEET GROWING USER NEEDS

During the last two decades, the greatly increasing volume of environmental satellite data has been accompanied by rapid growth in user demands for environmental information. In response, an array of new environmental data service providers has developed in all the major industrial nations. This environmental satellite data enterprise extends from the instruments, spacecraft, and operating systems of the satellite data providers through the brokers and their data servers that place information into the hands of end users. The system is characterized by a sequence of bidirectional interfaces between the functional units in the end-to-end process of satellite data utilization, as depicted in Figure 1.1, that must be addressed. The entire sequence of events is dynamic and changes at a relatively high frequency (e.g., annually) as a result of healthy push-pull, supply-demand activities.

"Added-value" products are in demand by industry, transportation, agriculture, the military, the science establishment, and many other constituencies. Amid this new world of users, operational environmental satellite data systems of the United States and other countries face not only requirements for meeting a large fraction of the data demand, but also the prospect of being able to draw on some exciting new technologies. A look ahead to 2010 and beyond is required to plan a best fit between needs for environmental satellite data and the opportunities to address those needs. Challenges extend well beyond the exploitation of new technologies to the development of a new system designed and staffed by the human principals of an emerging profession.

Contemplating the multiplicity of user needs for environmental satellite data and information, a number of recent studies by the National Research Council (NRC) (see Appendix C) and other groups have provided detailed information about some well-known segments (e.g., operational weather forecasting, climate science, water management, and others). To learn about user needs from other segments—including land use and water resources management, the agricultural industry, the media, the recreational industry, and others—CESDU held extensive fact-finding sessions. It not only noted numerous new and emerging user requirements but also discerned "chains" or "stages" of users, each drawing on services and products from farther up the chain. The implications range from the need for an active network of user information services to the education and training of career professionals who will facilitate activity and use at the multiple interfaces. Without a trained and informed system of brokers and data servers at these bidirectional interfaces, full and optimal utilization of environmental satellite data cannot occur.

While there is a focus today on the growth of environmental satellite data in the next 10 years, the longer term also requires special consideration at this time. From many lessons learned it is apparent that future user satisfaction will depend heavily on a sustaining, multidisciplinary, environmental-satellite research program. This research should continue to be led by NASA with contributions from universities, industry, and NOAA. The research must involve both the technology of instrumentation—including calibration—and the technology of data processing. It should include new technology demonstrations as well as NOAA-NASA Pathfinder program experiments with algorithms and analyses.

Furthermore the end-to-end system for utilization of environmental satellite data will have to evolve to satisfy users' needs in 2010 and beyond. That evolution must be guided by strong and ongoing research and development activities aimed at new and improved capabilities. This effort will require close synergy between research and operational satellite data system groups.

Fortunately some long-term continuity planning by some segments of the user community is available now. For example, the Climate Change Science Program (see National Research Council, *Implementing Climate and Global Change Research: A Review of the Final U.S. Climate Change Science Program Strategic Plan*, The National Academies Press, Washington, D.C., 2003) is an example of a well-planned federal strategy for which long-term (decades or longer) environmental satellite data are essential.

CHALLENGES POSED BY TECHNOLOGY ENABLERS AND TRENDS

Rapid technology development is occurring today in areas basic to operational environmental satellites—remote sensing, aerospace, communications, and information flow—and will continue at an accelerated rate. In addition to drawing on committee members' expertise in some of these areas, CESDU obtained special briefings by outside experts on both current and future technologies, including developments in computation and information technology.

Lessons from past planning by NOAA, NASA, and associated academic and private sector partners in environmental satellites have shown a repeated pattern of *underestimating* the effects of key technology developments. A portion of the growing technology gap—between what is being done by the federally funded environmental satellite data systems and what could be done—may be driven by the federal procurement process and the long cycle time between program changes. Because of the lessons from the past, CESDU in its present study places special emphasis on new technology implementation challenges.

Processing

The general trend of semiconductor-based computing capacity doubling every 18 months (known as Moore's law) will continue for at least the next 10 to 15 years. On a simplistic basis of instruction cycles per data bit, this increase is expected to keep pace with the increased volume and complexity of Earth satellite data streams. The primary challenge will be harnessing the available computing power to address these processing tasks.

Storage

For at least a decade, magnetic areal density (the capacity of disk drives to store a given number of bits on a given unit of disk surface area) has been increasing faster than would be predicted by Moore's law. This pace shows no signs of slowing. Since the volume of satellite observational data, while increasing, is not expected to double every 15 months, it will inevitably become cheaper over the next 10 to 15 years to maintain the cumulative satellite data record online. The committee found that no good alternative to online storage exists that satisfies all the identified needs.

It is difficult to overstate the importance of this simple fact: For the first time, it is technologically feasible to have near-instantaneous (within milliseconds, as opposed to within minutes) access to *any* satellite data. Such access will enable the assimilative, retrospective, and cross-sensor analyses crucial to developing reliable climatologies and Earth system models.

Inexpensive storage is likely to result in increases in standing orders for and bulk transfers of environmental satellite data and to an increasing number of sites able to function as long-term archives, i.e., having both the physical capacity and the stewardship (capability for security, maintenance, technology migration) needed to reliably maintain records of mission-critical importance.

Delivery

It is safe to assume that the next 10 to 15 years will see an increasingly networked world, one in which users of satellite data will have ready access to connections at a rate of gigabits per second, and continuous access to megabits-per-second connections (wired and wireless). Distribution of satellite data products on physical media will be relegated to niche applications (e.g., where uninterruptability or physical security are paramount considerations), because of the high cost of transcription and the relatively short market life of media technologies (e.g., several generations of optical disks have outlived any device that can read them).

Utilization

The explosive growth of commodity computing technology, and especially its penetration into personal electronics such as mobile telephones and personal digital assistants, will transform how people acquire and use satellite data. When there is substantial processing power under the user's control, it will no longer be incumbent upon the data provider to reduce the information to its least common denominator (e.g., a color-coded picture). Instead, end-user processing will rely on the availability of standardized data streams that can be manipulated by commodity software.

ADDITIONAL CHALLENGES

Ensuring Ready Access to High-Quality, Stable Data

NOAA and NASA groups already use some measures to gauge access to environmental satellite data by users, including (1) volume of data transfer, (2) latency from time of observation, (3) response time to meet a new user request, and so on. Such measures are a key aspect of a dynamic system of environmental satellite data utilization. Adjustments and re-planning will always be part of the system. Additional measures of user accessibility should be developed, should be discussed at user interface meetings, and should include those measures suggested or required by various user segments and chains.

Within the environmental satellite data user community, needs for access to data and information cover a wide range—from information for warnings and alerts by community disaster centers through data for providers of value-added products and services for the recreational community to data for use in scholarly research. Obviously a "one-size fits all" system of access will not efficiently meet this spectrum, or matrix, of data type, volume, timing, quality, and cost of access.

Transitioning to Advanced Polar and Geostationary Satellite Architectures

NOAA and NASA are working together to achieve significant improvements in the satellite collection of environmental data. Today's operational Polar-orbiting Operational Environmental Satellites (POES), Defense Meteorological Satellite Program (DMSP), and GOES provide for limited multispectral sensing of Earth's atmosphere, oceans, and atmosphere. The converged NPOESS, in three orbit planes, with a first launch in 2009, will deploy advanced replacements for every POES and DMSP sensor flying today. Consider just three examples:

- The Advanced Very High Resolution Radiometer (AVHRR), with six spectral bands, and the three-band Operational Linescan System (OLS) will be replaced with the 22-band Visible and Infrared Imager/Radiometer Suite (VIIRS). VIIRS expands upon the operational heritage of AVHRR and OLS with a better signal-to-noise ratio and better absolute accuracy, bringing the advanced spectroradiometry of the NASA Moderate-resolution Imaging Spectroradiometer (MODIS). At the same time, VIIRS brings the improved spatial performance and low-light/moonlight sensing capability of the OLS.
- NOAA's infrared sounder component of the Advanced TIROS Operational Vertical Sounder (ATOVS)—the High-resolution Infrared Sounder (HIRS) with 22 channels sensing broad bands of temperature, moisture, and ozone—will be replaced by the Cross-track Infrared Sounder (CrIS), a 1305-band hyperspectral sounder with sharper bands and 1-K-uncertainty temperature retrievals with direct heritage to NASA's hyperspectral Atmospheric InfraRed Sounder (AIRS).
- NOAA's Spectral Backscatter UltraViolet (SBUV/2), a 22-channel operational nadir sounder, and NASA's Total Ozone Mapping Spectrometer (TOMS), an eight-channel scanning radiometer, will be replaced by the NPOESS Ozone Monitor and Profiler Suite (OMPS). OMPS brings hyperspectral nadir and limb sounding capability to the heritage of the Space Shuttle Ozone Limb Scattering Experiment (SOLSE)/Limb Ozone Retrieval Experiment (LORE).[1]

In every case, the advanced sensors extend today's measurement sets, while providing significant evolved capability to meet the tightened requirements of the Integrated Operational Requirements Document (IORD/2). To reduce the risk of these advances in sensors and the operational conversion of the research algorithms, NASA will fly a bridge mission, the NPOESS Preparatory Project (NPP), in 2007. NPP will carry the VIIRS, CrIS, and OMPS.

Advances in POES are not limited to sensors and algorithms. NPOESS will replace the traditional once-per-orbit downlink with a 15-station "SafetyNet" (Figure 1.2). This improved communications topology will yield greatly improved timeliness, benefiting all operational users interested in near-real-time data.

With the NPOESS flight and ground segments under development, NASA and NOAA are now working to achieve similar advances in geostationary orbit. The advanced imaging and hyperspectral infrared sounding capabilities of the next generation of GOES (GOES-R) will be comparable to those of NPOESS. The Advanced Baseline Imager (ABI) will provide multispectral reflective and emissive

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[1] The SOLSE/LORE instrument was lost, along with the crew, on its last flight with Space Shuttle Columbia, STS-107.

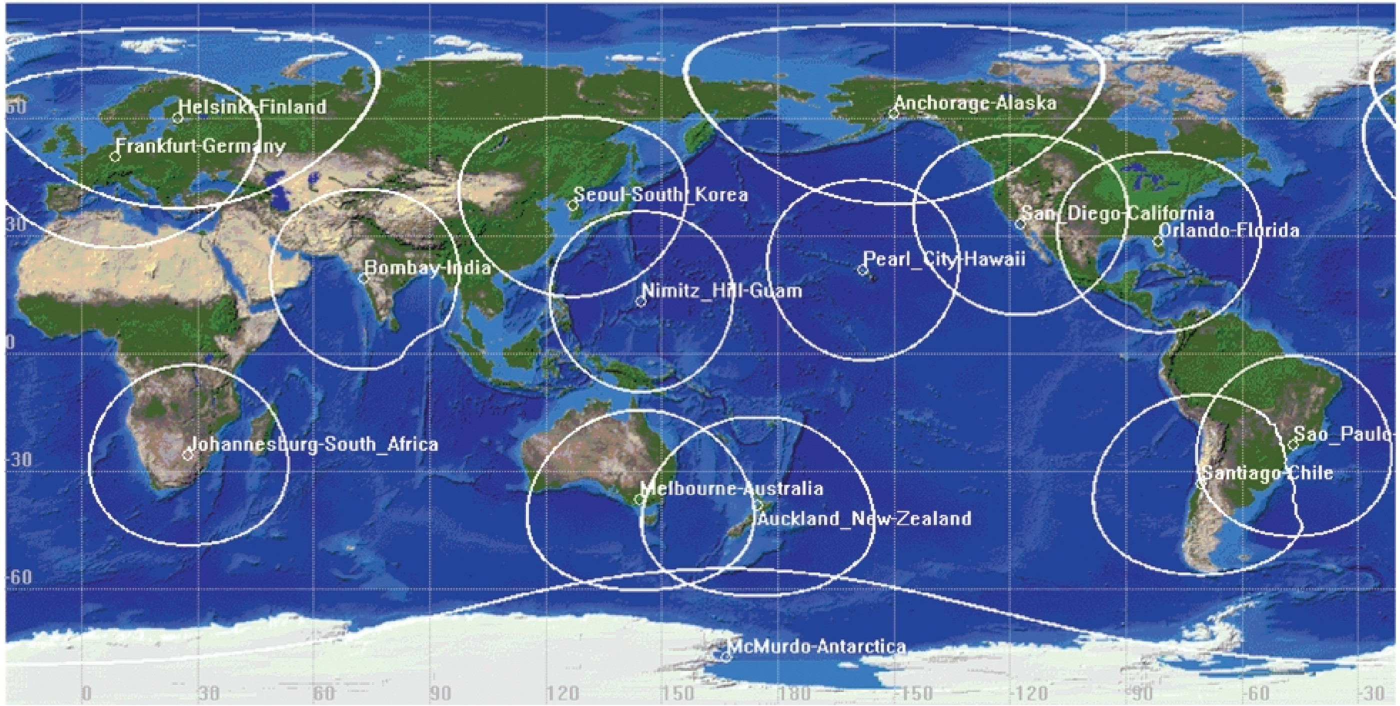

FIGURE 1.2 The NPOESS "SafetyNet," which leverages the global presence of high-bandwidth fiber optic cable into a globally distributed network of 15 receptors linked to processing centers via commercial fiber. SOURCE: Courtesy of NOAA; available online at http://npoesslib.ipo.noaa.gov/Maxi-2002/album/day3/3-0815-TRW-Raytheon.ppt (accessed September 19, 2004).

imagery comparable to that of VIIRS; rapid temporal refresh; simultaneous mesoscale, continental United States, and full-disk coverage; and reduced sensitivity to solar impingement on the sensor near local midnight. The Hyperspectral Environmental Suite (HES) will bring comparable infrared sounding capability to CrIS, while adding high-resolution reflective ocean-color coverage of U.S. coastal oceans and littoral zones (see also Box 1.1).

The added spectral bands, improved radiometric bit depth, sharpened ground sample distance, and accelerated temporal refresh have a consequence in data rate. With increases of 10X to 100X, NPOESS and GOES data requirements will demand improved downlinks and ground processing, storage, and dissemination systems capable of keeping up with the higher data volumes and more-complex data product algorithms.

Reconciling Stability and Change

The NOAA-NASA operational environmental satellite systems operate amid the opposing forces of (1) technology-driven change, (2) changing user requirements, and (3) requirements for an efficient, dependable system of access for operational users. Furthermore, the multidecadal lifetime of the satellite systems requires sustainability through numerous federal budget cycles and prioritizations. In partnerships with the aerospace industry, satellite data providers can employ certain systems engineering principles to bring flexibility and adaptability for the optimal utilization of satellite data. However, beyond the initial ground processing of a suite of satellite remote sensing output, each of the many user pathways requires individual attention for the reconciliation of stability and change. Some user segments or pathways are more change-averse than others.

Algorithm Development: Spiral Model—The "Virtuous Cycle"

Today's algorithms for reducing data acquired by increasingly sophisticated imagers, sounders, spectrometers, radiometers, and other instruments belong to a long and varied heritage of science and operational algorithms, based on multiple previous missions over the past two to three decades. For example, the Defense Meteorological Satellite Program (DMSP)/Optical Linescan System (OLS), NESDIS Polar Operational Environmental Satellite (POES)/Advanced Very High Resolution Radiometer (AVHRR), NASA Sea-viewing Wide Field Sensor (SeaWiFS), and EOS/MODIS form the principal electro-optical spectroradiometric heritage for future imagers, while the Nimbus-6 and Nimbus-7 Earth Radiation Budget (ERB) experiments, the NOAA-9, NOAA-10, and Earth Radiation Budget Satellite (ERBS) Earth Radiation Budget Experiment (ERBE), and the EOS Cloud and the Earth's Radiant

Energy System (CERES) form the principal Earth radiation budget heritage. Each of these missions, with varying levels of formalism and an integrated multimission science thread, involved algorithm development according to a spiral development approach (Figure 1.3).

Consider radiometry—moving from 8-, to 10-, to 12-, to 14-bit data reveals an increased quantity of new information with every generation. While driven by requirements for precision, higher radiometric precision does not translate directly to improved quality for geophysical data products. Every additional two bits are equivalent to a 4X-deeper look into the data, but undesired "noise" is also unmasked in these deeper looks, requiring that the retrieval algorithms be significantly revised so as to uncover the desired information that the sensor now provides—separating the new information from the "noise" present in other, competing phenomenological signals. Extracting new information from higher-bit data also drives the need for additional spectral data—in the form of cleaner specialized spectral bands—to fuel the emerging algorithm requirements. Coordinated validation activities, in the form

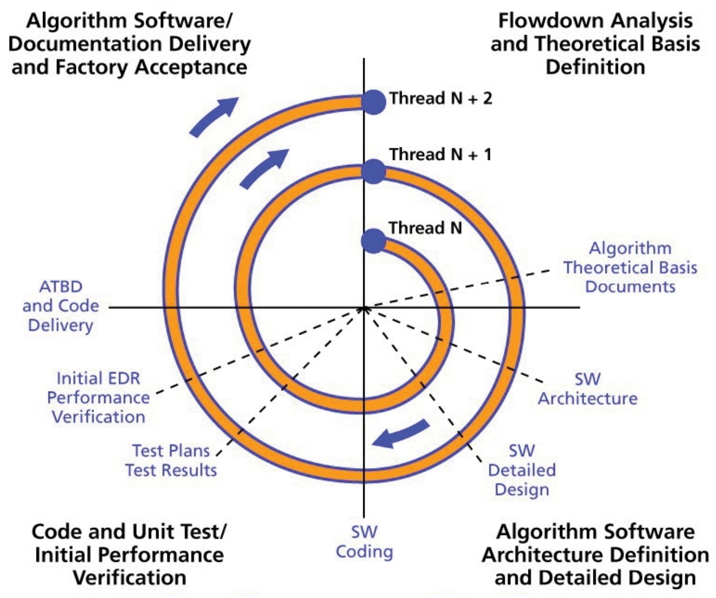

FIGURE 1.3 The traditional spiral model, as applied to algorithm development. SOURCE: Courtesy of Phil Ardanuy, Raytheon Information Solutions.

of in situ networks or targeted field campaigns for ground truth confirmation, guide the fine-tuning and quality-improvement process.

Traditional "waterfall" program management approaches often bring high risk when significant new capabilities are being developed and implemented. Schedule pressures may freeze milestones too early, often while the algorithm and hardware technologies are still maturing. The spiral development process, however, is designed to permit system development, yet not restrict the activities required to ensure this increasing maturity. Every turn around the spiral includes more detailed activities, including generation and inspection of test data sets, further algorithm development, more thorough testing and validation strategies, and more test cases leading to a deeper understanding of the stratified algorithm performance over a wider range of environmental conditions, e.g.:

- Across the measurement range,
- For all surface types and air masses,
- For diverse combinations of solar and viewing angles, and
- For cloud states ranging from subvisible to broken multilayer overcast.

The collection of test data sets, theoretical basis documents, architecture and design documentation, algorithm software, and test plans and reports is enlarged and enhanced by each turn of the spiral. With each revision, limitations and risks are identified and removed. The approach is derived from experience gained during heritage programs (previous turns around the spiral).

CHARACTERIZATION OF AN END-TO-END SYSTEM FOR OPTIMAL USE OF DATA

It may not be possible to devise a well-defined and complete end-to-end system for use of satellite data that addresses all concerns. While working on this report, the committee considered certain key aspects, which are summarized here. Usually an end-to-end process requires a full range of functions that, at a minimum, include enabling capabilities to design, assemble, execute, process, integrate, distribute, make decisions, and carry out other complicated and ill-defined tasks such as education, training, and outreach. As shown in Figure 1.1, satellite data utilization is a complex, end-to-end process with many opportunities for feedback between the processing steps. The end-to-end system may occasionally lack either end point, but specific functions and links in the sequence can be identified. Figure 1.1 also illustrates the circular relationship of each function and the links with many bidirectional interfaces supporting the chain of events. A satellite mission commonly starts with the mission concept, which is heavily influenced by detailed knowledge of users' needs, the available technology, and the requirements for successfully achieving the project. The end-to-end diagram in Figure 1.1 starts with the mission concept and ends with the study and assessment of the impact of the mission. The study and assessment of impact also provide significant inputs and lessons learned to the planning of any future missions and to the execution of current missions. The circular end-to-end system for the process of satellite data utilization can be summarized as follows:

- A vision of a mission by an expert, farsighted individual, team, or program office that demonstrates new ways of making unique and enhanced measurements or of meeting ongoing operational requirements;
- Incorporation of users' requirements and lessons learned into the guidelines for the configuration of the design and building of a new sensor system;
- Instrument characterization, including efforts in calibration and navigation, which enables consistent measurements that allow certainty and generation of quality data products;
- Product development and demonstration, and processing research, to ensure that the data products meet the requirements identified in the mission concept;
- Validation of data and data products to characterize the accuracy and long-term stability of the measurements and products, with feedback for algorithm development and product generation before distribution and use recognized as vital;
- Distribution and storage for downstream data access to allow indirect users and specific agencies to tailor the data for their own needs;
- Other final links in the chain, including weather forecast applications, data assimilation, application for decision support systems, impact studies, and mission assessment;
- Indirect use and applications utilizing a variety of satellite data product types and formats; and
- Training and education across all functions in the process and links in the chain to ensure proactive and iterative collection, understanding, and embracing of operational users' requirements and feedback.

2

Multiplicity of Environmental Satellite Data Uses

It is a fact that NOAA will never fly another "weather" satellite. The next generation of polar operational environmental satellites (POES) and geostationary operational environmental satellites (GOES) that will fly near the end of this decade are designed to expand observational capability beyond severe weather and near-term forecasting to take on the comprehensive environmental mission identified in NOAA's vision, mission, and goals (see Box 2.1). NASA's Earth Science Enterprise mission is "to understand and protect our home planet by using our view from space to study the Earth system and improve prediction of Earth system change."[1] Today's user community is already using data and information collected by NOAA's operational satellites, and NASA's research satellites, to address a multiplicity of environmental applications.

EXAMPLES OF USES OF ENVIRONMENTAL SATELLITE DATA IN 2010

In the second decade of the 21st century, information that in some way is derived from operational satellite data will be used ubiquitously. Much of this information will be generated directly by NOAA and NASA; the rest will be produced by other government agencies or commercial vendors as "added-value" material. Because accurate information is part of any decision-making process, the opportunity

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[1] See http://www.earth.nasa.gov/visions/ESE_Strategy2003.pdf.

BOX 2.1

NOAA's Vision

To move NOAA into the 21st century scientifically and operationally, in the same interrelated manner as the environment that we observe and forecast while recognizing the link between our global economy and our planet's environment.

NOAA' s Mission

To understand and predict changes in the Earth's environment and conserve and manage coastal and marine resources to meet our Nation's economic, social, and environmental needs.

NOAA's Mission Goals

1. Protect, restore, and manage the use of coastal and ocean resources through ecosystem management approaches.
2. Understand climate variability and change to enhance society's ability to plan and respond.
3. Serve society's needs for weather and water information.
4. Support the Nation's commerce with information for safe and efficient transportation.

SOURCE: Excerpted from "New Priorities for the 21st Century, NOAA's Strategic Plan for FY 2003–FY 2008 and Beyond," available at http://www.spo.noaa.gov/pdfs/FinalMarch31st.pdf.

for satellite data to be employed to aid decision makers (or simply satisfy curiosities) is essentially limitless.

Historically, the dominant use of operational satellite data has been to serve NOAA's mandated mission of weather forecasting through the arm of the National Weather Service (NWS). Thus, the bulk of the satellite-based products generated by NOAA were designed for these NWS applications. A new trend has developed, which will continue through the next decade, in which operational satellite data are used for all types of environmental monitoring of the Earth system. These operational data are now and will continue to be packaged and delivered to provide timely and targeted information for innumerable reasons, most of which relate to some type of decision-making process. Additionally, retrospective analysis of satellite products is also growing as demands for high-precision, long-term time series of environmental variables are required. Thus, new products based on operational satellite data are finding significant utility outside the traditional weather-forecasting arena. As a consequence, the user community is expanding rapidly, and NOAA's role in fulfilling this demand for increasingly precise and up-to-date environmental information beyond weather forecasts must be addressed. The following is a sampling of uses presented here to alert the appropriate agencies to the growing demand for information that at least in part will require operational satellite data. These examples extend beyond the typical research currently being performed within the traditional scientific disciplines.

Forecasting

In 2010, the dominant use of satellite data will likely remain unchanged as NOAA supports the NWS's mandated forecasting mission, thus allowing the government to fulfill its obligation to protect life and property. Users at the level of producing high-value forecasts include the NWS, DOD (for military operations), international partners, and major commercial interests. Agencies and corporations at this level would also support the assessment, prediction, and mitigation of environmental threats. Because hazards are having an increasing impact on economies, the importance of accurate space-based information to detect and predict their consequences will remain an essential function of the agencies in the coming decades. Not only are the effects of natural disasters (e.g., floods) increasing, but now those of human-induced catastrophes (e.g., large-scale terror attacks) must also be factored into the monitoring and forecasting mission of the appropriate agencies. Today the impact of satellite data is much larger than the impact of data from radiosondes in both the Northern and Southern Hemispheres (Figure D.1). There is now a stronger dependence on satellite data in the European Centre for Medium-Range Weather Forecasts (ECMWF) system, and the influence of other non-satellite data types is becoming less important (for details see the ECMWF case study in Appendix D).

Monitoring of Climate Variability

Satellite data now permit a global view, capturing the surface of the ocean and the land as well as the atmosphere. Remotely sensed sea-surface temperature fields and sea-surface elevation have provided the ability to track the evolution of large-scale patterns of climate variability involving the ocean, with the AVHRR and altimetry images of the evolution of the 1997-1998 ENSO a good recent example. Bringing such records together with remotely sensed vegetative index fields shows the impact on land of the drought and rainfall patterns linked to the large variability in sea-surface temperature. Improved accuracy and resolution in sea-surface temperature fields are sought not only by those studying and predicting climate variability, but also by the NWS community because of the role of sea-surface temperature in forcing the atmosphere, including its influence on hurricane tracks. High-quality surface vector winds and altimetry will also be sought because, together with in situ data from the ocean, these remotely sensed fields will allow estimation of the wind-driven currents and also the density-driven or geostrophic currents that together transport and redistribute heat in the ocean.

Detection of Global Change

Analysis of long time series of environmental data (e.g., the analysis of sea-surface temperature) has grown in importance, as have concerns about changes occurring in the Earth system and the role of human activity in those changes. Many of these changes are minuscule on a year-to-year and decade-to-decade basis, and detecting them therefore requires exceptionally meticulous, high-precision monitoring—which is a relatively new requirement for agencies. To achieve the levels of precision necessary for detection, retrospective reanalysis of many data sets is required. The recent finding that global terrestrial net primary production increased 6 percent between 1982 and 1999, the "greening of the biosphere" (see Plate 8), was possible only by building a climate data record for a normalized difference vegetation index (NDVI) based on the latest theory and algorithms applied to the full historical record[2] (see the section "The AVHRR NDVI Pathfinder" in Appendix D). In such cases the use of NOAA-NASA satellite data falls into a category of scientific research that has no specifically designated home and thus is difficult to perform, given the many years required to develop and establish such activities. In a slightly different vein, data-mining efforts will expand in the coming decades as new products based on old operational satellite data are discovered and developed. Retrospective analyses and data-mining research emphasize the need for convenient and rapid access to archived raw and processed data.

Because the weather forecasting mission has dominated the use of operational satellite data, product generation has generally been tied to atmospheric and hydrologic systems. Detection of global change requires measurements that can show variations and trends in all types of environmental data often gathered only serendipitously in the course of traditional weather monitoring. Of particular concern is the place of satellite observations of terrestrial conditions. As indicated below, there are significant legal and economic development issues related to precise measurements of terrestrial systems. Beyond those applications is the need to develop the science of terrestrial variability in the global context. Because humanity lives and grows its food on the surface of the planet, any threats to the carrying capacity of the terrestrial sphere would have considerable implications for policy decisions regarding land use.

Production of information about this vital component of the Earth system from the global change detection standpoint could be formally assigned a home in the federal government. Additional aspects of the Earth system, such as atmospheric

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[2] R. Nemani, C. Keeling, H. Hashimoto, W. Jolly, S. Piper, C. Tucker, R. Myneni, and S. Running, 2003, "Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999," *Science* 300:1560-1563.

chemical composition, habitat viability, and so on, will become more visible in science and policy initiatives as information on variations in such parameters is developed.

Economic Development

Economic growth and, in particular, sustainable development are themes likely to become a greater part of the environmental landscape in the next decade. To support the many civilian applications of the Global Positioning System (GPS), numerous companies have emerged with GPS-related technologies or services. For example, several companies now produce receivers, others focus on surveying and mapping, still others support navigation and guidance applications, and some are involved in tracking services and wireless technologies (see the GPS case study in Appendix D). Today the competition for economic opportunities is global and will likely only increase over the next decade. Environmental information is a necessary component in business decisions of this type. Because satellites in general are the only means of obtaining systematic measurements of the entire globe, it is possible that downstream products based on operational satellite data will be used extensively and with greater frequency in the coming decade to enhance a company's prospects for business recruitment and success.

Over longer time periods, environmental data will be valuable in efforts to assess changes in ecosystems that may result in certain regulatory measures which in turn have economic consequences. In large part, citizens, who are increasingly being effectively represented through advocacy groups, desire clean, robust, and natural environmental surroundings. Assessments of the state of a particular ecosystem and determining what to do about current conditions may hinge on the products created from space-based data.

Resolution of Legal Issues

An emerging aspect of environmental data use relates to legal issues for which certified and accurate information is now required. For example, to set premiums the energy-use insurance industry must factor in estimates of upcoming weather conditions, and NOAA GOES-R can improve the accuracy of energy load forecasting.[3] NOAA may find itself in the high-profile role of having to address these coming

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[3] Geostationary Operational Environmental Satellite System (GOES) GOES-R sounder and imager cost/benefit analysis, prepared for the GOES Users Conference, October 1-3, 2002, Boulder, Colorado, by the National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite, Data, and Information Service (NESDIS), Office of Systems Development, October 1, 2002.

situations on the basis of in situ and/or satellite data. Also, certification of environmental parameters and variation in them has the potential to become critically important in relation to bilateral or multilateral treaty obligations, particularly with respect to global climate change initiatives. In a more parochial sense, regulatory actions to deal with local pollution, for example, will have to take into account local weather factors and forecasts. The precise monitoring of such parameters, which can trip certain regulatory mandates, may have a large impact on local economic activity and, if not wisely applied, may result in significant legal challenges. Thus the means by and manner in which NOAA data are gathered and processed may increasingly become the subject of court disputes involving tremendous financial assets.

Public Health

Remote sensing has begun to be used by health authorities to monitor conditions in the breeding regions of disease vectors, such as malaria-carrying mosquitoes.[4] Data on rainfall, temperature, local vegetation, and soil moisture from satellites such as Landsat 7 and NASA's Terra orbiter are used to build a profile, which is combined with high-resolution imagery from commercial satellites, such as Ikonos and QuikBird, to determine where mosquito-spawning areas are likely to appear. Alerts are issued when the conditions for outbreaks can be predicted. The technique of "landscape epidemiology," first used in the 1960s, helps predict the spread of a disease, based on its surrounding geography and climate. Today, daily Earth examinations conducted by satellites in geostationary orbits have begun to provide epidemiologists with enough long-term data to begin making associations between climate and disease. "For a long time there was no good systematic collection of information that would let us establish that ecosystem-disease relationship," Assaf Anyamba, a research scientist with NASA's Goddard Space Flight Center, stated. "But now," he continued, "we have a coherent picture from which to begin to see how that relationship forms."

Transportation and Recreation

The lack of limits to the uses of environmental satellite data poses exciting possibilities. A recreational traveler today has a general idea of the road conditions ahead and how they might change during his journey. In the next decade, one can

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[4] Adapted from an article by Tariq Malik, "Satellites Keep an Eye on Epidemics," in Space.com, March 24, 2004.

imagine the same traveler purchasing a service that depicts kilometer-by-kilometer road conditions, tied in with high-resolution forecasts to let the traveler anticipate conditions for the entire trip. The next decade may also see recreational and commercial mariners being provided with up-to-date information on surface winds, wave heights and periods, sea-surface temperature, and other elements of marine weather—products and forecasts that will improve mariners' safety at sea and the efficiency of vessel routing. In such instances, NOAA will provide satellite data to support and complement NWS forecasts, which would then be tailored by a service provider for a particular traveler. The Department of Transportation, also using NOAA data as well as the department's own data sources, would generate road conditions and forecasts from which a service provider could again tailor the output. In this case, the chain of users has followed a path from NOAA to two government entities, to a service provider, and then to the end user. The end user is a fee-paying traveler with no requirement for IT sophistication, and so it is clear that intermediate users are essential to the successful delivery of the satellite-enhanced information.

The specific path (chain of users) of NOAA's environmental data from observation to end user is now, and will continue to become, an increasingly complicated web woven principally by the invisible hands of entrepreneurial visionaries. The role of NOAA in enabling such an information explosion is addressed in Chapter 5.

USERS OF ENVIRONMENTAL SATELLITE DATA IN 2010

As indicated above, users of operational satellite data will span a broad spectrum encompassing mainstream users such as government agencies that require massive and expensive infrastructure as well as casual Web-surfers who rely on inexpensive, hand-held devices. Some will require the fundamental radiance counts transmitted from spacecraft to Earth, but most will receive a heavily processed product whose interpretation requires no training. In utilizing products that in some way originate in operational satellite data, a single person, company, or agency may fall into several categories of end user. Though not exhaustive, the following list suggests "discriminating dimensions" according to which users of or customers for operational satellite data might be categorized:

- *Adequacy of funding base:* Cost of functional infrastructure essential for effective implementation;
- *Type of organization:* federal, state, local, commercial, educational, nonprofit/individual;
- *Location in chain of users:* end user, intermediate user, source;
- *Component or discipline of interest:* weather, hydrology, terrestrial/land use;
- *Site accessed for data:* National Centers for Environmental Prediction (NCEP),

NWS, Earth Observing System Data and Information System (EOSDIS), National Climatic Data Center (NCDC), vendor, university, media, non-profit;

- *Level of product needed:* digital counts, geophysical products, geolocated products for subsetting, highly processed images and information;
- *Requirement for timeliness:* real time, near-real time, retrospective;
- *Motivation:* profit, science, education, everyday life, curiosity, mandated mission; and
- *Cost sensitivity:* recurring and non-recurring costs of data and information access, e.g., Landsat user fees.

The committee was presented a classification of users based on the expertise of individuals who are themselves users of EOSDIS satellite data sets. "Expertise," then, may be considered another discriminating dimension. EOSDIS (discussed in "The Experience with EOSDIS" in Chapter 3) was designed to meet the needs of the relatively sophisticated Class 1 and Class 2 users described below, and so the data volumes discussed in the section that follows must be considered a fraction of what will develop as satellite data becomes more readily accessible.

- *Class 1:* Highly technically competent users with an extensive background in remote sensing and full familiarity with new sensors and algorithms, for example, the ECMWF, which is an operational institute with strong research activity in all aspects of weather prediction and a heavy investment in the use of satellite data (for details, see the case study on ECMWF in Appendix D).
- *Class 2:* Users who are competent in remote sensing but who lack familiarity with the new sensors and algorithms, for example, users of direct broadcast data, which is acquired by satellite sensors and broadcast in real time to any ground station within range of the satellite's current position (see the case study on direct broadcast in Appendix D for details).
- *Class 3:* New potential users with modest remote sensing training and minimal understanding of algorithms and data details. A primary objective of the NASA Earth Observing System has been to deliver usable remote sensing data products to a wider array of less sophisticated users (see the section "MODIS Fire Rapid Response System" in Appendix D).
- *Class 4:* Non-technical users (education, law, policy, etc.) with no background in Earth sciences who have limited occasional use—e.g., the many people who access satellite-based weather data several times per day (i.e., composite NWS images of weather conditions). Although it was developed by the military for military purposes and continues to be operated by the military, civil users worldwide have found many applications for the GPS (see the case study on the GPS in Appendix D).

VOLUME OF REQUESTS MADE FOR NOAA-NASA PRODUCTS

Few models exist today that will allow for a reasonable estimation of the data-request load in 2010 for operational satellite data. It is clear that the volume of satellite data available for use will be at least an order of magnitude greater than the current volume, and it is anticipated that the number of uses and users will grow substantially. Requests from approximately 18,000 unique IP addresses are made each month for the mostly scientific data in the EOSDIS.[5] In FY 2003, 228,000 distinct users received data and information products from EOSDIS. Depending on how "user" is defined, the range for EOSDIS extends from 7,000 distinct users (for the often-voluminous level-0 through level-4 scientific data products via the EOSDIS Core System) to more than 2.1 million distinct users (including Web page hits) based on e-mail addresses in FY2003. Designed to distribute the large EOS satellite data files, the EOSDIS Core System distributed 80 percent of the total distributed EOSDIS data volume.

The statistics on data use show a dramatic increase over 4 years in the number of products retrieved immediately from Web sites, FTP servers, and the data pools.[6] This asymptotic convergence suggests a nearly total reliance on electronic delivery in the future. About 10 to 20 percent of the users are from U.S. educational institutions; these tend to be higher-volume users, accounting for 40 percent of the products received. The archive is growing at around 4.5 terabytes per day while the daily distribution of data amounts of about 2.5 terabytes partitioned in about 10,000 specific files. By June 2003 the total EOSDIS storage totaled over 2,500 terabytes.

To accommodate the expected rapid expansion of users (e.g., those engaged in doing elementary school projects, farming, recreation, and so on) of traditional satellite data products, NOAA and other agencies must be prepared to make a significant investment in a data system that is in alignment with the complexity and scale of the challenge. The Comprehensive Large Array-data Stewardship System (CLASS) is being designed by NOAA to catalog, archive, and disseminate all NOAA environmental satellite data produced after 2006. At present, the goals of NOAA's CLASS are laudable:

- One-stop shopping and access capability;
- A common look and feel for access;

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[5] "EOSDIS Users and Usage: What We Know About Our Users," summary of presentation to ESISS Scripps Institution, February 17, 2004; Vanessa Griffin and Jeanne Behnke, NASA/GSFC ESDIS Project, Robert Wolfe, Raytheon, Kathy Fontaine, Global Change Data Center, and Steve Adamson, CSC. See http://www.earth.nasa.gov/visions/ESSAAC_minutes.html#.

[6] Ibid.

- Integration of data for the user, to include search, browse, and geospatial capabilities;
- High data quality and volume;
- An efficient architecture for archiving and distribution, including reduced implementation costs through centralization; and
- Capability for allowing NOAA to fulfill its requirements regarding archiving, accessing, and distributing large-array data sets.

As access to all types of digital information is made easier, so must the same be true of operational satellite data. As addressed in Chapter 3 of this report, the user interface has long been the greatest impediment to making satellite data readily accessible to public, private, and scientific communities.

SCIENTIFIC APPLICATIONS OF ENVIRONMENTAL SATELLITE DATA

As indicated above, the current flow of real-time and near-real-time information in NOAA is directly related to weather, ocean, and space monitoring and forecasting. These data are supplied to National Centers for Environmental Prediction (NCEP) users who may simply access a local NWS Web site and be directed to any number of satellite data products (essentially enhanced imagery) depicting current weather conditions and those of the immediate past. Other agencies (e.g., DOD, the U.S. Mission Control Center) and international partners (e.g., the United Kingdom) receive specific satellite data directly for their own operational purposes. Several satellite-based products (e.g., sea-surface temperature readings, soundings) are mounted to the Global Telecommunication System for access by member states. The level-1B POES, GOES (synoptic, event, continental United States), and other data product files are transmitted to the NCDC to be archived. Various other government and educational institutions house portions of the basic satellite data. As stated above, gaining access to these data is rather difficult for the typical scientist, and therefore almost insurmountable for the novice user.

Traditional disciplines in the Earth and biological sciences require satellite information as researchers seek to understand the global context of the component of the system being examined. NOAA supports data acquisition and dissemination for applications in meteorology, hydrology, oceanography, and agriculture and for studies of rivers, coasts, and fisheries, among others. Tropospheric ozone, for example, one of the Environmental Protection Agency's (EPA's) criteria pollutants, is observable from space as a result of the improved precision of algorithms (see the case study on ozone in Appendix D). Not to be overlooked is NOAA's task of monitoring and predicting space weather to better accommodate the variations in solar and other influences on the space environment and their impacts on human infrastructure both in space and on Earth's surface. Applications in other disciplines for operational satellite data are growing, and all such disciplines will continue to rely on satellite data as researchers work to increase our understanding of the Earth system.

COMMERCIAL APPLICATIONS

Ten years ago, most of us did not anticipate that we would be using cell phones, e-mail, and the Internet on a regular basis. Today these services are pervasive, and the communications activities thus made possible are commonplace. Commercial companies have been established to provide users with the tools and services they need to support these activities.

Private industry obtains data from today's NOAA and NASA environmental satellite sensors and packages it for end users, for example, as weather data available on television and via the World Wide Web. The GOES-R sounder and imager cost/benefit analysis found that billions of dollars in cost savings could be realized through the utilization of future geostationary operational environmental satellite data, based on its examination of the eight case studies quoted from below:[7]

1. "*Convective Weather Products: Benefits to Aviation*. GOES advanced sounder data are expected to substantially improve the ability to predict where convective weather such as thunderstorms will initiate within broad regions of unstable air. This information will significantly reduce the cost of operational delays because air carriers will be able to make better tactical dispatch and routing decisions and avoid last-minute actions to bypass these storms."
2. "*Volcanic Ash Advisories: Benefits to Aviation*. GOES advanced imager data will provide more accurate and timely warnings of the presence of airborne volcanic ash plumes that can seriously damage aircraft and jet engines and have the clear potential to cause serious aviation accidents. Winds derived from GOES advanced sounder data will enable more accurate and timely forecasts of the speed, altitude, and direction of these plumes. More accurate and timely volcanic ash advisories will reduce the cost of repairs and engine replacement from ash encounters and reduce the risk of catastrophic loss of aircraft, passengers, and crew from this hazard. . . ."
3. "*Temperature Forecasts: Cost Savings to Electric Utilities*. GOES advanced imager data on clouds and winds and advanced sounder data on humidity profiles

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[7] Prepared for the GOES Users Conference, October 1-3, 2002, Boulder, Colorado, by the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS) Office of Systems Development, October 1, 2002.

are expected to substantially reduce both the average and the variance in error in short-term (3-hour) temperature forecasts. Improved accuracy in temperature forecasts will increase the accuracy of electric utilities' short-term electricity load forecasts. Improved load forecasts will enable utilities to reduce their costs by reducing the average amount of generating capacity they keep in ready reserve (operating reserve) and the average amount of spot-power purchases they make in order to meet customer demand."

4. "*Temperature Forecasts: Benefits to Agriculture /Orchard Frost Mitigation*. As in Case Study 3, GOES advanced imager data on clouds and winds and advanced sounder data on humidity profiles are expected to substantially reduce the amount of error in short-term (3-hour) temperature forecasts. The increased data density provided by ABI and HES will also improve forecasters' ability to provide forecasts tailored for particular agricultural districts and areas. Improved temperature forecasts will improve orchardists' decisions about how much to spend on frost mitigation on a given night during sensitive budding and flowering periods and will decrease the average amount they spend on mitigation activities over time."

5. "*Soil Moisture Measurements: Benefits to Agriculture—Improved Irrigation Efficiency*. The GOES-R sounder will improve the accuracy of evapotranspiration (ET) estimates because of its ability to discriminate temperature and humidity changes at the lowest layer (boundary layer) of the atmosphere where plants and soils interact with air masses. In addition, the GOES-R sounder (if it uses the GIFTS sampling interval of 4 km) will provide these data with much more spatial detail than the current GOES sounder. The soil scientists at the University of Wisconsin (Norman and Diak) who are developing this technique state that the GOES-R sounder data will provide the greatest contribution to improving estimates of ET. In addition, they state that the GOES-R imager thermal channel will provide data on surface temperature changes (between sun-up and mid morning) on a substantially finer scale (2 km) than the current GOES imager (4 km). This is a four-fold improvement in spatial data and, when integrated with the GOES-R sounder data, will provide additional ability to discriminate ET at a scale closer to that of typical irrigated fields.

6. "*Hurricane Landfall and Intensity Improvements: Benefits to Recreational Boating—Damage Avoidance*. The increased spatial resolution and update cycle for GOES-R sea surface measurements will enable GOES-R to capture more continuous sea-surface temperature (SST) readings, thus providing the opportunity to more frequently re-initialize the SST data into models and therefore improve hurricane intensity forecasts. Rapid scan winds, tested on GOES 10, helped to better characterize the divergence, or lift, of the storm and thus the potential for intensification will be the norm on GOES-R. GOES-R improvements in the frequency and spatial resolution will improve the accuracy and density of wind-speed measurements (may double the number of wind vectors and double the accuracy of wind-speed esti-

mates). Improved knowledge of the location of the centers of circulation winds (storms) as well as the speed at which they are traveling (steering winds) will provide better information on when and where a particular storm will make landfall."

7. "*Temperature Forecasts: Benefits to Natural Gas—Load Forecasting Efficiency*. More rapid updates of clouds from the GOES-R imager, when assimilated into forecast models, will improve model predictions about temperature maximums and minimums because clouds moderate temperature peaks and lows. More detailed data on the lower layer of the atmosphere from the GOES-R sounder, combined with more frequent updates and smaller sampling intervals, will, when assimilated into forecast models, also improve the parameterization (input of data on temperature, humidity, winds) of the boundary layer in forecast models. In turn, the models should produce more accurate and specific predictions of temperature, humidity, winds, and precipitation. These potential improvements are based on studies of the contribution of current GOES data to the forecast accuracy of Eta and RUC2 models (Zapotocny, Benjamin, and others)."

8. "*Winter Weather Forecasting: Benefits to Trucking—Accident Reduction*. GOES-R will better anticipate near-term ice formation conditions: better models of precipitation as well as more timely and accurate information on land surface temperature to indicate when the ground temperature is below freezing. GOES-R will also provide a higher resolution real time fog product that will allow drivers to more efficiently reroute."

In looking toward the future, it is difficult to predict exactly what applications users will find for data from environmental satellite sensors (satellite-based or ground-based). However, it is clear that the demand for NOAA environmental satellite data will continue to increase and that users will expect and demand the commonplace availability of more and more processed data through their personal digital assistants or other such devices.

Imagine, for example, that recreational boaters will increasingly seek to determine ocean and weather conditions, both current and projected, in near real time before embarking on a recreational outing, and throughout the duration of the activity. Similarly, people will want to know the micro-climate weather conditions at an event (such as little-league games, weddings, or concerts) that they are planning to attend, and while they are in attendance.

Entrepreneurs will explore the market demand for data and services from NOAA sensors, and companies will be formed, with varying degrees of success, to provide users with the data and the services they desire. Although it was developed by the military for military purposes and continues to be operated by the military, civil users worldwide have found many applications for the GPS (see the case study on GPS in Appendix D). As technology continues to advance, more and more applications of environmental satellite data will find become apparent in commercial products and services.

LAND DATA AND LAND MANAGEMENT AGENCIES

NOAA, because of its historical agency mission focus on oceans and atmospheres, does not have much experience with land data sets. Major advances in land remote sensing have occurred in the last decade, fostered primarily by the development of the NASA Earth Observing System. These satellite data include derived biophysical variables such as vegetation cover, vegetation continuous fields, bidirectional reflectance distribution function, leaf area index, fraction of absorbed photosynthetically active radiation, photosynthesis, net primary production, and vegetation phenology. All of these are competed and selected MODIS land variables with established, documented algorithms and ongoing production by EOSDIS, yet none are listed as environmental data records (EDRs) for NPOESS. In fact, *out of 58 EDRs defined for NPOESS, only 6 are specifically for land and of these only two are vegetation oriented. For the 2012 flight of GOES-R, only 20 of the approximately 170 environmental observation requirements (EORs) are land-surface related; of these, only 4 are vegetation related.* Neither NOAA nor the land management agencies are effectively utilizing current satellite technologies and data sets for vegetation science, management, or applications.

Operational satellites provide global environmental weather and ocean monitoring data at kilometer spatial scales, sufficient to track hurricanes and other severe weather, and sufficient to monitor large-scale changes in surface conditions. NPOESS and the next-generation GOES will dramatically improve this capability, with spatial scales dropping from a few to one kilometer, and the frequency of observations improving severalfold. But current NPOESS and GOES-R plans appear to insufficiently address long-term terrestrial utilization trends, observations of which would enable climate monitoring and prediction to fulfill the new NOAA environmental observation vision. And current plans do not invoke a sufficiently fine spatial scale to allow the detailed assessment of land features that is required to track ecosystem health.

NOAA's vision, as stated in its latest strategic plan, "New Priorities for the 21st Century, NOAA's Strategic Plan for FY 2003–FY 2008 and Beyond,"[8] is "to move NOAA into the 21st Century scientifically and operationally, **in the same interrelated manner as the environment that we observe and forecast**, while recognizing

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[8] See "New Priorities for the 21st Century, NOAA's Strategic Plan for FY 2003–FY 2008 and Beyond," available at http://www.spo.noaa.gov/pdfs/FinalMarch31st.pdf.

the link between the global economy and our planet's environment" [emphasis added]. This suggests that the coupling between the land and the ocean surface and the atmosphere is critical, given that cycles of water, carbon, heat, and so forth are all about fluxes across these interfaces. NOAA's strategic plan also identifies five types of mission strategies and measures of success:

1. "Monitor and observe the land, sea, atmosphere, and space and create a data collection network to track Earth's changing systems."
2. "Understand and describe how natural systems work together through investigation and interpretation of information."
3. "Assess and predict the changes of natural systems, and provide information about the future."
4. "Engage, advise, and inform individuals, partners, communities, and industries to facilitate information flow, assure coordination and cooperation, and provide assistance in the use, evaluation, and application of information."
5. "Manage coastal and ocean resources to optimize benefits to the environment, the economy, and public safety."

The generation of an enhanced set of operational land vegetation variables from NPOESS and other operational systems would have high utility for land management. In addition, Landsat-type observations fill an important niche between the highly repetitive but coarse-spatial-resolution observations from the current NOAA AVHRR and NASA EOS MODIS and the future NPOESS VIIRS instruments and the ultrahigh-spatial-resolution, local observatories such as the IKONOS instrument operated by the Space Imaging Corporation. Landsat-class imagery provides systematic global coverage at a frequency sufficient to capture seasonal variations and at a spatial resolution where land cover dynamics, under the influence of natural processes and human activities, is clearly evident. If indeed we are to understand global change and its relationship to local environmental conditions, then Landsat-type observations will remain a fundamental requirement. These technical capabilities, combined with the 30-year archive, provide the underpinning for addressing emerging science and policy questions with environmental satellite data.

NOAA's second mission goal, to "understand climate variability and change to enhance society's ability to plan and respond," is also discussed in the recent multiagency "Climate Change Science Program Strategic Plan." It recognizes that "weather- and climate-sensitive industries, both directly and indirectly, account for about one-third of the Nation's gross domestic product, or $3.0 trillion." It continues:

> Seasonal and interannual variations in climate, like El Niño, led to economic impacts on the order of $25 billion for 1997-98, with property losses of over

> $2.5 billion and crop losses approaching $2.0 billion. Given such stresses as population growth, drought, and increasing demand for fresh water, and emerging infectious diseases, **it is essential for NOAA to provide reliable observations**, forecasts, and assessments of climate, water, and ecosystems to enhance decision makers' ability to minimize climate risks. . . . In the U.S. agricultural sector alone, better forecasts can be worth over $300 million in avoided losses annually. To enable society to better respond to changing climate conditions, NOAA, working with national and international partners, **will employ an end-to-end system comprised of integrated observations of key atmospheric, oceanic, and terrestrial variables**. . . . [emphasis added]

To achieve this mission goal, as well as pursue the first mission strategy and measure of success (monitor and observe), NOAA plans to "**invest in needed climate quality observations** and encourage other national and international investments **to provide a comprehensive observing system in support of climate assessments and forecasts**," with an "increased number of long-term observations collected, archived, available, and accessible. . . ." [emphasis added]

The land imperative has been demonstrated by NASA's Landsat program through a series of highly successful sensors that have been operating continuously since 1972. As a NASA program, however, Landsat has yet to achieve operational status and has not had the funding continuity to be part of NOAA/NESDIS's integrated operational environmental observation system. NASA has, however, proven Landsat's benefits and has recently demonstrated technology to dramatically lower operational cost. While the current Landsat 7 is still operating, it has reached its 5-year design life, and continuity is not assured even with immediate program restart.

As with the programmatic precedent in the NPOESS Preparatory Project (NPP), a second "span" of the NPOESS "bridge" could easily add climate and land observations with an Operational Land Imager (OLI). OLI technology has been demonstrated by the NASA Earth Orbiter 1 (EO-1) mission. After 4 years in orbit (twice its design life), EO-1 continues to produce data consistent in character with that of Landsat 7 via a sensor a tenth the mass of the Landsat 7 sensor. The reduced mass enables OLI to fit on a second NPP spacecraft with other sensors, including the Visible/Infrared Imager/Radiometer Suite (VIIRS). Coupled with parallel measurements from the NPP, such a second bridge mission could provide global measurements of the complete environment. Climate, atmosphere, land, and ocean would be observed with sufficient spatial scope and detail, frequency, and radiometric fidelity to address all the NOAA mission imperatives. NPOESS will continue the measurements and realize the integrated EOS vision.

VIIRS and OLI would provide complementary observations to complete NOAA's environmental satellite mission. VIIRS will offer almost daily coverage of Earth's entire surface in 22 spectral bands at spatial resolution from 400 to 800 m. OLI will afford less frequent coverage at 30-m spatial resolution in eight spectral bands optimized for vegetation and land. Large-scale change detected through VIIRS can be more closely evaluated, studied, and analyzed using OLI. Furthermore, VIIRS will provide data in spectral bands that can be used to atmospherically correct OLI, while OLI can be used to better calibrate VIIRS to validate climate and environmental data records derived from VIIRS. VIIRS will track dynamic Earth processes such as snow accumulation and melt-back, vegetation green-up and senescence, and fires on an interannual basis. OLI will focus on detailed land cover change, disturbance, and recovery, discerning the forces of change, and discriminating between natural and man-made causes, allowing us to predict key consequences and provide meaningful policy advice. Moreover, VIIRS and OLI synergy has been demonstrated by formation flying of the EOS Terra and Landsat 7 satellites. Terra MODIS and Landsat 7 Enhanced Thematic Mapper plus (ETM+) have proven VIIRS and OLI synergy and demonstrated the future of NPOESS to meet the complete NOAA vision.

NOAA needs to address the need to organize a multidisciplinary team to develop a land, vegetation, and agriculture product set for land management agencies and agricultural applications and for the ecological sciences. NOAA should convene an intergovernmental committee with NASA, the U.S. Department of Agriculture, the Department of the Interior, the EPA, and other interested parties to select operational land vegetation variables for generation from NPOESS, GOES, and other operational systems that will have high utility for land management. Only with direct and ongoing interaction with the land management agencies can the optimum mix of variables, time and space resolutions, variable units, data formats, distribution pipelines, and related details be determined. The land management agencies need to dedicate personnel and resources on their end to optimize reception and use of these data sets. The continuous and comprehensive monitoring provided by satellites of the millions of square kilometers of publicly managed land is not available in any other way.

3

Ensuring Data Access and Utilization

Users of NOAA's environmental satellite data fall into two distinct groups: those that receive data directly from NOAA and those that receive data indirectly as data-derived, value-added products from resellers. The group that receives data directly comprises a relatively small number of large institutions that individually consume huge amounts of data, such as the National Weather Service, the Department of Defense, universities, and other research institutions. The group that receives data indirectly includes a very large number of private citizens who individually consume a small amount of data from sources such as Accuweather and Weather.com. For this second group, the importance of environmental satellite data and the total volume consumed will grow dramatically as mechanisms for delivery of the data continue to improve.

MAKING IT EASIER TO USE ENVIRONMENTAL SATELLITE DATA

Data utilization by both direct and indirect users can be dramatically increased by making data easier to locate and use. The utilization of any data set is highly dependent on the following four "ease" factors: (1) the ease of discovering the data set, (2) the ease of understanding what the data set is, (3) the ease of acquiring the data set, and (4) the ease of translating the data set to a usable format. NOAA can best ensure utilization of its environmental satellite data by making certain that potential users can easily find, understand, obtain, and analyze the data.

The Internet has totally changed user communities' expectations regarding what acceptable data availability is. Twenty years ago a researcher looking for a data set began by searching in a library through card catalogs and periodical indexes, not uncommonly spending weeks finding relevant citations, locating the appropriate publication and its authors, requesting a copy of their data, and then waiting for the data to arrive by mail. Twenty years ago, a month was a reasonable and acceptable time for the entire data discovery and acquisition process. Today the expectation for that time frame has been compressed to less than a day.

Today's data users want to go to their favorite search engine and type in a few keywords describing the data they are looking for. They then expect to immediately see a listing of all relevant sources with direct links to Web pages that describe the data and are capable of delivering it directly to users' desktops with a simple click of their mouse. Finally, they expect the data to be in a format that is directly usable by whatever software package they happen to have. These are not unreasonable expectations for a potential data user, given today's technologies. In fact, NOAA could make this specific data discovery and delivery scenario integral to its goal for users' access to and use of its environmental satellite data. The achievement of the goal of near-real-time data availability is dependent on NOAA's fulfillment of the four "ease" factors mentioned above and discussed in more detail below.

Data cannot be used unless it has been found and understood. The first step in making data widely available is to specify a metadata standard that will be applied to all data sets produced by a data supplier. The purposes of a metadata standard are to provide a common terminology and set of definitions for documentation of the digital data being described. The standard should establish the names and the structure of data elements to be used for these purposes as well as their definitions and information about the values that are to be provided for the data elements. (Metadata for federal geospatial data are required by Executive Order 12906, "Coordinating Geographic Data Acquisition and Access: The National Spatial Data Infrastructure," which was signed in 1994 by President Clinton.) These metadata can then be used as a mechanism for distributing key words to agency Web sites and public search engines, thus enabling users to quickly and easily find and understand the data.

A user who has located data he believes will be useful will want to acquire the data as quickly as possible. If the data set is of a reasonable size, then the user should be able to download the entire set to a workstation via a widely accepted transfer protocol such as FTP or HTTP. If the data set is too large for such a transfer, then the user should be able to either view a compressed or degraded version of the data, or alternatively, download a subset of the data at its full resolution. The user can then order a CD or DVD of the data and have it delivered within a day or two.

Once a user has downloaded a data set to her desktop, it is imperative that the data be in a format that can be used easily—ideally, the most widely usable binary formats. When that is not possible, the format of the data should be fully documented so that the data can be easily imported into the user's application. All data sets should be readily usable by non-programmers.

MEETING USERS' REQUIREMENTS FOR ENVIRONMENTAL SATELLITE DATA

Direct Users

NPOESS and GOES-R will increase by several orders of magnitude the volume of NOAA data delivered to direct users. This increase must be accommodated by all the systems that support the operational and research environmental communities, and particularly by the components that support data production, storage, and distribution. For example, today the NOAA Satellite Active Archive/CLASS ingests approximately 0.2 terabytes per day. The launch of the first NPOESS satellite in 2009 will raise the daily archive rate to more than 5.3 terabytes per day. Subsequent NPOESS launches will raise the rate by approximately 1 terabyte per day per spacecraft until the predicted archive rate is in excess of 10 terabytes per day.[1] In addition, each satellite in the GOES-R series (first launch planned for 2012) is expected to produce much more than 1 terabyte per day of data. Therefore, adaptable data storage and distribution strategies, which can be tailored to the specific needs of users, are needed to achieve a cost-effective set of capabilities that are part of the Integrated Earth Observation System.

NOAAPORT, an important mechanism for broadcast distribution of operational weather data products, provides data at a rate of 1.5 Mbps. While incremental, or even step-function, increases in transmission bandwidth are possible via NOAAPORT-like direct broadcast system technologies, these systems do not scale well and offer limited additional capability unless the majority of the data products being broadcast are required by most of the user base. Although there will always be some high-volume users who can and want to receive all available data (e.g., NCEP), many other operational and scientific users would find such a data tsunami overwhelming and not useful. Then, the issue becomes how to get the right data to the right user at the right time.

The concept of operations for data distribution should center on tailoring data products to systems' and users' processing, storage, distribution, communications resources, and information requirements. Among the candidate strategies for meeting the needs of the broad spectrum of operational and scientific users of NOAA's data are the following:

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[1] NOAA/NESDIS, CEMSCS Overview, July 22, 2003.

- *Direct broadcast:* The current direct broadcast capabilities of POES, GOES, and NOAAPORT are critical elements of NOAA's overarching strategy to serve society's needs for weather and water information. NOAA POES, GOES, and NASA EOS satellites all currently provide direct-broadcast capability (for details, see the case study on direct broadcast in Appendix D). Although it is probable that Internet services for data distribution will satisfy a large fraction of the user community, it remains likely that because of the concerns about the availability and quality of commercially provided Internet service, as well as about the cost of maintaining private networks, direct broadcast will remain a valid option for many users, either as the primary data transport method or as a backup. The concerns of direct-broadcast users (e.g., data resolution, timeliness, bandwidth requirements, systems/technology/media, user upgrade cost, and transition approach) all have to be addressed.
- *Subsets and subsampling:* Subsets of data products can be tailored routinely and/or in response to a specific request (on demand). Routine subsetting is done in response to standing requirements (e.g., regional, or for a particular data characteristic) that can be defined a priori. On-demand subsetting occurs in response to current and forecast conditions. For example, routine subsetting can be used to cover areas of tropical storm formation that can be defined well in advance, whereas on-demand subsetting applies in the coverage of an existing storm's path, which must be defined and updated as frequently as several times a day. On-demand subsetting to cover thunderstorm and tornado conditions has to be continuously refined on a time scale of hours, or even minutes. Routine subsetting can also be done in a temporal context: for example, a standing requirement for general surveillance might require delivery of information only several times a day, rather than hourly or every time an area is observed.

  Subsampling is done in the context of either reduced spatial (e.g., 10-km resolution rather than a standard 1-km-resolution product) or, perhaps, reduced spectral (e.g., reduced number of channels) resolution.

  Subsetting and subsampling can be combined to provide a continuum of data products ranging from broad-area, low- to moderate-resolution products to regional (or smaller) high-resolution products.
- *Subscriptions:* Data products supplied by subscriptions can range from all of the data all of the time, to some of the data some of the time. For example, operational weather modelers may want all available data, whereas regional users may require high- or moderate-resolution data, but only for limited geographic areas and/or times. To fulfill validated subscriptions, NOAA can develop appropriate data products (e.g., for characterizing upper Midwest, tropical regions based on the use of subsetting and subsampling capabilities). Similarly, event-driven subscriptions (e.g., lifted index or cloud cover) can be used to provide data delivered to meet standing or ad hoc needs.

- *Search and order:* It will be difficult, if not impossible, to completely define a set of subscriptions that fully cover the range of conditions for which a user might need data. For example, an Advanced Weather Interactive Processing System (AWIPS) user who is monitoring an area might decide that additional information not already covered by a static or dynamic subscription would be useful. An ad hoc query, from either the AWIPS terminal or a user client, would allow the user to "drill down" into the data for more resolution, more bandwidth, more recent data, and so on, or to obtain data from other areas, time periods, or sensors that are helpful in understanding the current situation for forecasting.
- *Peer-to-peer access:* As data volumes increase, the traditional "person in the loop" search and order will be increasingly supplemented by peer-to-peer[2] system interfaces that automatically harvest NOAA data repositories for the data needed by users to generate their own domain-specific information products.
- *Maintaining a capability for data assurance:* Data assurance, the guaranteed delivery of scientifically valid data, is a key user requirement that system architecture, design, implementation, and operations must all support. Users must be able to tell, for example, if data has become corrupted during transmission, and so the data must have a defined, controlled format that ensures data integrity regardless of the delivery media. Similarly, data-compression techniques to reduce transmission and storage requirements must ensure the retention of scientific and operational validity and function from the perspective of the system and the user. Subsetting and subsampling create new products that must also meet NOAA's quality standards.

Despite the potential of each of these approaches to reduce communications requirements and enable the increased use of environmental satellite data throughout the operational and scientific community, these strategies pose additional requirements for data production, distribution, storage, and management.

Level-0 or level-1 data products have to be stored, and standard products produced must be based on operational and scientific needs. Dynamic requests create a need for ad hoc, on-demand processing to generate tailored products as described above. In addition, subscriptions based on data content (e.g., a parameter exceeding a predefined threshold value) are a source of additional requests for on-demand products and distribution. Simultaneous demands from many users or denial-of-

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[2] Generally, a peer-to-peer (or P2P) computer network is any network that does not have fixed clients and servers, but rather a number of *peer* nodes that function as both clients and servers for the other nodes on the network (in contrast with the client-server model). Any node on a P2P network is able to initiate or complete any supported transaction. Peer nodes may differ in local configuration, processing speed, network bandwidth, and storage quantity. Popular examples of P2P are file-sharing networks. See Wikipedia at http://en.wikipedia.org/wiki/Peer_to_peer.

service attacks could overload the data distribution system and degrade overall performance.

A long-term archive is needed to protect and preserve the permanent record, thereby enabling improvements in science through reanalysis, reprocessing, and development of new, time-series products. Requirements for access tend to be driven by long-term analysis campaigns and data volume rather than by timeliness. The archive must contain, at a minimum, the level-0 or level-1 products, the production software, and the control/initialization parameters used in operations. Selected higher-level products may also be archived to support distribution of historic data sets, provide a record for long-term studies and studies of trends, and support reanalysis and reprocessing. Reprocessing can then be performed on the data to improve algorithm performance or validate the impact of system changes via comparison with the operational products. Distribution of the archived data, reprocessed data, or new products is performed using the subscription and search-and-order capabilities described above.

Short-term storage is needed to meet users' immediate requirements and to provide a complete look at the recent and current environment, and so requirements for access are very time sensitive. Short-term storage also supports ad hoc subscriptions and search and order, and holds data between production and distribution for both data access and data distribution scenarios.

System management is required to resolve resource issues that arise when demand exceeds production, to provide for archiving/storage and distribution so as to ensure that needs are met in a prioritized manner, and to ensure that system security and integrity are maintained. System management can mitigate these challenges by allocation of additional resources (e.g., grid computing for processing), offloading service requests to back-up sites, or suspending service requests until higher-priority needs are met.

In summary, the higher-resolution data and improved temporal coverage offered by the NPOESS and GOES-R systems require innovative approaches to the production, archiving and storage, and distribution of the data so that NOAA's goals for the utilization of environmental satellite data by a broad range of users for the benefit of society can be realized.[3]

Indirect Users

Internet and cellular radio communication technologies are already expanding the use of NOAA's environmental satellite data by making data-derived products

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[3] P.E. Ardanuy, W.R. Bergen, G.E. Gray, T. Hickey, H-L. (A.) Huang, S. Marley, J.J. Puschell, and C. Schueler, "NPOESS and GOES-R—Building a 'System of Systems'," Paper 73919, January 2004 American Meteorological Society Annual Meeting.

such as weather maps and forecasts available to the private citizen via Web browsers and cellular phones. Such use of data should increase dramatically over the next 10 years as use of the Internet and cellular communication grows. For example, real-time lightning strike alerts in a user's local area could be easily accessible from the GOES-R (2012+ time frame) Geosynchronous Lightning Mapper, which will identify the time and location of each strike. With constrained budgets a fact of life, NOAA's emphasis should include the assured availability of a prioritized, validated data product set, beginning with calibrated-at-aperture radiances, atmospherically corrected radiances, cloud and other masks, and basic products of key utility (e.g., measurements of sea-surface temperature) before focusing on the complete spectrum of possible products. A possible consequence of this approach could be a focus on supporting the value-adding efforts of researchers and resellers rather than the interests of individual consumers (for every possible product). It is unlikely that NOAA will have the expertise or the resources to deal with the growing diversity of requirements and interests of hundreds of thousands of individual data users. Instead, NOAA should concentrate on developing and standardizing data portals suitable for data resellers, universities, and other value-adding parties.

TOWARD ENHANCED DATA UTILIZATION—A SAMPLING OF CURRENT EFFORTS

The Geospatial One-Stop Initiative

President George W. Bush's e-government strategy has identified several high-payoff, government-wide initiatives to integrate agency operations and information technology investments.[4] The goal of these initiatives is to eliminate redundant systems and significantly improve the government's quality of customer service for citizens and businesses. One of these initiatives is entitled "Geospatial One-Stop."

Geospatial data identifies the geographic location and characteristics of natural or constructed features of and boundaries on Earth. Although a wealth of geospatial

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[4] The E-Government Act (Public Law 107-347) of the 107th Congress was signed into law by President Bush on December 17, 2002. Its purpose is to "enhance the management and promotion of electronic Government services and processes by establishing a Federal Chief Information Officer within the Office of Management and Budget, and by establishing a broad framework of measures that require using Internet-based information technology to enhance citizen access to Government information and services, and for other purposes."

In his February 2002 budget submission to Congress, President Bush outlined a management agenda for making government more focused on citizens and results. The budget included expanding e-government, which uses improved Internet-based technology to make it easy for citizens and businesses to interact with the government, save taxpayer dollars, and streamline citizen-to-government communications.

information exists, it is often difficult to locate, access, share, and integrate in a timely and efficient manner. Myriad government organizations collect geospatial data in different formats and standards to serve specific missions. This can result in inefficient spending on information assets, and impedes the ability of federal, state, and local government to perform critical intergovernmental functions, such as homeland security.

The Geospatial One-Stop initiative will promote coordination and alignment of geospatial data collection and maintenance among all levels of government. The initiative's goals include:

- Developing portals for seamless access to geospatial information,
- Providing standards and models for geospatial data, and
- Creating an interactive index to geospatial data holdings at federal and nonfederal levels.

Encouraging greater coordination among federal, state, and local agencies as regards existing and planned geospatial data collections, Geospatial One-Stop will accomplish these goals by accelerating the development of the National Spatial Data Infrastructure (NSDI), which will provide federal, state, and local governments, as well as private citizens, with "one-stop" access to geospatial data. Interoperability tools, which allow different parties to share data, will be used to migrate current geospatial data from all levels of government to the NSDI, following data standards developed and coordinated through the Federal Geographic Data Committee using the standards process of the American National Standards Institute. A comprehensive Web portal will then be developed and deployed to provide "one-stop" access to standardized geospatial data.

Much of the data that NOAA is responsible for managing is geospatial in nature and is therefore subject to the requirements of the GeoSpatial One-Stop initiative. For example, hyper-dimensional environmental satellite data is obtained from observing Earth's land surface, oceans, and atmosphere in three spatial dimensions as a function of time, using multiple sensors and multiple orbit planes, each with specific solar-illumination and viewing-zenith angles, with multi- and hyper-spectral sensor capability. From these data are created multi-dimensional environmental data products with accompanying metadata. Typical utilization includes data development, processing and reprocessing, validation, and analysis. Many of these processes require integrating simultaneous and collocated "truth" data from ground-based and airborne in situ and remote assets, including data acquisition, management, imaging, and processing in arbitrary multiple dimensions, including spatial/relational methods in time and space.

The Experience with EOSDIS

The Earth Observing System Data and Information System (EOSDIS) manages data from NASA's science research satellites and field measurement programs. The system has been operating since August 1994. EOSDIS is a distributed system with many interconnected nodes, each with specific responsibilities for the production, archiving, and distribution of data products. Eight of these nodes constitute the Distributed Active Archive Centers (DAACs) around the United States.

Currently, EOSDIS is managing and distributing data from:

- EOS missions (Landsat 7, QuikSCAT, Terra, Aqua, Aura, and ACRIMSAT);
- Pre-EOS missions (UARS, SeaWIFS, TOMS-EP, TOPEX/Poseidon, and TRMM); and
- All of the Earth Science Enterprise legacy data (e.g., Pathfinder data sets).

EOSDIS holds more than 1450 data sets. In fiscal year 2000, EOSDIS supported more than 104,000 unique users and filled 3.4 million product requests (over 8.1 million products were delivered). Repeat users averaged 60 percent. EOSDIS customers include researchers; federal, state, and local governments; application users; the commercial remote sensing community; teachers; museums; and the general public. Anyone can access EOSDIS data at any DAAC through the EOS Data Gateway.

EOSDIS is managing extraordinary rates and volumes of scientific data. The Terra spacecraft produces 194 gigabytes of data per day with a data downlink speed of 150 megabits per second. The average amount of data collected per orbit is 18.36 megabits per second. In addition to Terra, Landsat 7 is producing 150 gigabytes of data per day.

In August 1999, NASA's entire Earth science data holdings were estimated at about 284 terabytes. Terra's data when processed through higher levels totals 850 gigabytes per day. The Terra satellite alone will have doubled NASA's Earth science holdings in less than 1 year. At 194 gigabytes per day Terra takes in almost as much data as the Hubble Space Telescope acquires in an entire year, as much data as the Upper Atmosphere Research Satellite obtains in $1^1/_2$ years, and as much data as the Tropical Rainfall Measuring Mission obtains in 200 days.

Figure 3.1 shows user demand for EOSDIS data products during fiscal year 2003.

Case Study of Temperature Measurements

One example of how NOAA has developed a means to take advantage of externally processed, value-added satellite data is found in global atmospheric tem-

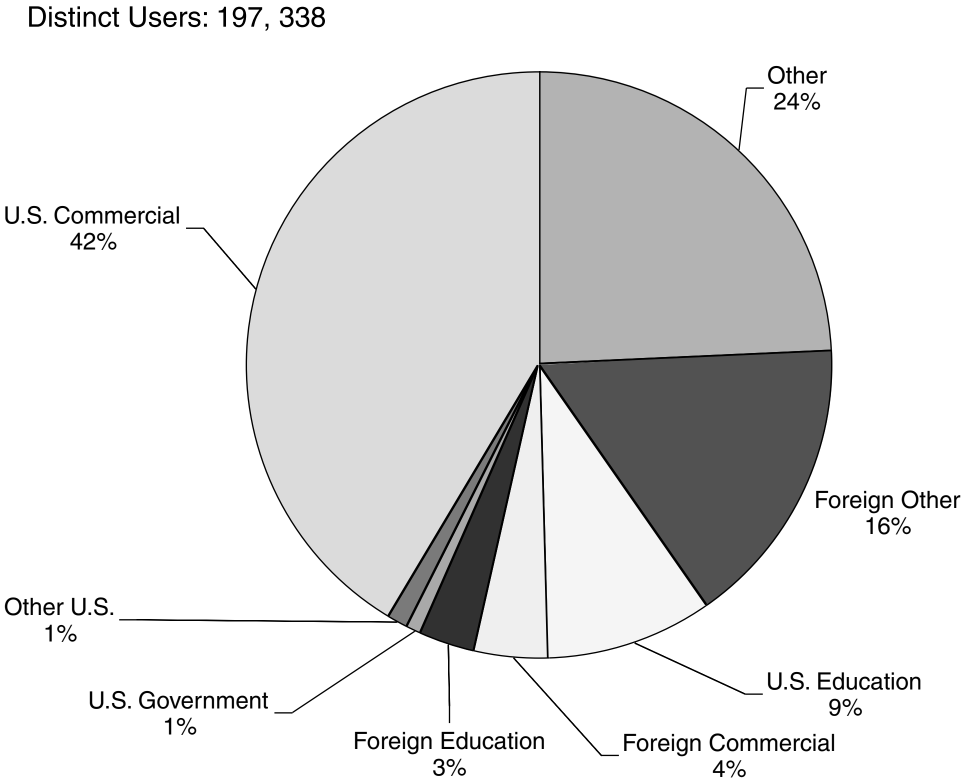

FIGURE 3.1 User demand for EOSDIS data products during fiscal year 2003. SOURCE: Presented to the committee by H.K. Ramapriyan, assistant project manager, ESDIS Project, NASA.

perature products generated from microwave emissions. In attempting to create global measurements of upper air temperatures with long-term stability, two University of Alabama, Huntsville scientists developed a relatively homogeneous time series of globally gridded, deep-layer temperature measurements in 1990. These products required highly specialized knowledge of the NOAA microwave instruments and of the spacecraft on which they flew. Years of subsequent research, funded through scientific grants and published in the peer-reviewed literature, have been necessary to discover minuscule, spurious effects that are of no consequence to the real-time weather forecasting mission, but that are significant for long-term climate monitoring. For example, adjustments were developed for errors introduced from orbital drift, calibration shifts, and unanticipated biases, all of which generally fall below 0.1 C in magnitude. Since knowledge of changes in global temperature needs to be precise to a few hundredths of a degree per decade, such errors are important to detect and resolve.

Producing a data set with precision of this level on a continuing basis might best be called operational research. Unfortunately, there has not been a source of funding for this type of project because it requires constant human attentiveness and intervention rather than a set period of performance.

Because of the highly specialized expertise required for the construction of these data sets, few scientists undertake such endeavors, and such efforts are generally outside the tasks mandated for NOAA employees. NOAA has deemed a few of these data construction activities as vital for its climate monitoring function and so has initiated small contracts with groups such as the University of Alabama, Huntsville, which then provide monthly updates of these products, usually by the tenth day after each month's end. As additional spurious effects are discovered and minimized, these data sets are updated, metadata files describing the issue are created, and if appropriate, the results are published in the peer-reviewed literature.

This case study presents a scenario in which NOAA's mission to provide climate-quality data records for national and international assessments is met through the expertise of university scientists at relatively low cost.

4

Assessing the Implications of Multidirectional Interfaces

DATA INTEGRITY AND QUALITY

Assuring data integrity and quality in a distributed federated system is perhaps the biggest challenge in planning for the effective utilization of environmental satellite data in the next 10 to 15 years. Four distinct but related aspects of data have to be addressed to ensure effective stewardship of distributed data: data integrity, identity, quality, and lineage.

Integrity

As data granules (delivery units) move among NASA, NOAA, and other agencies, brokers, value-added providers, and end users, there will have to be some way of assuring their integrity, that is, that content has not been altered. Digital signatures (e.g., checksums, one-way hash functions, and so on) provide a straightforward way to accomplish this. In the particular case of environmental satellite data, it will be most effective if the signature scheme is insensitive to lossless transformations (compression, reformatting, etc.) which are likely to occur as part of the data's normal utilization.

Implication: All data granules distributed by NASA and NOAA should include a digital signature calculated by a standard, open algorithm, so that NASA and NOAA and any subsequent users of the data can verify its integrity.

Identity

In addition to a signature derivable from their content, data granules need *names* that identify their content (semantics) independent of the content's representation (structure). The separation between identity and integrity is subtle but important, since although it is desirable for their relationship to be one to one, in practice it is likely to be one to many. It may simply not be possible for a lossless transformation of a granule (e.g., reformatting from HDF to TIFF) to preserve the same signature. Even if the relationship were always one to one, there is a general need to be able to refer to granules with names that make some sense to users, as opposed to the apparently random bit strings of digital signatures.

> **Implication: All data streams distributed by NASA and NOAA should have a well-defined granule naming convention. Where possible, services should be supported that map between granule names and signatures, so that names of granules may be recovered from their signatures.**

Quality

Quality is simply a set of assertions about a data granule that provide sufficient ancillary/contextual information (metadata) about the granule to enable effective interpretation of its contents. Conventionally these assertions either are packaged with the granule (as embedded metadata) or are implicit in the granule's parent data set (e.g., MODIS ocean color product). However, if a granule's identity can be reliably established, then quality assertions can be provided by services that accept the granule's name as input. This avoids the problem of constantly extending data formats to accommodate new forms of embedded metadata.

> **Implication: NASA and NOAA should provide services by which a data granule's name may be used to recover all metadata relevant to that granule.**

Lineage

Static assertions about a data granule are only part of the context required to interpret the data. Even more important is the *lineage* of the data: the graph of antecedent data granules and transformations from which the granule was produced. Lineage, the "pedigree" of a data granule, is often a key determinant of a granule's fitness for a particular use. For example, retrospectively updating the calibration of a low-level data product invalidates any derived products. If the lineage of the derived products is available, then such broken dependencies will be obvious.

It is a straightforward step from a system that maintains information about data granules to one that maintains connections between granules, but there is as yet no standard way to represent such connections. This is a key area for future development to ensure the reliability of data products generated in a distributed fashion.

Implication: NASA and NOAA should pursue the development of a system of maintaining lineage connections between data granule names.

DATA ACCESSIBILITY

The fundamental question regarding data accessibility is, Is the data readily available, in a form that I can use, at a cost that I can afford? Ready availability is primarily a combination of keeping the data online (as elaborated in the section "Storage" in Chapter 1) and published through well-defined services. In particular, the emerging Web services infrastructure (the UDDI, WSDL, and SOAP standards for discovery, specification, and invocation, respectively; all based on XML) should allow data access in ways directly supported by the development platforms (e.g., Java, Microsoft.net, etc.) with which most future applications will be built. Like massive online storage, support for Web services is expected to be ubiquitous, indeed the default means via which most satellite data will be accessed during the time frame of this report.

Implication: All NASA and NOAA satellite data should be accessible via standard Web services.

Data usability cuts directly to the contentious issue of data formats, that is, the logical structures (grids, geometry, embedded metadata, etc.) in which digital data are packaged for delivery. Digital data formats originated as "snapshots" of the internal state of specific software tools, for which it was more important to move data efficiently between the tool's memory and an online store. Only later were formats such as netCDF and HDF developed whose primary role was to move data between possibly dissimilar tools—i.e., formats for which interoperability was a primary design constraint. The problem to date with such "universal" data formats is that they have not supplanted the use of more specific formats within many communities of practice, nor have truly universal tools for translating between formats been widely promulgated. This situation can be expected to change; there are simply too many compelling benefits to be realized from having relatively few standard data formats to support. However, as the EOSDIS experience amply demonstrates, attempts to impose a standard data format on a community by fiat, and especially without comprehensive tools for supporting the community's existing format(s), are doomed to failure. It is thus critical that the overall system be designed so that data formats are not obstacles to data utilization.

Implication: NASA and NOAA satellite data should be available in the formats best supported by the *user* communities. If NASA and NOAA cannot supply data in these formats directly, they should supply the data in standard formats that have been *demonstrated* to be readily convertible to community formats, and should aggressively support the development of third-party services that can transparently provide such format conversion.

Finally, the accessibility of environmental satellite data can be hindered by the imposition of significant fees, or other constraints on use, as shown by NOAA's previous experience with the Landsat program in the 1980s. Landsat was originally a NASA program. In 1979, President Jimmy Carter transferred the Landsat program to NOAA. In 1983 President Ronald Reagan directed NOAA to place the program in the hands of a private corporation. The Land Remote-Sensing Commercialization Act of 1984, enacted by Congress, gave guidelines for this transfer. However, studies showed that federal government subsidies of up to $500 million were required to make the commercialization effort viable.

The Reagan administration offered only $250 million in subsidies to the prospective contractors. As a result, only one company was willing to bid for the Landsat commercialization contract. The company was named Eosat. It was a joint venture between Hughes and RCA. Eosat was to operate the existing Landsats 4 and 5 satellites and to build two new satellites, Landsats 6 and 7. Eosat would then hold the exclusive rights to market satellite images and digital data.

Eosat was never able to raise the government subsidies necessary to make its company profitable. So, it quadrupled the price of satellite images and data and also collected large fees from overseas ground stations. The company never became financially viable. The higher prices significantly reduced the use of satellite images and data, thereby hindering data use and further diminishing Eosat revenues.

It finally became clear to Congress that the market for satellite data was not ready to support a commercial company. A new law, the Land Remote-Sensing Policy Act of 1992, repealed the 1984 law and returned Landsat to the government. The price of Landsat images and data dropped and usage increased.

INFORMATION TECHNOLOGY

A significant benefit of a federated distributed system designed around public interfaces is an increased adaptability to technological change. As noted in the section "Processing" in Chapter 1, the various underlying technologies in the data management infrastructure are expected to experience cost/performance improvements at rates equal to at least that of Moore's law, for at least the next 10 to 15 years. This argues strongly for "just in time" implementation of specific system components, which in turn is much simpler if the components interact with the rest of the system only through well-defined, stable interfaces. This applies at both the system integration level (e.g., delaying purchasing storage hardware to take advantage of falling prices) and at the administrative level (e.g., multiple third parties making their products available to different user communities at different times, as the needs of those communities stabilize).

Moore's law-driven technological change is reasonably predictable, but an interface-based system is also more adaptable to revolutionary/disruptive change. For example, in the early 1990s, systems with tightly integrated graphical user interfaces (GUIs) had much greater difficulty making the transition to the World Wide Web than did systems whose GUIs were separated from the underlying functionality by well-defined interfaces, and could thus be replaced by clients based on Web browsers. In general, a disruptive change whose consequences can be contained between system interfaces stands much less chance of disrupting the entire system.

USER EDUCATION

As discussed above, there is a wide range of data users, from high-end users such as the numerical weather prediction centers to companies providing products derived from satellite data to individuals logging on to retrieve imagery to guide decisions about recreation. Because of this range, there is a corresponding diversity in the education needs of the users.

To facilitate and improve the use of environmental satellite data, education and/or training is needed to help users effectively address the following key issues:

- What environmental parameters are measured by satellite observations?
- For a desired parameter, how can data availability be determined?
- For that data, what are the coverage, sampling, and data storage characteristics?
- How can the data be obtained, from whom, in what form, at what cost, and with what delay?
- How can the data be worked with to produce desired products, information?

What are the quality and accuracy issues with the data, and where are the associated techniques and calibration procedures summarized? (see in Appendix D the section "Bilko: A Case Study in Educating Users").

In partnership with satellite data providers, operational users of high volumes of satellite data, such as the numerical weather prediction centers, need to educate staff and to conduct preliminary trials with synthetic data sets. They can ill afford to experience loss of productivity and/or degradation of forecast skill by introducing new data and associated assimilation methodologies. Education and outreach to such users must alert them far in advance about potential new sources and types of satellite data, the uncertainties in the data, the planned space/time sampling, and plans for the continuity of the observations in the future. These users must then work to develop the subsetting and assimilation tools they need to make optimal use of the data. Governmental, scientific, and commercial producers of derived and/or value-added products will seek similar opportunities to educate themselves about future satellite data and to prepare for its use in order to best serve their needs to prepare products or carry out research and assessments.

Many potential users of satellite data need less than the full volume fed to the high-end users. They are aware of the availability of satellite data and seek to use a space- or time-sampled subset. For them, the requirement of the interface is to guide them to access the geophysical variable they seek, and to explain the accuracy and sampling characteristics of the data. For these users, educational needs include learning what data is available from what servers and learning how to download and manipulate the data, including how to geolocate and subset the data.

Potentially, there can be much greater use of satellite data if new users have the opportunity for adequate training and education. For a new user, the volume of raw digital data and the trials of acquiring and manipulating that data can be a major obstacle. An approach that has had success in many instances is to provide user-friendly access to satellite-based imagery, allowing new users to become familiar with satellite fields and coverage by downloading or viewing image files. Training courses such as the United Nations Educational, Scientific, and Cultural Organization (UNESCO) Bilko software package (see Appendix D), which provides training in understanding and manipulating satellite images of oceanographic relevance, supply entry-level education for new users. For these users to effectively transition to working with digital data, additional educational needs must be met that include adequate training to efficiently locate, acquire, and manipulate digital data files.

For all levels of user sophistication, education is a nontrivial undertaking, and, to some extent, user education requirements can be mitigated by adhering to current standards and practices. This leverages knowledge that users are already likely to possess.

USER PARTICIPATION IN PLANNING AND PERFORMANCE FEEDBACK

Because of the long lead time associated with satellite missions and because of the limited involvement of the broad spectrum of potential end users in that planning process, the agencies must make a deliberate effort to actively involve end users in long-range strategic planning. They also need to derive the benefit of the experience of the community of end users and to create pathways for feedback on the performance of the environmental satellite sensors and missions.

Two formats for user participation have been successful. One is the formation of a panel or team (sometimes called science teams or expert panels) that has diverse representation inclusive of end users external to the agency responsible for the sensor. This team works on sampling characteristics, algorithm development, and data quality, beginning prior to launch and following through after launch. The science teams have achieved close engagement by some end users and added the value of intense external consideration of performance.

A second approach to gaining user participation and better suited for seeking guidance for planning future satellite observations is the convening of user workshops. These can, for example, be focused on a specific observable, such as soil moisture; on a possible mission, such as measuring sea-surface salinity; or on the suite of instrumentation to be flown on a family of satellites, such as NPOESS. The participants provide feedback on the performance of current missions and on what new observations, new sampling characteristics, or new accuracies are needed to achieve their goals.

5

Critical Factors Driving the Evolution of Operational Satellite Data Management Responsibilities

It is clear that, because of the growing multiplicity of environmental satellite data users, a "one size fits all" system will not provide the desired utilization of the data. Similarly, some factors and/or attributes critical to some in a versatile serving system will not be needed by, or even benefit, all of the user applications. This chapter identifies the driving requirements for operational data system management, captures the principal critical factors, and provides references to user segments where they are definitely required.

REAL-TIME PROCESSING

Latency—the amount of time it takes to progress from photons into the sensor to useful data products in the hands of the users—is a measure of product quality that is as significant as accuracy, precision, long-term stability, and spatial-temporal resolution. Product timeliness is a leading priority for operational users, numerical weather prediction centers, National Weather Service field office forecasters, the forest services, marine warnings and surveillance, and FEMA/homeland security. Getting the information to users involves the practical handling of:

- Data volume—ability to process and disseminate,
- Data reduction and fusion—knowledge extraction within an enterprise IT architecture,
- Integration of satellite data and information into decision aids, and

- Integrated sensor training to achieve the optimal use of information in operations.[1]

Several examples serve to illustrate the criticality of real-time processing. First, consider weather forecasting. Numerical weather prediction models are scheduled to be run twice daily, and they use the most recent data available at the time of execution. The fresher the data, the better the forecast, and the sooner the forecast is available for use, the more utility it provides. Louis Uccellini, director of the National Centers for Environmental Prediction (NCEP), stated, “Products have a 2.5 hour shelf-life—anything you can do to compress the front end that can give me minutes on the back end is critical.” For example at the local level, where a field-office meteorologist is assessing lifted index or convective available potential energy (CAPE) between clouds or near an approaching cold front (both are measures of severe thunderstorm potential), fine spatial resolution and timeliness are tied for the highest priority.

During the summers of 2001, 2002, and 2003 the collaboration of NASA, the U.S. Forest Service, and the University of Maryland streamlined the direct reception, immediate processing, and distribution of 250-m MODIS data identifying fire activity and perimeters directly to the National Interagency Fire Center in Boise, as well as to Regional Fire Coordination Centers (see in Appendix D the section titled “MODIS Fire Rapid Response System”).

The U.S. Navy’s Fleet Numerical Meteorology and Oceanography Center (FNMOC) and U.S. Air Force Weather Agency (AFWA) face equally challenging real-time applications and are engaged no less than the civilian side in the utilization of both operational and research products for operational exploitation. For example, on March 23, 2003, when a frontal passage over Iraq introduced deteriorating conditions over Baghdad, the Air Force stopped operations and Navy ships took over all operations in support of ground troops. “We are currently using the [Satellite Focus] products to determine the Abe’s track to safely support the mission,” stated AG2 Anthony Wade, USS ABRAHAM LINCOLN (CVN-72). “We check the [Satellite Focus] website twice per day . . . . thank you for the support, it has been helpful to us out here . . . . We use this [MODIS dust product] to monitor dust events over Iraq and the NAG and it is an awesome product,” stated AGC Steven Cole, USS KITTY HAWK (CV-63).[2] For the Forest Service, using data taken four times daily by NASA’s Moderate-resolution Imaging Spectroradiometer (MODIS) instruments flying on the Terra and Aqua platforms and processed and made available by the University

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[1] Jack Kelly, GOES Users’ Conference, October 1, 2002.

[2] “FNMOC Data Products Built from NPOESS Environmental Data Records,” Jeff Haferman, NPOESS NPP Calibration/Validation Working Group, June 12, 2003, National Conference Center, Leesburg, Va.

of Maryland as well as through direct broadcast, provides critical information to manage emergency response to emerging and evolving fire threats.

It is clear that, for these classes of operational users, real-time, or near-real-time, processing is a critical factor in the utility of environmental satellite data. There is value in reducing system latency until, as a goal, a pixel of information appears on a user's display as the corresponding detector is read out on orbit. As a philosophy, no system should be designed or implemented that unnecessarily adds latency into the end-to-end data stream. Here, the system level includes sensor tasking, processing, exploitation, and dissemination, including the time taken to command the acquisition of needed data, delays within sensor and satellite, buffering and delays in the satellite-to-ground downlink, delays in collection of all satellite and ancillary data at the processing centrals, the wall-clock time required to produce the end products, and the time required to notify the end users and deliver the valid products to their workstations.

Reduction of latency is an area ripe for exploitation in data system management. Current POES systems typically use infrequent contacts with polar ground stations or data relay satellites. This introduces one to two orbits (1 to 3 hours) of delay into the data acquisition even before the ground processing begins. The NPOESS implementation, termed "SafetyNet," leverages the global presence of high-bandwidth fiber optic cable. Not only is the solution cheaper than today's traditional approaches, but the globally distributed network of 15 receptors are also linked to processing centrals via commercial fiber to enable both low data latency and high data availability. Facilitated by the near-instantaneous and near-continuous data availability, ground processing executes efficiently, producing and delivering the first environmental satellite data products less than 4 minutes after they are sensed on orbit, completing more than 60 percent in 10 minutes, and 95 percent of the products in less than half an hour.

DATA STREAM AND PRODUCT TRANSPARENCY

Transparency is critical and has several applicable definitions. In one context, the term "transparency" means that users are unaware of, and unconcerned with, the system supporting their data utilization. This includes transparent data interfaces efficiently handling the tasking, processing, storage, formatting, exploitation, delivery, visualization, and decision support systems. An example of transparency is dial tone when you pick up your telephone receiver; another is the link between a computer keyboard and the screen where the character you just typed is displayed. One gives no thought to the complex systems that connect your action to the response—unless they don't work transparently. This simple concept has significant implications. Beyond simple latency, this implies a relentless focus on total customer satisfaction. It mandates intuitive user interfaces, pervasive ("anywhere, anytime") access, immediate response, and delivery of the requested data—and no more than the requested data—at the requested resolution and in the "right" data formats. In today's technology, this suggests Web-enabled technologies, backed-up total interoperability, and the maximum possible online storage, with the custom ordering of data (e.g., spatial, spectral, and/or temporal subsetting and subsampling) designed in. Portal technologies (e.g., "My NOAA") can facilitate this, greeting the "customer" with announcements of available—and even recommended—data, and remembering recent orders and preferences. Commercial providers such as Amazon.com provide glimpses of this new operational concept.

Transparency has a second context: the provision of comprehensive metadata that enables user high-level and drill-down capability for insight into the complete pedigree of a product, algorithm theoretical basis, sensor, calibration, ancillary data, and processing path, with error budgets all available on the Web. Taken as a whole, this information empowers the environmental satellite data users as comprehensive authorities on the products they are using. It also mandates a comprehensive product/algorithm revision history. Transparency also means that research and operations are managed as a continuum, with continuous improvement designed into the operations concept such that engaged researchers anticipate, and underpin, improved operational requirements satisfaction. Finally, it means transparent and efficient user interfaces to proactively and iteratively collect, understand, and embrace operational users' requirements and feedback.

DATA ARCHIVING AND RETRIEVAL

Meeting NOAA's NPOESS and GOES-R system goals will require a re-examination of how NOAA will do its weather business, its ocean business, its land business, and in fact the entirety of its environmental data business, to achieve full system potential. EOSDIS provides perhaps the premier example for environmental satellite data archiving and retrieval. The lessons learned on EOSDIS (see "The Experience with EOSDIS," in Chapter 3) brought about profound changes in the data system's topology and architecture at all levels.[3] The potential to improve performance will require rethinking much of the existing architecture and an end-to-end process from satellite system and instrument design (data utilization experts at the table) to end-user data utilization (satellite and instrument characterization engineers at the table). As described in "Making It Easier to Use Environmental Satellite Data," in Chapter 3,

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[3] "GES DAAC Lessons Learned from the Development of EOSDIS," Christopher Lynnes, systems engineer, Goddard Earth Sciences Distributed Active Archive Center.

the committee believes that the operations concept for data distribution should be built around tailoring products to the system's and users' processing, storage, distribution, communications resources, and information requirements, to include:

- Direct broadcast,
- Subsetting,
- Subsampling,
- Subscriptions,
- Search and order,
- Peer-to-peer access interfaces,
- Tailored delivery,
- Data assurance,
- Short-term storage to meet the immediate user needs, and
- Long-term archiving to enable product improvements through reanalysis, reprocessing, and new product development.

GEOSPATIAL ONE-STOP

Compliance with Geospatial One-Stop is discussed in "Geospatial One-Stop," in Chapter 4.

REPROCESSING

Operational timelines rightfully dictate that products be generated on rigid schedules to meet immediate end-user expectations. A purely operational weather forecasting system requires a minimum data throughput (after allowance for maintenance and repair) equal to the rate of data acquisition to avoid accumulating irreducible backlogs.

Frequently, whether science-initiated or a correction to repair an anomaly or error, operational algorithms are improved, refined, or otherwise revised or replaced. In addition, improved externally supplied, ancillary data are not fully available or available at their best quality in near real time. Every change to an algorithm, be it the theoretical basis or even the exception handling, breaks the continuity of the measurement time-series, even as it improves the instantaneous product quality.

For end-user applications that depend on self-consistent long-term data records, for example to assess inter-annual variability, predict the onset of the next el Niño event, or conduct change detection and/or monitoring, it is critical that the changed algorithm signal in the measurement time-series database ("the noise") not exceed the climate signal of interest. Recovery of this long-term measurement stability requires a reprocessing cycle using a consistent algorithm theoretical basis and implementation.

Traditionally, long-term data records—such as the 25-year total SBUV and TOMS ozone measurement record critical for assessing the growth and recovery of the Antarctic ozone hole—may undergo as many as 10 reprocessing cycles. The types of data users least concerned with reprocessing are associated with operational weather forecasting (environmental data records; EDRs) and four-dimensional data assimilation (using radiances and EDRs). Users most interested in reprocessed data sets include those involved with emerging operational climate forecasting and climate research. New remote sensing systems, such as NPOESS and GOES-R, will not fully meet NOAA climate data record (CDR) requirements, as discontinuities will be routine, and reprocessing is outside of the scope of the activity. The United States operates two satellites in geostationary orbits, over fixed equatorial positions (HES PORD; http://cimss.ssec.wisc.edu/goes/goes.html) (see in Appendix D the section "GOES Imager and Sounder" for details).

In these near-real-time operational data products, the sensor data records (SDRs) and EDRs, the leading signal will be the algorithm revision signal. For this very reason, NCEP performed a systematic re-analysis of its geopotential height data record to eliminate the false algorithm signal.[4,5] While the NPOESS sensors are generally designed to assure long-term stability, as will be the case for GOES-R, improvements to on-orbit sensor characterizations/calibrations will not be retrospectively applied to the operational products, and this required long-term stability will be achieved only when the data are consistently reprocessed.

The SBUV/TOMS case study, and many similar projects, including SeaWiFS and MODIS , have demonstrated the importance of self-consistent long-term climate data sets. NOAA/NESDIS and downstream end users have a critical need for high-quality, long-term, self-consistent time-series. Their common attributes will be standard SDR/EDR/CDR algorithms, consistently applied, common sensor characterizations, refined and peer-reviewed sensor calibrations, the best possible ancillary data. Any reprocessed data must be available in a reasonably timely manner, and validated to assure the high quality that will stand up to rigorous peer review.

Environmental satellite data processing systems are sized to process a day's worth of data in one day, or "1X." Such a system would be insufficient for reprocess-

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[4] B.A. Harris and G. Kelly, 2001, "A Satellite Radiance Bias Correction Scheme for Radiance Assimilation," *Q.J.R. Meteorol. Soc.* 127: 1453-1468.

[5] Geopotential height is the height of a pressure surface (e.g., 500 mb) above the geoid. It describes the space-time four-dimensional distribution of the atmospheric mass field, and—therefore—the pressure gradients that are the dominant force driving atmospheric circulations. These pressure fields have been collected from radiosonde ascents, analyzed, and archived for decades. To develop a self-consistent understanding of these circulations over these decades, it is critical that the pressure fields be consistently analyzed. A change in the analysis algorithm would create an apparent change in atmospheric circulation—when in fact no change had actually occurred.

ing a multiyear data set. For reprocessing a measurement record of several months duration, 3X is quite appropriate. In order to permit new algorithm development for research or operations, new retrospective analyses to detect climate or other trends, and so on, the aggregate available data processing capacity/throughput devoted to the overall system must be several multiples of the real-time data acquisition and processing capacity required by the operational satellite systems. For a measurement record spanning years or more, 3X is barely sufficient, and the recommended minimum threshold accelerated rate would be 5X, with a goal of 10X. Achieving this throughput requires as much attention to input/output data handling as to the data processing core itself. The question then becomes where the additional capacity should be located (e.g., in specialized research or service centers), and who should fund that capacity.

All future environmental satellite data systems should have, whether integrated or associated, full capability for both processing and reprocessing. A compatible data system capable of delivering reprocessed data sets must be able to do so at affordable cost. It also must be an agile system that can be reconfigured to respond to evolving science and practice, with a high 5X+ throughput to cycle through large data sets in a reasonable time, with assured reliability to help NOAA succeed in its evolving operational role, and standards-based to facilitate interoperability and community collaboration. Because of computer technology evolution, such as Moore's law and the equivalents, hardware refresh cycles built into the system design will provide faster reprocessing capabilities in proportion with the growing length of the environmental data set.

PRODUCT CHARACTERIZATION—ADDRESSING THE SKILL LEVELS OF USERS

The diverse environmental satellite data user community has equally diverse product characterization requirements. Not only do skill levels vary from lay person to experts in the field, but the required level of product characterization fidelity is also a function of the use to which the data are being put. A level of product characterization that is deficient with respect to the end user's needs will result in reduced utilization, while fidelity better than required is not cost-effective. Increasingly, materials available on the Web, and Web-based training, provide excellent mechanisms for users to pull information. Combined with customized workshops and partnerships, these can form the basis for easily accessed product characterization information to the level required by each user. Here, the committee considers several user communities, and differentiates their various product characterization needs.

NWP Data Assimilation Centers

Louis Uccellini, director of the National Centers for Environmental Prediction, NWS, has said, "It's not a question of *if* we use satellite data but *how* to make optimal use of all the data." As Figure 5.1 illustrates, the operational use of environmental satellite data is increasing rapidly. The amount of received data, the blue curve in the figure, is increasing annually. The quality of the data, and its "freshness," or latency, is also improving in parallel. The consequence is tremendous potential improvement in the quality of information available to a weather prediction model. Most of these data (green curve) pass the quality checks and can potentially be utilized. The red curve indicates the amount of data actually incorporated into the model's initial state. The gap in current utilization of environmental satellite data is illustrated in the light blue area between the red and green curves. This gap

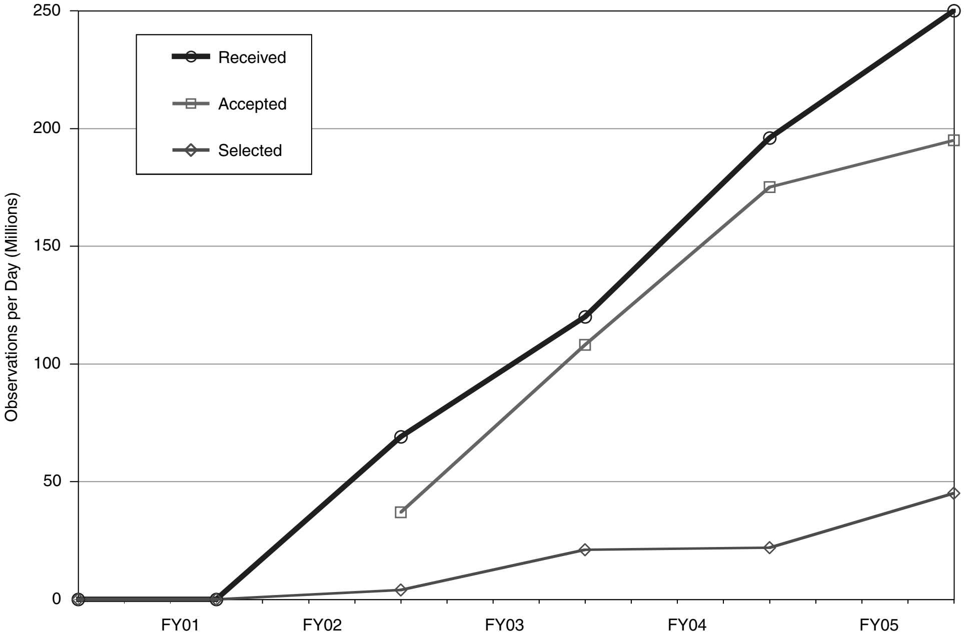

FIGURE 5.1 Use of operational satellite data over the past several years. SOURCE: "The Role of Satellite Data in Environmental Modeling," Louis Uccellini, director, NCEP, presentation to the National Research Council Committee on Environmental Satellite Data Utilization, September 11, 2003.

does not reflect a failure, but rather an extraordinary opportunity. Note that even though the red curve shows less than 20 percent of the data collected, the roughly 50 million daily observations that remain provide for some 98 percent of the data ingested into the models.

The rejected data contain significant additional information—information that is independent from the data currently utilized. They include cloudy observations, over-land observations, and cases that involve more complex phenomenology. The limiting constraints are (1) our understanding of the theoretical basis for scientific algorithms to "make sense" of the information in the data; and (2) our understanding of the spatial, spectral, and radiometric characterization of the flight sensors. Together, these constitute a remote-sensing system-level product characterization, and the delivery of this understanding into the "hands" of the end users. Reducing this utilization gap will require a fully funded, end-to-end process from satellite/sensor/system design (data utilization experts at the table) to data utilization (satellite/sensor engineers at the table). To accelerate use of research and operational satellite data in operational NWP models, the environmental satellite data teams must work with weather prediction operations staff as early in the process as possible, and continually coordinate in advance during operations so that processing changes don't "break the system."

NWP will always want to use promising new (and possibly complex) instruments. NWP's job is made much easier

- If the instrument is well characterized before launch, and
- If a simulated data stream is available in near real time, for 6 to 12 months before launch.

This has been the case with AIRS, enabling us to be ready for operational implementation within a year or so of launch (see in Appendix D the ECMWF case study for details).

Additionally, other nations' agencies, such as the U.K. Met Office, have a significantly larger number of trained staff in the environmental data assimilation area alone.

This nation is approaching a crisis stage in the data assimilation area—there are many new, advanced instruments in development for flight in the upcoming 5 to 10 years, but the system as currently staffed will be unable to handle them. Part of the answer is the Joint Center for Satellite Data Assimilation, created July 2, 2001. Partners include NOAA/NCEP/Environmental Modeling Center, NOAA/NESDIS/Office of Research and Applications, NOAA/OAR/Office of Weather and Air Quality, NASA/Goddard Space Flight Center (GSFC)/Data Assimilation Office, NASA/GSFC/Seasonal Interannual Prediction Project, U.S. Navy/Office of Naval Research, and

U.S. Air Force/Air Weather Agency. One goal of the center is to "accelerate use of research and operational satellite data in operational numerical prediction models," reducing the average time for operational implementations of new satellite technology from 2 years to 1. This is a laudable goal, and one that will be best supported through a comprehensive end-to-end system and multimission perspective.

Operational Forecast Centers and Decision Support Systems

Operational forecast centers are diverse and include NOAA centers such as the NWS Storm Prediction Center (http://www.spc.noaa.gov/), NWS Aviation Weather Center (http://aviationweather.gov/), the NWS Tropical Prediction Center and National Hurricane Center (http://www.nhc.noaa.gov/), the many NWS local field offices, and other agencies including the Air Force Weather Agency (https://afweather.afwa.af.mil/ and http://www.af.mil/factsheets/factsheet.asp?fsID=157). The single most-important constraint for these operational users is the operational time line, and their chief interest is assured delivery of timely environmental satellite data to them. As Uccelini summed up, "The users will slap me on the back for meeting a 99.5 percent on-time delivery, not a small, incremental improvement in quality." Secondarily, they require a characterization of the spatial, spectral, and radiometric properties of the sensors, and of the underlying sensing platform and algorithms.

With the initiation of NPOESS and GOES-R, with significant increases in data volume, product complexity, and underlying information content and potential, future operational forecasters will require a sufficient characterization of the information and products to enable their efficient and appropriate utilization. As an example, the current DOD polar orbiting imager returns a single reflective and emissive spectral band, whereas the NOAA POES and GOES imagers transmit five spectral bands. With 22-23 spectral bands of information on NPOESS VIIRS, and a planned 16 on the GOES-R imager, this is a factor of 5X to 10X greater complexity. The Advanced Baseline Imager (ABI) is the primary GOES-R cloud, land, and ocean imager. ABI is a significant upgrade to the current GOES imager capability, intended to provide enhanced spatial and temporal resolution and spectral capability to meet data product requirements described in the mission requirements document (MRD) for atmospheric, ocean, and land environmental sensing (ABI PORD) (see in Appendix D the section "GOES Imager and Sounder" for details). To this end, NPOESS has produced basic users' guides to assist with the utilization of the imagery.[6]

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[6] See the NPOESS "User's Guide for VIIRS Cloud Imagery Products, Version 5: March 2002," available online at http://npoesslib.ipo.noaa.gov/atbd/viirs/Y2466b-Imagery-ATBD-v5.DOC.

Research Users

Research users of satellite data make use of unique attributes of these data to investigate underlying physical phenomena. For example, small changes in the gravity field detected by NASA's Gravity Recovery and Climate Experiment (GRACE) (http://www.csr.utexas.edu/grace/) can show important changes in the underlying aquifer over broad regions; inspection of the 12-year altimetry time-series over large reservoirs from NASA's TOPEX/Poseidon and Jason missions (http://topex-www.jpl.nasa.gov/index.html), once the seasonal cycle is removed, shows variability of reservoir height over seasonal and inter-annual periods. These serve as proxies for agricultural efficiency. This altimetric data also has high value for oceanographers and climate scientists who use it to track sea-surface height changes linked to ENSO (http://topex-www.jpl.nasa.gov/science/el-nino.html) and longer-period variability in the ocean, including the rise of sea level associated with global warming (http://www.csr.utexas.edu/gmsl/main.html) and, by assimilating altimetric data into models, seek to improve forecasts of climate variability linked to the ocean (http://www.giss.nasa.gov/research/projects/cafe/summary.html). These analyses are possible only with the most detailed characterization of a product. Perhaps the most critical characterization element is that of long-term stability. Without reprocessing, often the leading signal in an environmental satellite data set is the manmade signal deriving from changes in sensor and algorithm. Only if these are understood can the data be effectively utilized. Product characterization for this class of user will require comprehensive descriptive information, termed "metadata," that includes insight into all input data sets, algorithms, and look-up tables. Detailed information on the sensors' spectroradiometric characterization (e.g., relative spectral response of each band) is also essential, even more so with the increased utilization of the radiances themselves for use in numerical assimilation schemes.

RESOURCES

Ready access, easy utilization, and assured preservation of our nation's environmental satellite data are essential to achieving NOAA's four mission goals, which directly relate to improving the quality of our weather forecasts, advanced notification of severe weather, understanding the impact of global climate change, sustaining an optimized long-term energy and agricultural policy, transportation management, and even homeland security planning and scenario development. The next generations of environmental satellites, NPOESS and GOES-R, represent a taxpayer investment in system development in excess of $10 billion.

The FY2004 budget from NASA for EOSDIS functions that are equivalent for the CLASS responsibilities of satellite Earth data archiving and distribution is $65 million, of which $1.5 million is for CLASS. This figure provides a starting point for NOAA to estimate the future cost of a sufficient data system. This budget does not include platform mission operations, data downlinking, algorithm processing, or permanent archiving. As illustrated in other chapters of this report, the number of data products, data volumes, and numbers of users are all increasing rapidly, and in many cases exponentially. While computer hardware costs are also going down, the number of staff required to handle, document, and distribute these data sets will probably stay proportional to the number, complexity, and diversity of the products and level of support to be supplied to the users.

A number of recent analyses have raised the question as to whether NOAA can meet these data utilization needs. For example: (1) a 2001 NOAA report, *The Nation's Environmental Data: Treasures at Risk*, states that the influx in volume of satellite and other environmental data will far exceed NOAA NESDIS archive and access capabilities; and (2) the General Accounting Office (GAO) has documented (GAO-02-684T-July 2002) that NOAA lacks a comprehensive plan and sufficient funding to address the utilization of the nation's current and future environmental satellite data.

NOAA recognizes the challenges and investments needed to provide for improved utilization of these data. In response to the analyses and reports, NOAA has performed a comprehensive evaluation of its data utilization capabilities that identified the shortfalls and challenges. NOAA Administrator VADM Conrad C. Lautenbacher, Jr. (Ret.), has stated, "If Earth observations are going to be useful, it requires more than just developing more sensors. We are also faced in the near future with the need to double—even triple—existing data management capacities to match sensor system capacity." Even with the brightest staff, and the best intent, NOAA will be seriously challenged to succeed in providing the level of utilization these expensive and most-capable orbital systems and their end users merit unless: (1) sufficient and stable funding is identified and allocated to enable transparent data access; and (2) partnerships with industry, academia, and other government agencies, modeled after NASA/NOAA Pathfinder program partnerships that have worked so well in the past, are created, sustained, and leveraged.

PARTNERSHIP RESPONSIBILITIES

Many of the issues that NOAA is facing and will face in migrating from today's state to a near-future state where, say, 20 times the data are readily and comprehensively accessed by 20 times the users, have already been faced by NASA's Earth Observing System Data and Information System (EOSDIS), which provides a wealth of lessons learned. NASA and NOAA have a long-standing partnership where NASA provides technology readiness development and NOAA provides on-orbit operations. NASA has developed and transitioned technology in polar and geostationary environmental instrumentation from research to operations for NOAA's fleet of environmental satellites. Every primary GOES, POES, and NPOESS sensor has a direct heritage to research instruments flown on prior NASA missions (e.g., MODIS to VIIRS, AIRS to CrIS, SBUV/TOMS to SBUV/2 and OMPS). Additionally, as described in the committee's SBUV and TOMS ozone data case study in Appendix D, NOAA and NASA have partnered to achieve great success in the calibration, validation, algorithm development, and technology evolution of long-term, global, daily ozone observations. Historically, this partnership has not extended to the transfer of data system technology that NASA developed as part of NASA's environmental science mission infrastructure. Extending the NASA-NOAA "research to operations" cooperation provides NOAA with proven technology without incurring system development costs.

Cross-cutting international partnerships in environmental satellite data sharing, processing, and utilization have also been successful within the weather and climate areas for more than two decades. As the international cooperation to observe Earth's environment makes a transition into the sustained implementation phase in the next decade, facilitated through the Integrated Earth Observation System (IEOS), it is expected that international partners will be increasingly engaged, for their mutual benefit, to assist with many facets of an advanced utilization system.

It is worth recalling that Mars is now being comprehensively sensed by multiple spectrometers from orbit (http://themis.asu.edu/, http://emma.la.asu.edu/) and miniaturized spectrometers on the ground (http://minites.asu.edu/). Often, such NASA planetary missions serve to demonstrate new flight, ground, and data utilization technologies and capabilities that have direct application to environmental satellite data utilization here on Earth.

The synergies that are emerging across many maturing technologies are enabling the increasingly meaningful application of environmental satellite data to diverse real-world problems. The committee expects that natural partnerships will emerge where environmental satellite data help users to solve their problems. Recently, for example, satellite data have become an essential part of decision support systems such as forest fire management (http://activefiremaps.fs.fed.us/) through moderate-resolution thermal monitoring from orbit; global aquifer (http://www.csr.utexas.edu/grace/) and reservoir monitoring (http://iliad.gsfc.nasa.gov/opf/usda.html) through gravity field change, altimetry, and precision orbit determination; and "nowcasting" of coastal ocean states (http://ourocean.jpl.nasa.gov/aosn.cgi) through satellite scatterometry and coupled modeling. New applications, such as geostationary real-time and predictive monitoring of lower-tropospheric air quality and pollution, are on the horizon, enabled through breakthroughs in compact hyperspectral devices such as Fabry-Perot interferometers. In every case, it is an effective partnership between the data collection and the data use that underpins the effective utilization of the environmental satellite data.

USER PULL: INNOVATION—IN THE EYE OF THE BEHOLDER

Environmental satellite data exists for only one reason: to meet users' needs. Responsiveness to users' changing needs, their "value stream," is essential to facilitating the comprehensive utilization of environmental satellite data. It should be clear from the sections above that every one of the core technologies required to make NPOESS, GOES-R, and the IEOS successful in meeting the needs of the user community are either already in place today or will be in place when they are needed. For example, thanks to Moore's law, computing capacities in 2012 at the launch of the first GOES-R will be 64 times (2^6) greater than today. This means that, as was the case for NASA's EOSDIS, maximum data utilization is "not a technological challenge—rather it is a sociological challenge."[7] It is exactly this set of exponential changes in technology that creates the sociological drivers for data use. The key to maximizing data utilization is to seamlessly fuse research and operations in full partnership with the user community. In doing so, one hopes to achieve balance and combine freedom and stability to achieve agile, consistent, repeatable, continuous adaptation.[8] As Wheatley notes, we don't have to look any further than the definition of stability to find out why change is hard to accomplish: "Stability—that attribute of the system which enables it to develop restoring forces between the elements thereof, equal to or greater than the disturbing forces so as to restore a state of equilibrium between the elements."

Success in the optimal use of environmental satellite data will come only if end users' needs are well met. "Listening to customers, users, will yield the insight to develop innovative solutions. Listening to the customer makes it possible to respond to and deliver the unarticulated needs of the customer—true innovation."[9] To succeed, to enable change in response to the pull of the end users, requires the application of a process that includes the routine utilization of emerging disruptive technologies at its very core. As the CONNTRO final report stated, "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."[10] The report pointed out that opportunities exist at the system level

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[7] Personal communication, K. Ramapriyan, NASA/GSFC, 1991.

[8] See M. Wheatley, *Leadership and the New Science*, Berrett-Koehler, San Francisco, Calif., 1992.

[9] Rebecca Rhoads, 2003; see http://www.raytheon.com/newsroom/speeches/rr062503.pdf.

[10] National Research Council, 2003, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, p. 18, The National Academies Press, Washington, D.C.

and include both advanced satellite sensor systems and enhanced data exploitation. Merging research and operations, in partnership with the end users, can help to foster a culture that supports judicious risk taking and a common sense of urgency. This approach can be underpinned through an advisory process focused on keeping pace with and anticipating user needs, finding ways to proactively meet them, and building a culture that demands, rewards, and adopts innovation. An excellent example of this is the set of GOES user workshops, which bring together some 200 government, commercial, academic, scientific, and international participants. These workshops typically inform users of future capabilities and applications; determine user needs for new products, distribution of GOES data, data archiving and access to stored data, instruments of opportunity, access to sample data sets (prior to the launch of the next series), and future training; assess user and societal benefits; and improve communication between NOAA and users.[11] Ensuring that users' needs are met may be bolstered through a system of knowledgeable environmental satellite data utilization brokers who can work among the communities involved—essentially, trained practitioners who develop effective linkages, connecting people with people throughout the end-to-end system.

VALIDATION

The objective of validation is to independently determine and document the performance (accuracy and uncertainties) and the limitations (assumptions and constraints) of the environmental satellite data at the end-to-end system level, including the sensor, ancillary data, processing approaches, and algorithms, thereby establishing standard quantitative measures that can be assigned to the measurements (SDRs, or level 1) and derived products (EDRs, or level 2). As depicted in Figure 1.1, validation of measurements and products to characterize their accuracy and long-term stability is an important link in the end-to-end process. Usually validation of environmental satellite missions is achieved through the following five activities:

1. Monitoring instrument performance, including radiometric calibration, over the lifetime of the mission. This includes a constant upkeep of the health and safety of the instrument and updates to the calibration procedures and maintenance of a consistent measurement standard.

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[11] J.J. Gurka, T.J. Schmit, and R.R. Reynolds, 2004, "Highlights from the Second GOES Users' Conference: Recommendations for the GOES-R Series," paper P2.1, 20th International Conference on Interactive Information and Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology, 84th Annual Meeting of the American Meteorological Society, Seattle, Wash., January 14, 2004. Available online at http://ams.confex.com/ams/84Annual/techprogram/paper_68746.htm (accessed September 21, 2004).

2. Detailed assessment of errors and shortfalls in processing methods, including assessment of the sources of error and the maintenance of error budgets to track performance and mitigate negative effects of errors on the quality of measurements and data products.

3. Independent on-orbit confirmation and substantiation of prelaunch estimates of the uncertainty of the derived products, defined as a combination of processing-method-introduced uncertainties and measurement uncertainty, using direct and indirect techniques. This includes the validation of measurements and product accuracy and uncertainty by way of direct comparison to in situ measurements; the validation of measurements' and products' performance by means of indirect comparison of measurements; intercomparison with other environmental satellite measurements and products; and the documentation of measurement and product error characteristics for retrospective evaluation of the statistical performance.

4. Historical evaluation of the statistical distribution in records produced by the environmental satellite instruments. This includes the derivation and documentation of the statistical performance of all products.

5. Updates to the processing algorithms as and when required, and data/products reprocessing as part of a circular cycle of validation activities. This includes updated algorithm processing and reproduction of measurements and products, current and historical, using the updated algorithms, as well as the derivation and documentation of self-consistent, long-term measurement and product records for climate and other environmental studies.

ALGORITHM DEVELOPMENT

Decades of experience have established the following five salient points:

1. Algorithms that will be successful at launch or shortly thereafter can be developed and tested only in the context of the complete end-to-end system within which they operate.

2. Relatively small investments, in parallel with operations, ensure algorithm refinement to eliminate areas of performance shortfall, while identifying promising areas for advanced product development and improvement—further satisfying end users.

3. Agile approaches that incorporate lessons learned, often in parallel research and operational environments, reduce risk while improving product quality and user satisfaction.

4. An integrated "spiral" approach to implementation reduces schedule pressure and risk, allowing early system implementation and thus removing uncertainties while ensuring a simple mechanism for ready insertion of improved algorithms

as they become available, unlike the "waterfall" approach more appropriate to stable technologies.

5. The tighter the communications and advisory linkage among research, operations, and the end users, the more rapid the acceptance of the data products, and the more comprehensive their utilization.

As shown in Figure 5.2, the progress of enabling technologies in the upcoming decade may be equivalent to that of the past two or three decades. By 2009-2012, many of today's technologies will be obsolete. Yet progress is iterative. It is critical to obtain maximum benefit from today's prototype systems. Research and operations, properly managed, planned, and coordinated as a partnership with the user community, provide an integrated basis for future operational system, sensor, and algorithm stewardship.

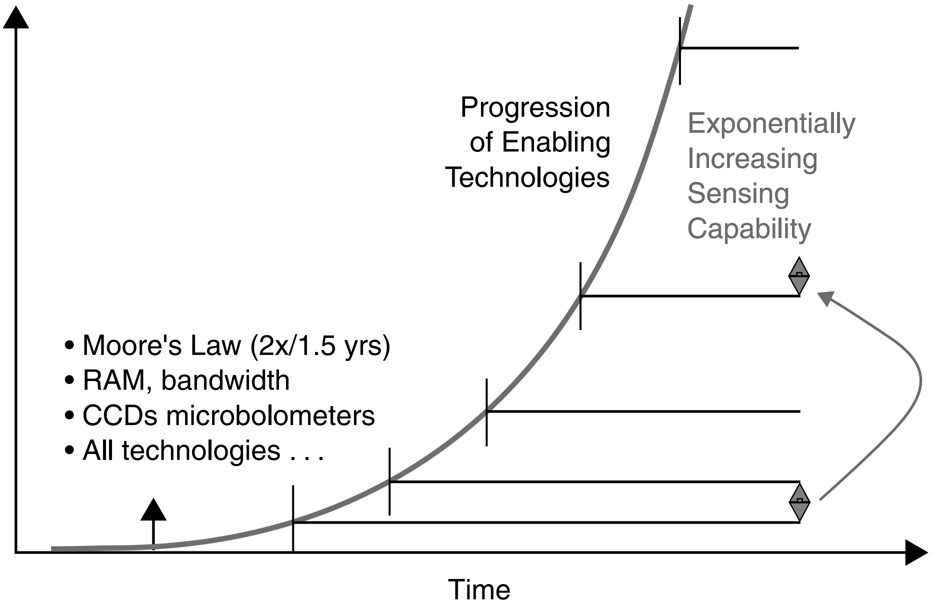

FIGURE 5.2 The chart portrays that the exponential increase of remote sensing capability is enabled by the corresponding growth in specific technologies such as computer processor chips (whose performance improves by a factor of two every 1.5 years according to Moore's law), random-access memory (RAM), signal bandwidth, and charge-coupled devices and microbolometers for imaging and infrared detection. Related technology generally seems to follow this trend.

First, consider the instruments and scientific algorithms that enable the sensing and conversion of sensed data into useful environmental information. It is critical that lessons learned in sensing Earth be not only publicized, but also quantitatively stated, and then efficiently incorporated into next-generation systems. Every NPOESS and GOES-R planned sensor either has a counterpart in orbit today or will within the next year. Ongoing intensive validation of environmental products created from these new sensors is exposing, for the first time, specific areas of algorithm theoretical basis shortfall. These can be addressed through the collection of refined spectroradiometric data (a new or revised spectral band, for example) to fill in missing information, or improvement of the retrieval algorithm to more robustly account for the local phenomenology. The challenge is in achieving this so that the lessons learned are rapidly exposed, socialized, and assimilated—thereby affecting next-generation systems. This requires quantitative, not qualitative, findings so that cost-benefit assessments can be performed, understood, and communicated. Business "as in the past" may mean that the lessons learned are available just in time—for a third generation—skipping a near-future system that could otherwise have benefited.

The algorithm development process, including mechanisms for algorithm portability, update, and documentation, discussed below, are critical components in a system capable of routinely producing environmental satellite data records and products that will be broadly and fully utilized.

Standard and Synergistic Development Process

Algorithms that convert raw satellite measurements, termed "raw data records" (RDRs, or level-0 or level-1A), to geo-referenced and radiometrically calibrated physical units, termed "sensor data records" (SDRs, or level-1B), and furthermore, to products ready for end-user applications, termed "environmental data records" (EDRs, or level-2 or level-3), provide a complete satellite data processing chain. A standard algorithm development process must be designed and demonstrated in the prelaunch period for every environmental satellite.

This "standard," or "baseline" processing algorithm suite can be defined as that algorithm set meeting the mission's critical operational requirements, though possibly without achieving the full system potential and/or enhanced capabilities. Standard processing algorithms must meet all operational requirements, including threshold quality, time latency, and distribution and availability to the users. "Synergistic," or "evolved" algorithms, on the other hand, often require the use of multiple SDRs and/or EDRs, significant processing resources, and both development and production time to produce the best achievable satellite products—these enable the satisfaction of challenging operational requirements and the monitoring and understanding of long-term climate signals and climate change. For example, these climate data records (CDRs) are suitable for the study of climate and environmental system evolution and underpin the monitoring of global change, which requires highly accurate, self-consistent measurements of the Earth-atmosphere system in global and decadal scales.

It is prudent to bring a long-term, strategic vision when designing the standard and evolved algorithms, taking full advantage of heritage approaches, for the next-generation NPOESS and GOES-R satellite systems that will fly in the upcoming decade. This vision must include early algorithm processing demonstrations of the following components:

- Full cycle, end-to-end, simulation of sensors' theoretical model and physical measurements—physical modeling of sensor signal, information content, noise sources, geolocation, calibration, and validation (using a judicious mixture of proxy and synthetic simulated data).
- Complete demonstration of RDR conversion to SDRs and to EDRs—testing and verifying processes required transferring records from raw to user-required states from both standard and evolved processing algorithms.
- Proactive, routine early and ongoing availability of all standard and evolved SDRs, EDRS, and CDRs to engaged end users for evaluation and feedback.
- An integrated "spiral" approach to implementation that reduces schedule pressure and risk, allowing early system implementation to remove uncertainties while ensuring a simple mechanism for ready insertion of improved ("evolved") algorithms as they become available, often from heritage research aircraft or satellite systems (e.g., EOS MODIS for NPOESS VIIRS, EOS AIRS for NPOESS CrIS, EOS ATMS for NPOESS ATMS, and EOS OMI for NPOESS OMPS—see Appendix G for definitions). The outdated "waterfall" approach, where a single implementation is effected years before launch, has been demonstrated over many research and operational flight missions, including UARS, EOS, DMSP, and POES, to add risk due to a decoupling between the parallel and advancing state of the research algorithms and the operational algorithms, which become outdated even before launch.

Availability of Documentation

RDRs, SDRs, EDRs, and their associated processing algorithms and external ancillary data should be documented in a consistent and accessible manner, where all metadata and processing procedures are included to the extent that retrospective users following the "recipe" would be able to successfully repeat the production process.

Mechanism for Portability

All environmental satellite operational algorithms are adapted from heritage and research-grade approaches and implemented in the operational processing infrastructure—this continuity is the *only proven or known approach* that ensures useful products from any research or operational system. The two-way portability between heritage/research and operation must be designed to be easy, agile, and transparent. There are many instances where revolutionary sensors and algorithms are demonstrated but are unable to bridge the transition to operational implementation. The CONNTRO report documents that committee's findings and recommendations on this issue in great detail.[12] Many of the recommendations are directly and equally relevant to environmental satellite data utilization, and they should be considered and responded to by policy makers.

Perhaps the utmost and critical aspect of algorithm portability with respect to the transition of research capabilities to operational use "is the development not only of the retrieval schemes but also assimilation methods. In either case, parallel development and funding are required to achieve operational use of the satellite data."[13] As a possible real-world example, the Joint Center for Satellite Data Assimilation (JCSDA) could be chartered not simply as a "virtual center." Rather, it could become an interagency mechanism expanding its responsibility beyond data assimilation to ensure that most of the critical NWP-focused operational processing algorithms are ideally transitioned from research to operations.

Update Process

Rigorous measurement quality and product accuracy validation efforts are required for any exemplary environmental data and product utilization. This is possible only in the satellite post-launch period when the operational, and not just proxy or synthetic, data are acquired. As a consequence of these validation activities, not-infrequent updates of the implemented processing algorithms will be mandatory, especially when sensors' characteristics are fully understood in the constantly changing thermally and optically stressing space environment. Reprocessing is then required for the measurements and products already produced using the outdated algorithms. This is critical for achieving self-consistent long-term measurement

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[12] National Research Council, 2003, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, The National Academies Press, Washington, D.C.

[13] National Research Council, 2003, *Satellite Observations of the Earth's Environment: Accelerating the Transition of Research to Operations*, The National Academies Press, Washington, D.C.

records where the leading signal is the environment, not the change in algorithm of calibration. To ensure efficient reprocessing, the update mechanisms must be well-defined in the beginning to allow agile and consistent reproductions of measurements and products. Otherwise, inconsistent and sub-optimal uses of the respective measurements and products for environmental monitoring, applications, and research will result. Proactive, rather than reactive, management of the algorithm update and reprocessing will avoid draining scarce resources, disrupting operational scheduling, and impacting users' confidence. To succeed, up-front and integrated life cycle cost estimates and planning that include this essential update process require flexible and comprehensive understanding of the process itself.

CONSISTENT SPECTRORADIOMETRIC SCALES

Obtaining Desired Accuracies

Four-dimensional data assimilation for NWP, as well as less-esoteric remote sensing data applications such as nowcasting, rural and urban environmental development monitoring, and research, all depend on satellite data in the form of estimated top-of-the-atmosphere (TOA) radiances. Clearly, the more accurate these estimates are, the more effective the applications. So, key ingredients in any effective remote sensing system are excellent satellite radiometers and well-characterized and validated radiative transfer models. While radiometer performance must be characterized by spatial and spectral coverage and resolution, "radiometry" is fundamental. Radiometry is characterized, in turn, in terms of both coverage and resolution, as well. In the case of radiometry, radiance "dynamic range" defines the sensor's ability to measure radiance from the smallest to the largest magnitude to be encountered in a given application. Radiance "sensitivity" defines the sensor's ability to distinguish the smallest variations in radiance to be encountered.

Increasingly, utilization of environmental satellite data is expanding toward a focus on calibrated, geolocated radiances as a critical end point, as opposed to the geophysical data products themselves. Driving this transition is the increasing incorporation and complexity of three-dimensional and four-dimensional direct radiance-based assimilation techniques into operational NWP and climate research models, and the increasingly diverse, multidisciplinary, heterogeneous, and distributed nature of the final products and applications. This shift places an added premium on the quality, readiness, robustness, stability, and consistency of the associated spatial, spectral, and radiometric characterization, calibration, and validation algorithms and approaches. Such so-called level-1, or SDR-quality, data must be ensured even more aggressively than the downstream level-2 (EDR) and level-3 (gridded) geophysical data products, or the environmental data records themselves. Unless they are matured and validated early, the radiance products, produced upstream of the geophysical products, therefore can delay or otherwise impact operational production, validation, and utilization.

While spatial coverage and resolution must be accurate in terms of geolocation, this accuracy can be obtained across platforms and sensors via a common "global" reference frame, Earth itself. Radiometric accuracy, however, defined as the error between a measurement of TOA radiance and the "true value" of that radiance, is difficult to measure consistently because every sensor must carry its own calibration reference, or refer to a common reference provided by another sensor that happens to be making precisely the same environmental measurement at the same time. Common radiance sources do exist that are known to a high degree of accuracy, and these can be used to develop accurate transfer reference radiance sources that can be carried aboard each sensor.

In the reflective spectral range from ultraviolet to short-wave infrared (SWIR) from 0.3 to 2.5 μm, the Sun itself provides a direct reference source. This source has been estimated to a high degree of accuracy via continuing experimental and now more routine measurements by the National Institute of Standards and Technology (NIST) based on pioneering research conducted in the 20th century by Neckel and Labs.[14] The result is an excellent spectroradiometric solar characterization at fine spectral resolution. This reference provides the basis for a solid standard that all radiometers can use. The difficulty is in transferring the solar reference to the sensor, as most sensors are not capable of looking directly at the Sun.

The Moderate-resolution Imaging Spectroradiometer (MODIS) uses a Spectralon solar diffuser reflectance reference, reducing the reflectance with a partial screen so that the reflected light is within the MODIS dynamic range. To compensate for solar diffuser reflectance variation over time, MODIS carries its own lamp-illuminated integrating sphere calibration reference standard. This solar diffuser stability monitor (SDSM) comprises a radiometer that views the lamp-illuminated integrating sphere and the Sun-illuminated solar diffuser, comparing the ratio of the two measurements over time to detect and estimate solar diffuser reflectance variations. These results are used to update the reflectance spectral calibration coefficients used in the MODIS ground calibration processing. These coefficients were initialized before launch based on MODIS measurements of the output of the NIST-calibrated laboratory integrating sphere radiance. The NPOESS Visible Infrared Imaging Radiometer Suite (VIIRS) will copy the MODIS reflectance calibration process.[15]

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[14] H. Neckel and D. Labs, 1984, "The Solar Radiation Between 3300 and 12500 Å," *Solar Physics* 90: 205-258.

[15] "NPOESS and GOES-R: Building a 'System of Systems'," Philip E. Ardanuy, William R. Bergen, Gary E. Gray, Tom Hickey, Hung-Lung (Allen) Huang, Steve Marley, Jeffery J. Puschell, and Carl Schueler, AMS 2004 Annual Meeting (ams.confex.com/ams/pdfpapers/73919.pdf).

In the emissive portion of the spectrum, it is necessary to create an approximation of the ultimate reference, the classical Planck “blackbody.” The blackbody is an ideal (not perfectly attainable) device that can remain at constant temperature in thermal isolation while absorbing radiative power at visible to SWIR wavelengths. It does this by emitting the same power at longer wavelengths, because otherwise its temperature would rise. The Kirchoff expression “power emitted = power incident” defines a blackbody. A greybody, on the other hand, reflects some incident light, and the Kirchoff expression includes the reflectance and a multiplicative factor in front of the emission term called the “emissivity,” which is less than unity, indicating that the device is not emitting the same power incident on the device. Were it possible to create a perfect blackbody, then a superb emissive spectral band calibration reference could be built, because the emission from a blackbody at any temperature is perfectly defined by the Planck radiation law. The approach would be to measure the emission of the blackbody at a series of temperatures covering the range of anticipated Earth scene temperatures. The known blackbody emission provides a “universal” reference frame, and the only problem left is to ensure that the temperature is well known.

Obtaining Inter-Comparable Data Sets

Polar and geostationary satellite data already constitute the vast majority of the data ingested in NWP models. As these systems are improved, the ability to extend severe storm forecasts for the United States depends on consistent radiometry between current and future systems, and between the next-generation POES (NPOESS) and GOES (GOES-R) systems. Further success in extending severe storm warnings across the globe to benefit all nations will depend on extending the benefits of U.S. environmental satellite calibration consistency to other international satellite systems.

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Findings and Recommendations

Environmental satellite data have grown in volume, complexity, and information content over the last 10 years, and there is every indication that this trend will continue and will accelerate exponentially. In the upcoming decade, growth in that volume may equal that over the last two or three decades. Our nation's next generation of polar-orbiting (2009) and geostationary (2012) satellite systems will deliver improved operational data products to an increasingly diverse environmental satellite data user community. The increase in the volume of data delivered to NOAA, and from NOAA to end users, will be orders of magnitude above the present volume. The committee strongly recommends that action be taken to prepare for that increased volume of data and to support the growing diversity of users that attends the data becoming more accessible and a more pervasive and essential part of everyday life. The increases in complexity and volume of environmental satellite data, and corresponding increases in user expectations, must be anticipated and accommodated by all the systems that support the operational, research, and other end-user environmental communities. Particular attention is recommended to the components that support data production, storage, access, and distribution, and to the interfaces with users. By 2014, many of today's technologies will be obsolete. To obtain the maximum taxpayer value from the U.S. investment in environmental satellite data requires an approach that is as aggressive and proactive in developing and managing our data access and distribution systems as in developing and launching new satellite systems.

THE VALUE OF AND NEED FOR ENVIRONMENTAL SATELLITE DATA IN ADDRESSING SPECIFIC USER NEEDS

Finding: Improved and continuous access to environmental satellite data is of the highest priority for an increasingly broad and diverse range of users. Their needs include real-time imagery for decision making in response to events such as forest fires, floods, and storms; real-time data for assimilation into numerical weather prediction models; recent imagery for assessment of crops and determination of impacts on the environment resulting from diverse human activities such as marine and land transportation; and data coverage spanning many years that allows assessment of patterns and long-term trends in variables, such as sea-surface temperature, land use, urbanization, and soil moisture. Users of environmental satellite data include individuals; federal government agencies; state and local managers, planners, and governments; commercial producers of added-value products; and Web, print, and TV/radio broadcasters.

Recommendation 1: To best serve the diverse user communities and to meet growing demand, the committee recommends that, as soon as is practical, agencies providing environmental satellite data and products collaborate, with NASA and NOAA taking the lead, to develop an explicit strategy and implementation plan for data distribution systems, user interfaces, and increased user engagement and education. The goals of this plan should be to facilitate access to current, historical, and future environmental satellite data and products in ways that acknowledge the range of skills and evolving needs of the user communities and to support these users by providing appropriate supporting information and educational material.

Finding: The national and individual user requirements for multiyear climate system data sets from operational environmental satellites, as currently delineated in the Climate Change Science Program strategic plan,[1] are placing special demands on current and future data archiving and utilization systems. These demands include more stringent requirements for accurate cross-platform radiometric calibration, new combinations of multiple satellite and instrument data, and algorithms for generating advanced biophysical variables. Detecting climate change trends often involves evaluating data at the limits of

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[1] U.S. Climate Change Science Program, *Strategic Plan for the U.S. Climate Change Science Program: A Report by the Climate Change Science Program and the Subcommittee on Global Change Research*, available at http://www.climatescience.gov/Library/stratplan2003/default.htm, accessed July 12, 2004.

measurement precision, and so periodic, absolutely consistent reprocessing of climate data records is a fundamental requirement.

Recommendation 2: Creating climate data records (CDRs),[2] which quantify subtle but important global change trends, is not a task that can be accomplished solely in routine operational environments (such as with the National Polar-orbiting Operational Environmental Satellite System (NPOESS) and Geostationary Operational Environmental Satellite (GOES)). The committee recommends that NASA, along with NOAA, select multidisciplinary, research-oriented, end-to-end science teams that will select those NPOESS, GOES, and other systems' data products and variables that are scientifically important and technologically feasible for long-term CDR development. These science teams will design and maintain a proactive strategy for the stewardship and multidecadal production of the selected CDRs.

Finding: NOAA has limited experience with land data sets because historically its mission has focused on the oceans and atmosphere. Major advances in land remote sensing have occurred in the last decade, fostered primarily by the Earth Observing System developed by NASA, that are not reflected in NPOESS planning. The committee found that NOAA has so far not effectively utilized current satellite technologies and data sets for vegetation science, management, or applications. For example, of 58 environmental data records (EDRs) defined for NPOESS, only 6 are specifically for land, and of these only 2 are vegetation oriented. For the 2012 flight of GOES-R, only 20 of the approximately 170 environmental observation requirements (EORs) are land-surface related; of these, only 4 are vegetation related.

Recommendation 3: NOAA should convene an intergovernmental committee with NASA, the U.S. Department of Agriculture, the Department of the Interior, the Environmental Protection Agency, and other interested parties to select the variables for land vegetation data for generation from NPOESS, GOES, and other operational systems that will have high utility for both land management and the hydroecological sciences.

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[2] A preliminary report by the NRC's Board on Atmospheric Sciences and Climate (*Climate Data Records from Environmental Satellites: Interim Report*, The National Academies Press, Washington, D.C., 2004, p. 1) defines a climate data record as "a time series of measurements of sufficient length, consistency, and continuity to determine climate variability and change." The report adds, "In addition we further segment satellite based CDRs into Fundamental CDRs (FCDRs) which are calibrated and quality controlled sensor data that have been improved over time, and Thematic CDRs (TCDRs), which are geophysical variables derived from the FCDRs, such as sea surface cloud temperature and cloud fraction."

THE DISTRIBUTION OF ENVIRONMENTAL SATELLITE DATA

Finding: The constellations of satellites now in space and planned for the future include platforms launched by several nations, and more complete and comprehensive coverage of environmental data fields can be achieved by combining the data from these different national efforts.

Recommendation 4: The U.S. Environmental Satellite Data Program should work to facilitate user access to data from other nations' satellites as well as its own and to facilitate synthesis of data across platforms by providing supporting metadata.

Finding: The Comprehensive Large Array-data Stewardship System is being designed by NOAA to catalog, archive, and disseminate all NOAA environmental satellite data produced after 2006. Given the magnitude of this effort—and considering the growing volume, types, and complexity of environmental satellite data; the increasingly large and diverse user base; and expectations for wider and more effective use of the data—the committee emphasizes the importance of NOAA's (1) having a comprehensive understanding of the full scope of the technical requirements for data cataloging, archiving, and dissemination and (2) ensuring implementation based on that knowledge. Key to successful implementation of a strong system that will serve operational users and the nation well are detailed planning, proactive follow-through, and NOAA's incorporation of lessons learned from previously developed, similarly scaled initiatives with similar systems requirements.

Recommendation 5:

a. NOAA should conduct an immediate review of the entire Comprehensive Large Array-data Stewardship System (CLASS) program. This review should aggressively solicit and incorporate recommendations from the designers, builders, operators, and users of similar systems, particularly those systems comprised by the Earth Observing System Data and Information System.

b. CLASS should be designated and developed as NOAA's primary data archive system for environmental satellite data and other related data sets. NOAA should ensure that CLASS is designed to adequately serve the full spectrum of potential environmental satellite data users. In addition to end users, CLASS should be designed to disseminate data to the broadest possible community of data brokers and value-added providers. The CLASS architec-

ture should explicitly include the public programmatic (e.g., Web services) interfaces that these third parties require.

c. NOAA should plan for and identify resources required for an increased CLASS effort to fulfill the needs outlined in a and b above.

Finding: NOAA does not appear to be effectively leveraging the substantial and growing third-party resources available for creating, archiving, and distributing environmental satellite data products. In particular, the current CLASS effort appears to include end-user services (such as Web ordering, e-commerce, and product customization) that could just as easily be provided by third parties, while ignoring the lower-level programmatic interfaces that value-added providers require.

Recommendation 6:

a. NOAA should consider both centralized and decentralized approaches to managing the generation and distribution of environmental satellite data products to ensure cost-effective and efficient utilization of existing human and institutional expertise and resources. Centralized handling should be provided for operationally critical core products and should include the acquisition, processing, distribution, archiving, and management of calibrated, navigated radiances and reflectances at the top and bottom (atmospherically corrected) of the atmosphere, as well as for selected key products and metadata. Specialized higher-level environmental data products could be handled (processed, reprocessed, and distributed) in a physically and organizationally distributed (and diverse) manner.

b. NOAA should take maximum advantage of the exponentially decreasing costs of computing resources and allow for distributed implementations by third parties.

c. NOAA should consider mutually beneficial partnerships and partnering models with the private sector (e.g., commercial value-added data and product services providers) that have the twin objectives of ensuring user-oriented open access to the data and providing the best value to end users.

Finding: Over the life of a project the cost of ownership of online (disk) storage is competitive with, and decreasing more rapidly than, that of offline (tape or optical) storage. The ability to store and process large volumes of satellite data online will thus become ubiquitous. More than any physical medium, Internet connections to these online data sources will prove a stable, economical, and widely available mechanism for data transfer.

Recommendation 7:

a. NOAA's default policy should be to maintain all public satellite data online, in archives that can be accessed (partitioned) to maximize throughput and replicated (mirrored) to ensure survivability.

b. NOAA should transition to exclusively online access to satellite data. Distribution on physical media should be provided as a custom service by third parties.

c. NOAA should plan for and identify resources to support handling of the anticipated increase in archival and dissemination requirements beyond 2010.

DATA ACCESS AND UTILIZATION

Finding: Data from diverse satellite platforms and for different environmental variables must often be retrieved from different sources, and these retrievals often yield data sets in different formats with different resolution and gridding. The multiple steps currently required to retrieve and manipulate environmental satellite data sets are an impediment to their use.

Recommendation 8: Data access and distribution should be designed, and associated products tailored, to be compatible with users' processing, storage, distribution, and communications resources and their information requirements.

a. NOAA should improve access to its data by allowing users to focus searches by geographic region, dates, or environmental variables, thus helping provide the means to search from one user interface across all environmental satellite data held by U.S. agencies. Tailored subsets of data products should be made available for routine distribution and/or in response to a specific request.

b. Further, NOAA's user interfaces should allow stored environmental satellite data sets and/or images to be retrieved in a common data format and with geolocated gridding selected from a list of options by the user. Subsetting and subsampling should be combined to provide a continuum of data products from broad-area, low/moderate-resolution products to regional, high-resolution products.

c. NOAA should concentrate on ensuring the commonality, ease, and transparency of access to environmental satellite data and providing no-cost data streams in a few standardized, user-friendly formats selected primarily to maximize ease of translation into community-specific formats.

d. NOAA should support the development of third-party format translation services and the adaptation of existing community-standard tools to NOAA-standard formats.

e. The data that NOAA provides to users should be accompanied by metadata that documents data quality, discusses possible sources of error, and includes a complete product "pedigree" (algorithm theoretical basis, sensor and calibration, ancillary data, processing path, and validation status and component uncertainties).

Finding: Some major segments of the user community currently do not have the resources to fully utilize all of the environmental satellite data available to them. The principal obstacles to expanded use have been inadequate and/or discontinuous funding for applied research as a part of data utilization programs, the lack of support for education and outreach programs, and the lack of trained professional brokers and facilitators available to work with the various bidirectional interfaces between users and providers within the environmental satellite data utilization system.

Recommendation 9: A continuous level of adequate resources, especially for applied research and education of the work force in the use of environmental satellite data, is needed to exploit the huge investments already made in the satellite system. Satellite data providers and the scientific research community should also take a leading role in facilitating collaboration with their end-user partners. These efforts should include outreach, training, and technical assistance for the more sophisticated user communities as well as for the rapidly emerging nonscientific, nongovernmental user groups, with the ultimate goal being to enable straightforward and effortless user access to environmental satellite data and data products.

Finding: Early and ongoing cooperation and dialogue among users, developers of satellite remote sensing hardware and software, and U.S. and international research and operational satellite data providers is essential for the rapid and successful utilization of environmental satellite data. Active research and development is required to achieve operational sustainability—today's research anticipates and underpins the satisfaction of tomorrow's operational requirements. Many of the greatest environmental satellite data utilization success stories (see, e.g., the case study on the European Centre for Medium-range Weather Forecasts in Appendix D) have a common theme: the treatment of research and operations as a continuum, with a relentless team focus on excellence with the freedom to continuously improve and evolve.

Recommendation 10: To ensure the ongoing development of future operational environmental satellite data products that have high quality and value requires an ongoing evaluation of the U.S. effort to collect and provide environmental satellite data. An integrated, sustainable basis for the stewardship of future operational systems, sensors, and algorithms should be fostered by establishing close cooperation between the research and operational agencies responsible for the utilization of environmental satellite data (including their development, collection, processing and reprocessing, validation, distribution, and exploitation), with research and operations viewed as a continuum and not as two independent areas of effort. To meet evolving customer requirements, this cooperation between research and operational agencies should be coordinated in close partnership with the user community. Only a fully funded, end-to-end system, from satellite sensor design to data assimilation/utilization, can fully optimize the investments that have been made.

Appendixes

A

Letter to NOAA/NESDIS

April 27, 2001

Dr. Gregory W. Withee
NESDIS Exec Route: E
Building SSMC1—Room: 8338
1335 East West Highway
Silvery Spring, MD 20910-3284

Dear Greg:

It was a pleasure to work with you and your staff during the NRC-NOAA workshop on Opportunities for NOAA's Environmental Satellite Program. Your attendance at essentially the entire workshop was very much appreciated by the participants. In the following I will outline my recollection of the principal points of discussion that could lead to one or more formal NRC studies in the areas of interest to NOAA/NESDIS.

As you observed, we followed the background presentations by dividing our participants into splinter groups devoted to system architectures (including ground systems), data utilization, and technology infusion. However, when we brought the groups together to deliver their reports it became evident that the separation, while convenient to carry out the workshop effort, was artificial in terms of offering possible studies for your consideration. Therefore, the studies listed below reflect the overall workshop discussions and have not been categorized according to splinter group.

Potential Study: An Unencumbered Vision for the Future

All three splinter groups recommended the development of a largely unencumbered vision for the future architecture of NESDIS's satellite and ground systems. In side discussions, several participants quoted the familiar, "Form follows function." NOAA/NESDIS is the *de facto* and *de jure* national agent for the conduct of operational Earth observations from space and for the archiving of the resulting data; this places NOAA in an extraordinarily important position in the federal structure.

In a formal sense, NOAA's roles are assigned through legislation and administration policy, but NOAA's roles are also shaped by the agency's aspirations and the needs of society. Advances in technology and emerging societal needs lead to requirements or "desirements" for enhancements to existing measurements and entirely new measurements as well. The stimulus for such improvements is as often through visions and inspirations as it is from the formal requirements tabulation processes so attractive to systems engineers. Therefore, the workshop participants believe that it would be productive to articulate a vision for NOAA/NESDIS in the 2015-2020 era that begins with the core responsibilities of the agency and then expansively looks at what the future might yield. It is often said that, while the future cannot be predicted, it can be invented. The workshop participants believe that a well-crafted study in the near future can advance the process of inventing NESDIS's future. Given the time scale of space system planning, development, and deployment, the period 2015-2020 is closer than we might wish. NESDIS's near-term concerns are inevitably dominated by the current GOES program, POES program, DMSP, and the evolution of the latter two low-altitude systems into NPOESS. While many of the core functions will remain in any future architecture, a broad study should not be limited to only those systems or their present architectures. A more unencumbered, but realistic, view is needed of both the satellite architecture and its accompanying ground system, and of the role that NOAA will play in the future.

Participants suggested various ways to visualize NOAA's future role that ranged from concentric circles to Venn diagrams. The fundamental idea is that NOAA has a present set of core responsibilities to carry out, but that advancing societal needs will cause NOAA to accrete new responsibilities and the related observations. Examples were cited in oceanic, solar, and ecological disciplines as being areas of likely accretion, and it was noted that the NESDIS customer base should be considered in all of its dimensions (government, commercial, civilian, and scientific).

The study should likewise be unencumbered in terms of the satellite orbits and the satellite configurations. Without prejudging what the outcome might be, Low-

Earth Orbit (LEO), Medium-Earth Orbit (MEO), Geostationary (GEO), and shared opportunities on other unmanned satellites or the International Space Station should be considered. Likewise, large, mid-size, and smaller satellites should be considered to meet cost effectiveness, performance, and flexibility needs. International opportunities should be sought where appropriate partners can be secured. Beyond the obvious programs of Europe and Japan, the participants noted the environmental satellite program of China as one deserving of consideration for possible partnership. It was assumed by the participants that current political tensions will subside, and normal relations resume. Several people noted the favorable climate for cooperation that exists in China at the science and applications agency level.

The NESDIS vision could, in the view of the participants, encompass the full end-to-end milieu within which the NOAA measurements fit. A study could reexamine the present requirements on the system to assure their continued validity, project potential evolved NPOESS, GOES, and possibly other satellite configurations, and also seek revolutionary architectures going beyond the incremental evolution of the current plans. An examination of the space segment could address satellite size, but also on-board processing, "bent-pipe" data communication, the role of direct broadcast, space cross-links, spacing on orbit, and the scheduled or unscheduled use of excess capacity on launch vehicles such as the Atlas-5 and Delta-4. A sense of the workshop was that a growing launch vehicle capacity exists that may outstrip user needs. Access to space will always be a major concern in terms of NESDIS's overall space architecture and its sustenance, and in providing for the flight of research and test articles in the next study to be suggested. Aspects beyond the space segment that could be addressed include data processing, distribution, modeling, the Internet and its derivatives, and flexible ground architectures. Needless to say, the issue of transition from the present architecture to some future architecture would need to be considered.

Potential Study: The Transition from Research to Operations to Further Operations

A continuing theme which was expressed by all of the splinter groups was the need for NOAA to have a systematic approach to transitioning new measurement techniques, research instruments, data types, and software to initial operational use (usually within the agency or its DOD partner) and then on to a wider set of operational users outside the agency. Considerable success can be observed in collaborations that have occurred between NASA and NOAA, and there is much to be commended in the largely ad-hoc efforts of recent years. Nevertheless, nothing has replaced the Operational Satellite Improvement Program (OSIP) conducted and funded by NASA from the 1960's through the early 1980's. Budget pressures forced the cancellation of the program, and the effect has been the transfer of risk and cost from NASA to NOAA without an accompanying transfer of funds, facilities, and capabilities. NOAA long relied upon NASA to develop "first-of-a-kind" spacecraft and instruments at NASA expense, with NOAA then procuring subsequent copies without the burden of paying nonrecurring engineering and development costs. This no longer takes place. At best, very successful research instruments flown by NASA serve as exemplars and conceptual test beds for NOAA's later consideration, but they produce little or no reduction of NOAA's nonrecurring engineering and development costs in moving the instruments to operations.

A related element to the disappearance of OSIP affects the existence of what has been termed a "spannable distance," which is a measure of the cultural and knowledge gaps between R&D and operations. The gap between the two is reduced and made manageable when the R&D personnel, often in another agency as in the case of NASA, are intimately aware of present and potential future operations. Likewise, the gap is reduced when personnel in the operational entity understand thoroughly the technology being transferred. The technology transfer process needs both a smart provider and a smart buyer. This concept extends to the need for skilled in-house personnel in both NASA and NOAA. The agencies rely upon the private sector, but the sensors and their applications are not things that can be "bought by the yard" in a routine fashion. Numerous examples exist that demonstrate the importance of in-house capability, and that capability should be an element in the study of the technology transition process.

There is another new source of risk that has been injected into the NOAA satellite program. For many years, NOAA shared a production facility with the Defense Meteorological Satellite Program at the then RCA Astroelectronics. Risk was shared between the two programs, with each serving as a precursor for the other in various aspects of the program. Trained, expert personnel moved from one set of spacecraft to the other and provided numerous efficiencies. Corporate reorganizations and the merger of the two programs have eliminated this advantage, and the NPOESS effort must stand on its own—without sharing of development costs and without an easy means to smooth fluctuations in workload as occurred between the separate POES and DMSP activities. None of this can be resurrected, and it would not be a purpose of a study to attempt to do so, but the loss of capability and efficiency does add further urgency to the need to carefully manage the transition from research (or simply conception) to operations.

NASA has conducted a very successful Earth observations program that has greatly benefited NOAA, and indeed the entire world. NASA and NOAA will likely continue to collaborate in a very successful manner in the future. However, the systematic evolution of sensors and spacecraft from research to operations is not assured, and must be regularly renegotiated based on changes in one or the other of the agencies. A study could be conducted to examine in detail the heritage of the current sensors (and to capture the lessons that can be gleaned from that history) and to 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.

A major aspect of such a study is the infusion of new technology into the operational system. Workshop participants cited a number of issues deserving of scrutiny that ranged from mutual planning and shared R&D efforts to the flight of proof-of-concept instruments and spacecraft. The matrix of possible approaches could 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. In the last of these, modestly capable international collaborators might, for example, provide small satellites to carry less complex, but important, instruments in support of either research or operational goals. The partners might then continue to provide such measurements, or simply provide a demonstration of technological readiness for an instrument to be incorporated into a U.S. operational satellite. At the other end of the possible spectrum of cooperation, international partners might provide highly capable sensing satellites as permanent additions to the operational constellation. Naturally, the current difficulties surrounding the International Trafficking in Arms Regulation (ITAR) and the problems it creates in the exchange of hardware, software, and data will have to be conquered. At some point natural self-interest seems likely to lead to more rather than less cooperation, but participants cited examples of where the current ITAR procedures are interfering with the productive activities of universities, companies, and government agencies.

Naturally, beyond the ITAR issues, the engagement of international partners in the overall NESDIS effort may be complicated by the POES/DMSP merger, and by the DOD's understandable requirement to be assured of the availability of its data sources. The workshop participants did not offer responses to this concern, but one can imagine the DOD users welcoming the availability of a richer set of information than they would otherwise have. The degree to which military users would incorporate the additional information based on the contributions of international partners into DOD's operational needs would likely vary from situation to situation.

The workshop participants noted that there are many intriguing possibilities, should NOAA have the resources to carry them out. As mentioned in the preceding discussion on system architectures, there are a large number of possible new measurements that would be logical for NOAA to adopt and sustain. Many of these involve new instruments or radically modified existing instruments requiring a new flight test. The participants noted that emerging *smaller* satellite technology (and, perhaps, *small* satellite technology) would likely offer the possibility to fly instruments in tandem, constellation, cluster, or tailored orbits at relatively modest cost. For example, it could be imagined that oceanic measurements might be carried out, either initially or permanently, by an adjunct set of satellites with tailored Equator-crossing times or in non-Sun-synchronous orbits that would avoid tidal aliasing. Naturally these comments intersect with the international cooperation issues mentioned in the preceding paragraph. Likewise, these comments would also be consistent with NASA providing first-of-a-kind satellites and instruments for such tailored orbits for NOAA's later replication and continuation.

Intertwined with all of the above threads is the desire for the timely implementation of program changes. The ten-year (or more) cycle time for major program changes is inhibiting. While this time period may be rooted in system economics that are difficult to overcome, a more systematic transition process might aid in making the system more responsive to user wishes. At the same time, the use of auxiliary satellites (domestic or international) may improve responsiveness as well.

The title for this potential study was made consciously redundant to point out that the extension of new measurements into operations can involve layers of users. NOAA will always have a certain core of major users around which its activities tend to revolve, but the agency's expanding roles and missions can bring NOAA into support of varied users of global, coastal, and regional information. A significant part of transitioning research to operations is the entraining of new classes of users through their joint involvement in pilot tests and other collaborations. An essentially unbounded set of user communities can be imagined. Particular mention was made of the U.S. Navy's oceanographic work at Bay St. Louis, Mississippi. It is feasible to imagine analogs to this effort in the civil sector, and not only in oceanography, but in many areas. Several workshop participants stressed the regional nature of many societal problems—flooding being an example that was cited. Several participants observed that one cannot move from global models in successive steps all the way down to a local application. No global model can be expected to carry within it all of the details that affect local data and forecast needs. On the other hand, some participants also noted how future enhancements in weather forecasting would involve not only the atmosphere but also the integration of still further ocean and land data into the forecasting models, so the complexity of those models will continue to grow despite not encompassing all local needs. Extending the time over which effective weather forecasts can be made will require a better characterization of all of the boundaries of the models, and of the internal variables of the models as well. While there will be vital interfaces with the private sector and other government agencies (federal, state, and local), there seems to be a permanent and highly productive role for NOAA to play. This leads naturally into the third of the potential studies that the NRC might undertake.

Potential Study: Data Utilization

Just as the first two possible studies noted above are related to one another, a study of data utilization will be tied to both system architecture and technology infusion. In addition, data utilization can be thought of as having a 360-degree, bi-directional interface. In the analysis of conventional data networks, an engineer describes the various linkages using drawings and computers, and examines the capacities and blockages that may occur. It is an appealing picture, and it is tempting to seek to apply this concept to data utilization in NOAA's data world. While some of the same principles would apply, NOAA's world is infinitely complicated, and this is a good thing.

Environmental data collected by NOAA's satellites are applied to numerous disciplines: research, operations, meteorology, oceanography, rivers, coasts, fisheries, hydrology, agriculture, solar-terrestrial interactions, etc. Orthogonal, related, and parallel uses abound, hence a 360-degree interface. The collected data are not blindly delivered to a passive user community, but may (should) be shaped by the needs of the user community. Hence, the interface must be bi-directional. Furthermore, it is not simply the individual data bits that must flow in all directions and be tailored according to their destination, it is likewise the overall conception of the system and its segments that must also serve multiple uses and respond to the special requirements of those uses. Particular mention should be made of the third-party "added-value" commercial and non-profit users who broker applications by converting the data to more usable form. Such groups can play an important role at the bi-directional interface.

User communities served by NOAA include intragovernmental (at all levels), international, regional, researchers, for-profit, non-profit, and educational entities and consortia. The increasing sophistication of requirements spawns increasing complexity in applications. The need to lessen adverse consequences demands greater timeliness in responses to observed phenomena. NOAA's satellite and data systems must be designed to meet the nation's and—in many instances—the world's environmental information needs. Those information needs will expand as noted in the preceding two study descriptions.

However, expanding information needs carries with it serious implications for ready accessibility of high-quality, stable data in each of the research and applications areas. Users will require education on the nature and quality of the data, but the providers of the data will require an equally intense education on the needs of the user community and the data forms that will best meet those needs. Even in advance of the new needs that will inevitably emerge in the 2020s, the crest of an enormous wave of data is already approaching NOAA/NESDIS and its data centers. The sheer quantity of data is vastly greater than what the agency has accommodated in the past, and the rate at which the data will flow into and through the NOAA system is unprecedented. Estimates of increases by factors of 100 and more were offered in the workshop discussions, and they were based only on systems already in the pipeline.

At the same time, user needs will evolve and change. The production of real-time, high-resolution data products involving as little as a single observation will coexist in the overall information system with the development of synthesized, derived products involving data taken over decades, with all of the concomitant data quality issues. Long-term archiving of environmental data is an accepted NOAA responsibility, but the impending data crest will make new demands for data stream transparency, traceability, access, and characterization. The archives will have to provide carefully documented descriptions of algorithms and models that are employed with the data. Changes in understanding will require extensive re-processing of data. Modifications in interpretive algorithms will be common, and especially for so-called "difficult" variables, e.g., all-weather atmospheric soundings over land and soil moisture. Such modifications will lead to a need to re-process massive amounts of data.

The NOAA environmental data system includes the community conceiving of a sensor, manufacturer building a sensor, data and information system that processes the sensor data, distribution system delivering data to users, short-term active archive, long-term permanent data archive, and the myriad users who will employ the data in various ways. In some instances those users may be principally concerned with relative measurements, e.g., a time series showing how a particular phenomenon evolves where the desired information is in the changes rather than their absolute values. In other instances, as in the measurement of climate change, issues of data continuity, calibration, and long-term stability will dominate as researchers examine data over the extended lifetime of an individual sensor or from several sensors on multiple space platforms. The ubiquitous presence of the Internet also shapes the way that we think of data availability and distribution.

A study could be conducted of end-to-end data utilization involving all of the above issues, or some selected subset. Regarding the engagement of the science and applications community, and mentioned at the workshop, an element of the study could particularly address the issue of enhancing the utilization of both active short-term and long-term archives and the conduct of pilot studies involving NOAA and visiting scientists. Pilot studies can be used to develop and transfer knowledge from NOAA to the user community and from the user community back to NOAA on the most efficacious data forms and products. The two-way flow of information can foster the greater utilization of the NOAA real-time and archival data. While the workshop participants were skeptical of the 15% data utilization number cited for satellite data (believing it to be understated), the target of 500% utilization that you cited would certainly be a worthy target, and would require extensive use and re-use of NOAA's environmental data. The workshop participants strongly believe that there is much more of value that can be mined from NOAA's archived and real-time data.

I have chosen to package the possible work that the NRC might do for NOAA in three large studies, with each possibly taking the better part of two years at a cost of the order of $500-700K. There are undoubtedly other ways in which the work could be arranged. The NRC staff will be glad to explore those with anyone you designate. As I said at the workshop, NOAA occupies an extraordinarily important role in the federal hierarchy. We all perceive that the NOAA role will be a growing and increasingly important one. We look forward to participating in developing that role in whatever manner is appropriate.

Sincerely yours,

John H. McElroy
Director

cc: J. Alexander, SSB
J. Friday, BASC
L. Snapp, ASEB

B

Statement of Task

Background: Environmental data collected by the nation's operational satellite systems are applied to numerous disciplines: research, operations, meteorology, hydrology, oceanography, rivers, coasts, fisheries, hydrology, agriculture, solar-terrestrial interactions, etc. Orthogonal, related, and parallel uses abound. The collected data are not blindly delivered to a passive user community, but may and often should be shaped by the needs of the user community. Hence, the interface must be bi-directional. Furthermore, it is not simply the individual data bits that must flow in all directions and be tailored according to their destination, it is likewise the overall conception of the system and its segments that must also serve multiple uses and respond to the special requirements of those uses. The third-party "added-value" commercial and non-profit users who broker applications by converting the data to more usable form are particularly notable. Such groups can play an important role at the bi-directional interface.

User communities served by NOAA as the satellite systems operator include intra-governmental (at all levels), international, and regional researchers and for-profit, non-profit, and educational entities and consortia. The increasing sophistication of requirements spawns increasing complexity in applications. The need to lessen adverse consequences demands greater timeliness in responses to observed phenomena. These satellite and data systems must be designed to meet the nation's and—in many instances—the world's environmental information needs. Those information needs will expand in the future.

As a consequence of the rapidly evolving and expanding number and kinds of users of operational environmental satellite data and of the changing relationships between government system providers, users, and third-party stakeholders, there is a need to articulate a new vision for the future of operational environmental satellite data utilization and to assess the implications for what this will mean for how the systems operator plans and carries out its functions.

The nation's current operational environmental satellite system has made possible today's 3 to 5 day weather forecasting, as well as provision of data for a broad range of science and applications users. Currently, the civilian geostationary and polar operational environmental satellite systems are acquired by NOAA through NASA, and an ongoing NRC study is addressing the transition of new technology into the satellite systems that NOAA acquires and operates. The next generation of polar orbiting operational environmental satellites is being developed by NOAA, DOD, and NASA in a collaboration to produce a converged military and civilian system that will also continue the climate-quality record of observations begun by portions of NASA's Earth Observing System. New measurements that may be undertaken in an operational mode over the next decade include ocean topography and ocean surface winds, as well as requirements identified but not met in the aforementioned military/civilian convergence process. New data types from the evolving polar and geostationary will lead to new applications and new users as well as larger data volumes.

The nation's expanding environmental information needs carry serious implications for ready accessibility of high-quality, stable data in each of the research and applications areas. Users will require education on the nature and quality of the data, but the providers of the data will require an equally intense education on the needs of the user community and the data forms that will best meet those needs. Even in advance of the new needs that will inevitably emerge in the 2020s, the crest of an enormous wave of data is already approaching NOAA/NESDIS and its data centers. The sheer quantity of data is vastly greater than what the agency has accommodated in the past, and the rate at which the data will flow into and through the NOAA system is unprecedented. Estimates of increases by factors of 100 have been projected, based only on systems already in the pipeline.

At the same time, user needs will evolve and change. The production of real-time, high-resolution data products involving as little as a single observation will coexist in the overall information system with the development of synthesized, derived products involving data taken over decades, with all of the concomitant data quality issues. Long-term archiving and retrieval of environmental data is an accepted NOAA responsibility, but the impending data crest will make new demands for data stream transparency, traceability, access, and characterization. The archives will have to provide carefully documented descriptions of algorithms and models that are employed with the data. Changes in understanding will require extensive reprocessing of data. Modifications in interpretive algorithms will be common, especially for so-called "difficult" variables, such as soil moisture and all-weather atmospheric soundings over land. Such modifications will lead to a need to reprocess massive amounts of data.

The operational environmental data system includes the community conceiving of a sensor, the manufacturer building a sensor, the data and information system that processes the sensor data, the distribution system delivering data to users, the short-term active archive, the long-term permanent data archive, and the myriad users who will employ the data in various ways. In some instances those users may be principally concerned with relative measurements, e.g., a time series showing how a particular phenomena evolves where the desired information is in the changes rather than their absolute values. In other instances, as in the measurement of climate change, issues of data continuity, calibration, and long-term stability will dominate as researchers examine data over the extended lifetime of an individual sensor or from several sensors on multiple space platforms. The ubiquitous presence of the Internet also shapes the way that we think of data availability and distribution.

Plan: The Space Studies Board (SSB), in cooperation with the Board on Atmospheric Sciences and Climate (BASC) and the Aeronautics and Space Engineering Board (ASEB), will conduct an end-to-end review of issues pertaining to the utilization of operational environmental satellite data for the period 2010 and beyond. A committee of approximately 12 experts will be assembled to conduct this study. The study will include the following tasks.

1. Review the likely multiplicity of uses of environmental data collected by the nation's operational environmental satellites, both in terms of the disciplinary applications of the data (e.g., research, operations, meteorology, hydrology, oceanography, rivers, coasts, fisheries, hydrology, agriculture, space weather) and in terms of the institutional or organizational origins of the users (e.g., intra-governmental (at all levels), international, regional, researchers, for-profit, non-profit, and educational entities).
2. Characterize the likely interfaces between NOAA as a data provider and the range of data users, as well as third-party "added-value" commercial and non-profit users who broker applications by converting the data to more usable form.
3. Assess the implications of these multi-directional interfaces in terms of needs for (a) data accessibility and quality, (b) compatibility and cross-accessibility with data from other government sources, (c) data volume, (d) information technology, (e) user education, and (f) user participation in planning and performance feedback.

4. Identify critical factors that may drive the evolution of data management responsibilities in areas such as real-time processing; data stream transparency, traceability, access, and characterization; data archival and retrieval; and reprocessing.

5. Recommend appropriate approaches to secure the engagement of the science and applications community in successfully dealing with the challenges identified in the tasks above and in enhancing the utilization of both active short-term and long-term NOAA data archives.

C

Previous NRC Statements, Findings, and Recommendations

TABLE C.1 Previous NRC Statements, Findings, and Recommendations

Category	Statement, Finding, or Recommendation	Report[a]
Concepts for Organizational Structure and/or Responsibility	"NWS should establish a continuing process for assessing the state of EMC's technology and for updating it as needed to accomplish EMC's national mission. This process should be part of a broader NWS plan for technology infusion. This requires a plan based on assessment of life expectations for major equipment, a capital budget that reflects realistic costs for the required upgrade of equipment, and an assessment of the organizational structure (staff requirements, opportunities for alliances, etc.) needed to utilize this technology efficiently." (p. 6)	*From Research to Operations in Weather Satellites and Numerical Weather Prediction: Crossing the Valley of Death* (2000)
	"NASA and NOAA should implement a replacement to the Operational Satellite Improvement Program (OSIP) having the following characteristics: • A planned path for a 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)	

Category	Statement, Finding, or Recommendation	Report[a]
Concepts for Organizational Structure and/or Responsibility (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 Operations for Climate Research. Part I. Science and Design* (2000)
	"Research studies on the socio-economic 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 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* (2001)
	"Budgets for mission operations and data analysis should be included as an integral part of mission and/or program funding. Reviews, including NASA's nonadvocate review, which is required to authorize project funding, should include assessment of the data analysis elements, including archiving and timely provision of data to users. While reviews of some projects already follow this recommendation, its implementation is not uniform across all NASA programs. The appropriate balance between hardware and software investment is best determined jointly by NASA managers and the user communities involved in the mission." (p. 5)	*Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data* (2002)

continues

Category	Statement, Finding, or Recommendation	Report[a]
Concepts for Organizational Structure and/or Responsibility (cont'd)	"NASA planning and project funding should continue to include provisions for the timely generation and synthesis of data into information and the dissemination of this information to the diverse communities of users. This plan should take into account the needs—and the contribution to information generation—of end users, including other federal and state agencies, educational organizations, and commercial enterprises. The plan should include provisions for ongoing assessment of the effectiveness of data transfer and its educational value." (p. 8)	*Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data* (2002) (cont'd)
	"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." (p. 5) "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." (p. 6) "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." (pp. 7-8)	*Satellite Observations of the Earth's Environment: Accelerating the Transition from Research to Operations* (2003)
	"The NWS should establish an independent advisory committee to provide ongoing advice to it on weather and climate matters. The committee should be composed of users of weather and climate data and representatives of the public, private, and academic sectors, and it should consider issues relevant to each sector as well as to the set of players as a group, such as (but not limited to) • improving communication among the sectors, • creating or discontinuing products, • enhancing scientific and technical capabilities that support the NWS mission, • improving data quality and timeliness, and • disseminating data and information." (p. 4)	*Fair Weather: Effective Partnerships in Weather and Climate Services* (2003)

Category	Statement, Finding, or Recommendation	Report[a]
Data Handling	"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 availability 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* (2000)
	• "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 Operations for Climate Research. Part II. Implementation* (2000)
	"The use of internationally recognized 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 sets." (p. 6)	*Transforming Remote Sensing Data into Information and Applications* (2001)
	"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* (2001)
	"NOAA should begin now to develop and implement the capability to preserve in perpetuity the basic satellite measurements (radiances and brightness temperatures). "The development of long-term, consistent time series based on CDRs [climate data records] requires access to the lowest level of data available. In general, this means the raw data records (RDRs), or Level 1A data. The low-level data can be used to develop refined CDRs as scientific and technical understanding of Earth processes and sensor performance improves over time." (p. 4)	*Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites* (2001)

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Category	Statement, Finding, or Recommendation	Report[a]
Data Handling (cont'd)	"NOAA should guarantee climate researchers affordable access to all RDRs in the long-term archive, with an emphasis on large-volume data access. "Development of CDRs requires access to enormous data volumes, but it is likely that only a small number of researchers will need such extensive access to the raw data. Thus, a well-designed set of basic services would meet this basic function without being too costly." (p. 4)	*Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites* (2001) (cont'd)
	"NASA, in cooperation with NOAA, should support the development and evaluation of CDRs, as well as their refinement through data reprocessing. "Because the CDR process is driven by science understanding, there will be a continuing need for the involvement of researchers. The NOAA/NASA Pathfinder shows that the agencies can generate critical data sets for transitioning research products into operational data products. Over the next decades, the committee expects that a few experimental CDRs may become effectively 'operational' products and will be produced by NOAA." (pp. 4-5)	
	"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. "NASA's Distributed Active Archives Centers, as well as components of NASA's Earth Science Information Partners, are gaining experience with responding to data requests and setting up user services. Although the focus is on the order entry process (catalog, data location, browse, etc.), more attention needs to be given to quality assurance and the order fulfillment process (metadata, subsetting, electronic data delivery, etc.). Emphasis should be given to reducing cost through automation. It is essential that the large-volume data sets from the archive be affordable for the science user community." (p. 5)	
	"NOAA, in cooperation with NASA, should invest in early, limited capability prototypes for both long-term archiving and the NPP data system. "Data systems that do not develop, test, and evaluate on a frequent, regular basis are nearly always late and over budget. System development costs generally increase as the cube of the number of years in development. A climate data system will build on existing components and existing capabilities, but new functions and new interfaces must be developed and implemented to meet the requirements for climate research." (p. 6)	

Category	Statement, Finding, or Recommendation	Report[a]
Data Handling (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. "NASA and NOAA should consider a hybrid mode of operation rather than building a rigid, centralized system or relying on structure to emerge from an uncoordinated set of data systems. The government should ensure and manage the activities it does best, while fostering innovation and flexibility in those parts of the overall system that do not need to be closely managed." (p. 6)	*Ensuring the Climate Record from the NPP and NPOESS Meteorological Satellites* (2001) (cont'd)
	"NASA should assume formal responsibility for maintaining its data sets and ensuring long-term access to them to permit new investigations that will continue to add to our scientific understanding. In some cases, it may be appropriate to transfer this responsibility to other federal agencies, but NASA must continue to maintain the data until adequate resources for preservation and access are available at the agency scheduled to receive the data from NASA." (p. 6) "NASA should encourage efforts by the scientific community to develop plans for federations of data centers and services that would enable complex querying, mining, and merging of data from different instruments and missions in order to answer complex, large-scale scientific questions." (p. 7)	*Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data* (2002)
	"Data produced by the private sector in a public-private partnership should be archived for subsequent redistribution to scientists and for creating long time series of data. The government partner should negotiate for permission to do this." (p. 5) "In the process of negotiating a public-private sector data partnership, the parties should agree to use commonly accepted standards for metadata, data formats, and data portability." (p. 6)	*Toward New Partnerships in Remote Sensing: Government, the Private Sector, and Earth Science Research* (2002)
	"The NWS should make its data and products available in Internet-accessible digital form. Information held in digital databases should be based on widely recognized standards, formats, and metadata descriptions to ensure that data from different observing platforms, databases, and models can be integrated and used by all interested parties in the weather and climate enterprise." (p. 6) "The NWS should retain its role as the official source of instrumentation, data, and data collection standards to ensure that scientific benchmarks for collecting, verifying, and reporting data are maintained. It should lead efforts to follow, harmonize, and extend standards, formats, and metadata to ensure that data from NWS and non-NWS networks, databases, and communications technology can be integrated and used with relative ease." (pp. 7-8)	*Fair Weather: Effective Partnerships in Weather and Climate Services* (2003)

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Category	Statement, Finding, or Recommendation	Report[a]
Data Handling (cont'd)	"With their user communities, data centers should accelerate work toward standardizing and making formats more transparent for data and metadata and thereby improve distribution and interoperability between data centers, between data centers and users, and between users. Metadata formatted in XML would assure that recipients would be able to parse data automatically and feed them directly to their applications." (p. 2) "Data centers and their sponsoring agencies should shift the primary storage medium from tape to disk. In addition, data centers and their sponsoring agencies should enable direct random on-line access through networks and provide support for remote queries on databases." (p. 3) "Data centers and their sponsoring agencies should implement database technologies. When applicable, these technologies can improve data search and query, access and acquisition, interoperability, and retrieval from storage." (p. 3) "To ensure that the greatest use is made of environmental data, (1) data producers should include data lineage and authenticity information in the metadata; (2) data centers should improve management of and access to metadata through standard formats and database technologies; and (3) users should routinely cite the data products they use in their investigations, using agreed upon dataset identifiers. To the greatest extent possible, data centers and data producers should rely on automatic tools for creating and managing metadata." (p. 4) "Data centers should adopt commodity hardware and commercial and open-source software solutions to the widest extent possible and concentrate their own efforts on problems that are unique to environmental data management. In addition, data centers and user communities should take advantage of federated distributed systems for making data available." (p. 5) "Data centers and their sponsoring agencies should create independent demonstration data centers aimed at testing applicable technologies and satisfying the data needs of a range of users, including interdisciplinary and nontechnical users. These centers might best prove technological approaches through several participants working in parallel." (p. 6) "Data centers should aggressively adopt newer, more "bleeding edge" technical approaches where there might be significant return on investment. This should be done carefully to minimize the inevitable failures that will occur along the way. Even with the failures, the committee believes the cost savings and improvements for end users will be substantial when compared to the methods practiced today." (p. 6)	*Government Data Centers: Meeting Increasing Demands* (2003)

Category	Statement, Finding, or Recommendation	Report[a]
Research to Operations	"Joint research and operational opportunities such as the NPOESS Preparatory Project should become a permanent part of the U.S. Earth observing remote sensing strategy." (p. 6)	*Issues in the Integration of Research and Operations for Climate Research. Part I. Science and Design* (2000)
	"The full, life-cycle cost of developing and using remote sensing data products goes beyond obtaining the data and includes, among others, staff for data processing, interpretation, and integration; education and training; hardware and software upgrades; and sustained interactions between technical personnel and end users. . . . Although many of these costs are incurred at the time a technology is first employed, the life-cycle costs and benefits of remote sensing applications are not well understood." (p. 3)	*Transforming Remote Sensing Data into Information and Applications* (2001)
	"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* (2001)
	"The insertion of technology raises issues of hardware and software capability and capacity. Once a major system design . . . 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 the . . . system definition and risk reduction (SDRR) phase and continue into the subsequent stages of design" (p. 39)	*Issues in the Integration of Research and Operations for Climate Research. Part II. Implementation* (2001)
	"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 by 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 models, public or private, is best suited for a particular operational requirement." (p. 14)	*The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* (2002)

continues

Category	Statement, Finding, or Recommendation	Report[a]
Applications and Users	"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, nongovernmental, 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* (2001)
	"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 the scientists and engineers who develop applications for remote sensing data and the agencies that use them. "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. "For example, NASA, NOAA, and USGS should create an extern program in collaboration with potential user agencies, such as the EPA . . . and in so doing could produce trained staff to serve as brokers for information and further training." (pp. 4-5)	
	"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 Climate Services Vision: First Steps Toward the Future* (2001)
Gaps and Interfaces	"*The financial gap between the acquisition of the remote sensing data and the development of a usable application*. The purchase of data is only the first of a large number of steps affecting the cost of a successful application. An organization, commercial firm, or government agency that wants to incorporate remote sensing applications into its operations must be prepared for a long-term financial investment in staff, ongoing training (both technical and user training), hardware, and software, at a minimum. Alternatively, the potential user organization should be prepared to purchase these services from a value-adding provider." (p. 3)	*Transforming Remote Sensing Data into Information and Applications* (2001)

Category	Statement, Finding, or Recommendation	Report[a]
Gaps and Interfaces (cont'd)	"*The gap between raw remote sensing data collected and the information needed by applications users*. Users need information, and the process of transforming data into information is a critical step in the development of successful remote sensing applications." (p. 3)	*Transforming Remote Sensing Data into Information and Applications* (2001) (cont'd)
	"*The gap in communication and understanding between those with technical experience and training and the potential new end users of the technology*. Producers and technical processors of remote sensing data must be able to understand the needs, cultural context, and organizational environments of end users. Education and training can also help to ensure that new end users have a better understanding of the potential utility of the technology." (p. 3)	

[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.

D

Case Studies

The committee identified several representative case studies that illustrate various aspects of the utilization of environmental satellite data.

OZONE DATA UTILIZATION: PAST, PRESENT, AND FUTURE

A Brief History

Ground-based ozone measurements were first taken in the 1930s. In the 1960s, a primitive, multiband ultraviolet (UV) photometer sensitive to ozone was flown on an Air Force satellite. In August 1970, the National Aeronautics and Space Administration (NASA) launched Nimbus-4, a meteorological research-and-development (R&D) satellite, carrying a backscatter ultraviolet (BUV) instrument for globally monitoring the vertical distribution and total amount of atmospheric ozone. The early interest in ozone was for possible meteorological applications and science—ozone was not yet an environmental issue.

The Early algorithms followed the radiative transfer work of Dave and Mateer[1] developed for ground-based measurements of ozone. The profile retrievals used the Umkehr (reversal) technique, which provides important vertical ozone information

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[1] J.V. Dave and C.L. Mateer, 1967, "A Preliminary Study on the Possibility of Estimating Total Atmospheric Ozone from Satellite Measurements," *Journal of Atmospheric Sciences* 24: 414-427.

by using a spectrophotometer to measure UV radiation. In this approach, scattered UV radiation is observed at multiple wavelengths—some strongly absorbed by ozone and the others weakly absorbed. The satellite total-column ozone retrievals were similar to the ground-based Dobson band-pair technique. The Nimbus-4 system did not include an onboard radiometric calibration source or stability monitor, and the BUV hardware was a direct current (dc) system. While consequent calibration challenges combined with problems concerned with the South Atlantic Anomaly and the nadir-only views gave a rough estimate of the global ozone climatology, the 2 years of measurements provided key lessons for later flights, which required and provided better coverage and accuracy.

The next-generation ozone measurements were obtained from the very successful Nimbus-7 Solar Backscatter UV (SBUV) and Total Ozone Mapping Spectrometer (TOMS), launched in October 1978. For more than 10 years the Sun-synchronous SBUV and TOMS on Nimbus-7 provided daily, near-global (the nighttime polar regions were not observed) maps and ozone profiles along the satellite track. These measurements included detailed mapping of the Antarctic "ozone hole" after it appeared. Improvements to the flight hardware included an alternating current (ac) chopper, a shared solar diffuser for reflective radiometric calibration, and swath coverage in the case of TOMS. The nature of BUV sensing (viewing the solar spectral irradiance and Earth's spectral radiance, the Earth bidirectional reflectance distribution function (BRDF), through the same optical path) mitigated many calibration challenges. In addition, examination of the consistency of multiple band pairs (six UV wavelengths were sampled by the TOMS) helped to take out the total ozone drifts in time. The community is still struggling for consistency in the profiles in which absolute BRDF knowledge is used.

The Nimbus-7 observation time series was of fundamental importance. The more-than-10-year duration of the data set provided a unique climate record because of its long-term accuracy. The onboard calibration capability helped provide for stability of the measurement record.

The timing of the Nimbus-7 mission included a period of rapid deepening and discovery of the ozone hole. The significant lowering in total ozone over Antarctica caused a rethinking of the autonomous ground quality-assurance programs that otherwise would reject the "unrealistic" low values. The success of the mission exceeded expectations—exemplified at the 32,768th orbit, when the two-byte word for the orbit number no longer sufficed.

The Nimbus-7 SBUV legacy (November 1, 1978, through June 21, 1990) was extended into the operational realm starting with the NOAA (National Oceanic and Atmospheric Administration) -9, -10, -11, -14, -16, and -17 satellites, the present-day Polar-orbiting Operational Environmental Satellites (POESs). These satellites carry the SBUV/2, which includes an onboard solar diffuser stability monitor to help characterize the time-dependent radiometric calibration changes. Following the Nimbus-7 TOMS (November 1, 1978, through May 6, 1993), subsequent NASA research flights included Meteor-3 (August 22, 1991, through November 24, 1994); Advanced Earth Observation Satellite (ADEOS) (July 25, 1996, through June 28, 1997); and Earth Probe (EP) (July 25, 1996, to the present). The most recent EP TOMS uses a solar diffuser carousel to ensure long-term measurement stability knowledge and control.

Corresponding improvements in the ground algorithms kept pace with hardware improvements on the series of NASA research flight missions. With the urgent need to improve measurement accuracy and precision, the ongoing validation activities revealed anomalous ozone amounts under certain conditions (e.g., the presence of aerosols). Analysis into the root causes of these anomalies led to the inception of new products that were by-products of the "noise" in the ozone. For example, extracting information about aerosol optical thickness and single-scattering albedo was a significant development from this measurement record. Unlike other techniques (e.g., Advanced Very High Resolution Radiometer [AVHRR]-based), the TOMS aerosol measurements could be made over ocean and land and under clear and cloudy conditions. In addition to aerosol information, TOMS today also produces information or fields of tropospheric ozone, UV irradiance at the surface, and volcanic sulfur dioxide (SO_2).

Today, because of the iterative improvements from validation, refinement, and revalidation—in what is called a spiral development process—the TOMS and SBUV products stand at Version 8. For example, Version 6 improved the calibration, Version 7 accounted for aerosol effects, and Version 8 refined the solar zenith angle dependence. For each version change, a retrospective reprocessing of the entire measurement record was necessary in order to retain the value of the data for climate research use (to avoid unphysical data discontinuities).

A number of current issues make the retrieval of the ozone profile in the lower stratosphere and troposphere challenging. The passive nadir backscatter technique uses rather broad weighting functions that limit the ability of the system to resolve the profiles vertically. There is also a lack of information in the lower stratosphere and below, which are regions that are of most interest for air quality and climate research. New technology, being developed to mitigate this deficiency, will be available for the Ozone Mapping and Profiler Suite flying on the next-generation operational satellites—the National Polar-orbiting Operational Environmental Satellite System (NPOESS). This technique involves observing scattered radiation in both UV and visible wavelengths in the limb direction.

Observations of tropospheric ozone, one of the Environmental Protection Agency's (EPA's) six "criteria pollutants" used as indicators of air quality, are also possible from space as a result of improving the precision of the algorithms. This observation is accomplished by subtracting a best estimate of stratospheric ozone from the total-column amount (e.g., TOMS-Stratospheric Aerosol and Gas Experiment [SAGE], TOMS-SBUV/2, TOMS-Microwave Limb Sounder [MLS], and Ozone Monitoring Instrument [OMI]-High Resolution Dynamics Limb Sounder [HIRDLS]).

Reasons for Success

Six important factors, described below, were fundamental to the utilization of the SBUV and TOMS environmental satellite data: (1) an integrated team, (2) funding stability, (3) career commitments, (4) freedom to continuously improve and evolve, (5) Moore's law, and (6) integrated interagency (NASA-NOAA) cooperation.

- *Integrated team*. The joint civil servant, contractor, and university team centered at NASA/Goddard Space Flight Center's (GSFC's) Code 916 (Atmospheric Chemistry and Dynamics Branch) worked together in a badgeless manner (without differentiation between civil servants, contractors, or academics), with strong determination to succeed.
- *Funding stability*. Owing to the national mandate to monitor and understand ozone changes and because of NASA's success in maintaining itself as a cutting-edge research institution, a sufficient and constant level of funding permitted an uninterrupted focus on resolving the scientific challenges without the distractions imposed by the effort of sustaining support from year to year.
- *Career commitments*. The integrated team has been largely populated by a community of individuals who have dedicated their careers to excellence in the area of ozone remote sensing. The low personnel turnover, in large part a consequence of the two factors listed above, ensured the strong reservoir of corporate knowledge needed to overcome knotty scientific problems.
- *Freedom to continuously improve and evolve*. The culture, including management, surrounding the ozone processing team at Goddard nurtured the systematic validation and refinement of the algorithms, sensors, and data set. This exemplary environment led directly to the high quality of the products, algorithms, and current and future flight sensors.
- *Moore's law*. The SBUV and TOMS spatial resolution and associated algorithmic complexity do not drive either storage or central processing unit requirements. With computer capacity doubling every 18 months, it is possible to reprocess the entire decadal climate record in a relatively short amount of time.
- *Integrated interagency (NASA-NOAA) cooperation*. NASA and NOAA partnered to transfer the maturing ozone remote sensing technologies from the GSFC research environment to the National Environmental Satellite Data and Information Service (NESDIS) operational environment. The shared missions of the two

sister agencies (NASA performs stratospheric research, NOAA conducts stratospheric monitoring), close teamwork between the staffs of the two agencies, and a cross-subsidization between the two groups owing to the natural synergies have led to both a comprehensive operational implementation and improved research opportunities and quality.

A Look to the Future

Low Earth Orbit (LEO) Sensing

The NPOESS Ozone Mapping and Profiler Suite (OMPS), to be flown operationally in 2008-2009 and on a NASA bridge mission (NPOESS Preparatory Project [NPP]) in 2006, will replace observations taken by SBUV/2 and TOMS, with significant improvements. SBUV/2 has provided continuous global stratospheric ozone concentration measurements (10 to 50 km) for more than 12 years. OMPS both continues the total ozone mapping of TOMS and the nadir profile record of SBUV/2 and simultaneously includes limb scattering for improved vertical profiles in the lower stratosphere. All three of the OMPS spectrometers employ a carousel with working and reference solar diffusers to assure accurate, long-term monitoring of OMPS radiometric stability.

The Ozone Monitoring Instrument, a contribution from the Netherlands to be flown on the Earth Observing System (EOS)-Aura satellite in early 2004, will bridge NASA's TOMS and the operational OMPS instruments. OMI and its predecessor, Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) flying on the Environmental Satellite (ENVISAT), are hyperspectral imagers that provide an even deeper understanding of the amounts and distribution of trace constituents in the atmosphere by employing differential optical absorption spectroscopy.

Lagrange Point Sensing

Triana, currently in storage at GSFC and renamed Deep Space Climatic Observatory (DISCOVR), will be the world's first Earth-observing mission to L1, the neutral gravity point between Earth and the Sun. This unique observing position will provide a continuous view of the sunlit portion of Earth as the planet rotates "below" the satellite. Continuously, every 15 minutes, data will be collected on Earth's radiation budget, cloud cover, aerosols, ozone, vegetation canopy, and the interplanetary medium. This low-cost mission will rely on heritage retrieval algorithms.

Geosynchronous Earth Orbit (GEO) Sensing

Owing to the cost of flights to the higher altitude and because of the lower spatial resolutions that result, geosynchronous Earth orbit (GEO) sensing has not been as fully exploited as has low Earth orbit (LEO) sensing. Unlike the L1 orbit, GEO observations offer unique advantages due to their fundamental nature—the satellite "sits" over a fixed location, constantly reimaging a broad Earth disk that extends 60 degrees of latitude and longitude from its equatorial subsatellite point. While the global coverage of LEO is lost, GEO gains time-continuity. With capabilities to continuously reimage with 5 to 10 km horizontal resolution—and possibly 1 km, depending on technology development—this platform affords the ideal opportunity for monitoring and mapping spatiotemporal ozone variations over continental scales. The challenge of vertical sounding suggests a high-spectral-resolution (e.g., wave number <0.1 for resolving line fine structure for altitude resolution) infrared spectrometric approach, similar to the Aura Tropospheric Emission Spectrometer (TES).[2] Co-manifesting an ultraviolet/visible/near-infrared (UV/VIS/NIR) hyperspectral instrument similar to OMI and SCIAMACHY would round out a powerful platform for observing the sources and distribution of pollutants and their precursors and other key Earth science parameters that have important diurnal timescales.

GEO ozone and atmospheric chemistry/trace gas/pollution/air quality represents the next remote sensing frontier. Laying the groundwork are the early instrument incubator activities at NASA GSFC and the Jet Propulsion Laboratory, and early Earth science application partnerships with NASA and EPA centered on EOS Aura data product. The proven interagency model of the NASA-NOAA partnership on SBUV/2 ozone observations shows how much can be accomplished through collaboration.

Challenges to a GEO air-quality flight (operational and research) include the following:

- Getting an affordable "ride" to GEO,
- Refining NASA programmatic focus on an air-quality role,
- Understanding NOAA's interest in an air-quality role,
- Overcoming the lack of a proven ability to achieve EPA's requirements,
- Rising to the need for additional technical maturity (signal to noise, reliability), and

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[2] "A high-resolution infrared-imaging Fourier transform spectrometer with spectral coverage of 3.2 to 15.4 μm at a spectral resolution of 0.025 cm^{-1}, thus offering line-width-limited discrimination of essentially all radiative active molecular species in the Earth's lower atmosphere." See "Introduction to TES" at the Web site http://aura.gsfc.nasa.gov/instruments/tes/introduction.html. Accessed June 18, 2004.

- Providing an adequate data rate to accommodate the great volume of data collected by a hyperspectral imager.

There already exists a vision for the future of air-quality remote sensing—to include monitoring, nowcasting, and forecasting of stratospheric and tropospheric O_3, CO, NO_2, SO_2, aerosols (e.g., dust, haze, smoke, smog, particulate matter [PM]-2.5), and so on. The next step is to envision and carry out a roadmap for the operational utilization of these future GEO satellite data for the benefit of the public. The LEO NASA-NOAA success story with BUV, SBUV, SBUV/2, TOMS, OMI, SAGE III, and OMPS has identified a working paradigm. The NPOESS Integrated Program Office has demonstrated the advantages of partnerships between operational and research agencies, along with industry, in judiciously leapfrogging ahead with advanced technologies for operational LEO sensing. The challenge is for NASA, NOAA, and the EPA to act together to develop an integrated, prioritized set of operational GEO air-quality requirements (with thresholds and objectives so that cost-benefit and CAIV[3] trade-offs can be conducted; to fly a demonstration GEO air-quality mission in the second half of this decade; and to allocate margin for and initiate an operational line of GEO air-quality spectrometer-imagers over the continental United States in the Geostationary Operational Environmental Satellite (GOES)-R time frame.

As satellite sensors move from 8, to 10, to 12 or 14 bits of information, every added bit pair provides a potential factor of up to four in added information. Extracting that added information from the data helps to meet user requirements but adds a corresponding multiple of greater than four times onto the complexity of the retrieval algorithms and their external data requirements. This growing complexity suggests a continuance of the spiral development paradigm, present since the early days of BUV sensing, through the present, and well into the future—along with the need for a next generation of scientists and technologists to achieve these refinements.

Corresponding innovations in high-performance ground processing—computing and mass storage—and optical and/or microwave space-to-Earth downlink would facilitate the most complete utilization of the environmental data. As NOAA's operational requirements increasingly turn to climate monitoring (in addition to meteorology), NESDIS operations will need to take responsibility for the stewardship of consistent, long-term climate records, without the artificial trends and

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[3] CAIV, or cost as an independent variable, trade-offs hold the total budget and year-to-year funding envelope fixed and seek to optimize performance against a set of prioritized requirements. Typically, performance of at least threshold level is mandated, and the designers seek to progress as far as possible toward important objectives. Simulations and sensitivity studies are used to assess the "knee in the curve" to optimize the design at a total system level.

discontinuities caused by algorithm or calibration changes. To do so will require a robust ability for climate data record processing and reprocessing, with retrospective processing following a version upgrade accomplished at a rate much greater than one data day per calendar day.

GLOBAL POSITIONING SYSTEM

The Global Positioning System (GPS) was developed by the Department of Defense to provide the military with accurate location and time information. The nominal GPS system consists of 24 satellites; five ground stations located around the world to control, monitor, and track the satellites; and GPS receivers on the ground that collect the satellite signal and convert it into time and position data. The first satellite was launched in 1978, the 24th in 1994.

Although GPS was developed by the military for military purposes and continues to be operated by the military, civil users worldwide have found many applications for GPS. Civilian applications include the following:

- *Vehicle tracking*—to determine the current location of delivery trucks, shipping containers, emergency vehicles, and the like;
- *Emergency services*—to locate the nearest responder in an emergency situation;
- *Surveying*—to determine precise locations;
- *Hiking*—to determine a current location;
- *Earthquake research*—to measure crustal deformation;
- *Automobile navigation*—to pinpoint a location on a map;
- *Boating*—to determine a precision location; and
- *Agriculture*—to assist with ground leveling and precision automated planting.

To support the many civilian applications of GPS, numerous companies have emerged with technologies or services related to GPS. For example, several companies produce receivers, others focus on surveying and mapping, still others support navigation and guidance applications, and other companies are involved in tracking services and wireless technologies.

Two lessons to be learned from the GPS example apply to NOAA. First, the user community may find many applications of a system that were not the original intent of the system designers. While new applications are a good thing, they can put additional demands on NOAA to produce more data faster to support the user community.

Second, industry will respond to the needs of the users. As technology improves and data are available from new NOAA systems, new applications and uses of the data are likely to be found. As happened in the case of GPS, companies are likely to form or expand to satisfy users' needs. NOAA needs to be prepared to work with these companies, and it needs to have a strategy regarding the commercialization of its data.

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

A Successful Environmental Satellite Data User

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an operational institute with strong research activity in all aspects of weather prediction and with a heavy investment in the use of satellite data. ECMWF and other numerical weather prediction (NWP) centers and their partners continue to use a wide variety of operational and research satellite data for model validation and data assimilation, for the study of and for related applications of research on the following:

- *Atmosphere*—dynamics (wind, temperature); physics (rain rate, clouds); composition (trace gases, aerosols);
- *Ocean*—upper-ocean dynamics (sea-level sea-surface temperature, the Los Alamos Sea Ice Model [CICE], salinity); upper-ocean biology; ocean surface waves; and
- *Land*—soil moisture, vegetation, hydrology (if available), cryosphere.

ECMWF, in common with leading NWP centers, has a preference for engineering-calibrated, Earth-located measurements (radiances, normalized radar cross sections, and so on) rather than for retrieved products. Forecast work with radiances puts heavy demands on the users' telecommunications capacity, high-performance computing resources, and resources for archiving data.

ECMWF has invested heavily for the past 6 years in developing a portable, parallel relational database system (ODB, or Observation Data Base) to cope with the forthcoming flood of satellite data, some of which is already here (e.g., from the Atmospheric Infrared Radiation Sounder [AIRS] and ENVISAT). Along with every observation, ECMWF keeps a comprehensive history of the treatment of the data in the assimilation system, including differences from the initial state and analysis, quality control, and decisions for data filtering. The ODB has powerful off-line diagnostic capabilities for data monitoring, which provides valuable feedback to the data producers.

In the 1980s and 1990s, ECMWF did have some "bad experiences" assimilating remote sensing data and obtaining positive results in the accuracy of its forecasts, mostly involving three factors:

- Poorly characterized instruments (the early generation of the High-resolution Infrared Radiation Sounder [HIRS]/Microwave Sounding Unit [MSU]/ Stratospheric Sounding Unit [SSU]) often had inconsistent calibration or spectral response when measured by the same instrument on successive satellites.

—Much effort was needed to understand the characteristics of a new instrument and to retune bias corrections.

—Instruments (such as the MSU) were not always stable in time on a given satellite. These problems returned to adversely affect ECMWF and the NWP centers during production of the ERA-40 reanalysis, which required analysis schemes to make old data consistent.

- Derived products (retrievals/preprocessed radiances) suffered the problems noted above, compounded by the fact that data producers were slow to get new data out to users (delays of about a year, while the data producers developed an understanding of the new data).
- Changes in algorithms during the lifetime of an instrument had to be done in close liaison with users, with adequate notice given.

—Properly managed changes of analysis and assimilation tools should be encouraged. ECMWF personnel found it frustrating to work with operational products that had well-known deficiencies when improved retrievals were available.

ECMWF's "good experiences" with improving accuracy of forecasts using remote sensing data tend to be related to the converse of the earlier situations mentioned above. The Advanced Microwave Sounder Unit (AMSU)-A stands out as a stable and reproducible observing system that provides data with substantial beneficial impact on the performance of ECMWF's forecasting system. It took the ECMWF about a year after the launch of the first AMSU instrument to go operational with raw-radiance assimilation. With NESDIS ensuring good data flow soon after launch of the AMSU-A, it was possible to start using data from the NOAA-16 satellite within 6 weeks of its launch. With NOAA-17, all NWP centers had to be somewhat more careful to ensure that its system would respond well to the assimilation of data from this polar orbiter, but the data were being used operationally a little more than 4 months after launch.

ECMWF's successes relating to NWP assimilation of satellite data can be summarized as follows:

- Space agencies' (including U.S. agencies') funding for new instruments, relying on experts working at the NWP centers where the data will be used, facilitates early adoption of data from these new instruments (giving a more effective return on the investment).
- Dialogue and liaison between the NWP centers and space agencies are

important to ensure that requirements, plans, and priorities for data supply are communicated and understood by all concerned.

- ECMWF attaches great importance to the following:
  —Annual North American/European data exchange meetings,
  —Regular bilateral liaison meetings with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), and
  —Participation in EUMETSAT and European Space Agency (ESA) advisory bodies on observation requirements and mission selection.
- ECMWF's regular program of data impact studies, which assess the contribution of many different observation systems to forecasting skill, is an important support to the global meteorological and environmental community and to the space agencies.
- Funding regimes differ between the United States and Europe. It may be a caricature, but until recently it seemed that U.S. research teams were funded only if they competed fiercely with each other. By contrast European Union (EU) funding encourages extensive collaborations across Europe.
- EU and ESA together fund extensive collaborations to develop the use of new instruments and to deliver new products (e.g., Global Monitoring for Environmental Security [GMES]).
- ECMWF has benefited from many EU/ESA-funded collaborations to develop the assimilation of various types of data:
  —Altimeter data on ocean waves and ocean circulation,
  —Rain-rate data using Tropical Rainfall Measuring Mission-Precipitation Radar (TRMM-PR) and TRMM Microwave Imager (TMI),
  —Cloud and rain-rate data (preparatory studies on ESA's EarthCARE mission), and
  —Ozone data for ENVISAT, including CO_2 assimilation for AIRS/Interferometer Atmospheric Sounding Instrument (IASI)/Cross-track Infrared Sounder (CrIS), and reanalysis.

Most of these initiatives have led or will lead to operational implementations—at which point ECMWF takes over the funding of the human resources.

NWP centers will always want to use promising new (and possibly complex) instruments. The work of the centers is made much easier if the following apply:

- An instrument is well characterized before launch, and
- A simulated data stream is available in near real time, for 6 to 12 months before launch.

This has been the case with AIRS, enabling NWP centers to be ready for operational implementation within a year or so of launch.

Close liaison between NWP centers and the science team for each new major instrument is of significant mutual benefit:

- NWP centers can provide their analysis fields for calibration/validation and instrument checkout, which ECMWF does for all ESA and EUMETSAT missions and for NASA missions such as AIRS and QuikScat (Quick Scatterometer).
- NWP centers can pass new data through their assimilation systems in passive mode, to identify and attribute anomalies. EUMETSAT and ESA receive a significant payoff from funding the human resources needed to conduct data assimilation (for optimal use and more accurate forecasting, for example) for such work at ECMWF.
- EUMETSAT and ESA also receive a significant return in improved forecasts, for example, from funding the human resources for long-loop monitoring of instrument performance at ECMWF.

The uses of satellite data are not without setbacks and frustrations owing to the lack of understanding of satellite measurement information content and imperfections in model and data assimilation. In the late 1980s, satellite retrievals of atmospheric profiles were removed from the operational optimal interpolation system in the Northern Hemisphere owing to the negative impact. In the early 1990s, the use of one-dimensional variational (1DVAR) data assimilation using satellite retrievals was reintroduced to the Northern Hemisphere interpolation system, but the impact was small. In the mid-1990s, operations changed to three-dimensional variational (3DVAR) data assimilation, and direct use of radiances improved the Northern Hemispheric forecasts, with their impact similar to that of radiosondes. Today the impact of satellite data is much larger than that of radiosondes in both the Northern and Southern Hemispheres (Figure D.1). Lessons learned include the following:

- Good prelaunch characterization of instrument measurements is vital.
- Dedicated expert support is needed at the NWP center for each new instrument.
- Innovation and flexibility are important (e.g., radiances from layers,[4] four-dimensional variational [4DVAR] data assimilation system).
- Better use of observations over land and in clouds is needed.

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[4] G. Kelly, E. Anderson, P. Bauer, M. Matricardi, T. McNally, J-N. Thépaut, M. Szyndel, P. Watts, and many others, 2003, "Use of Satellite Radiances in the ECMWF System," presentation at the International TOVS Study Conference XIII, Sainte Adele, Canada, October 29–November 4, 2003.

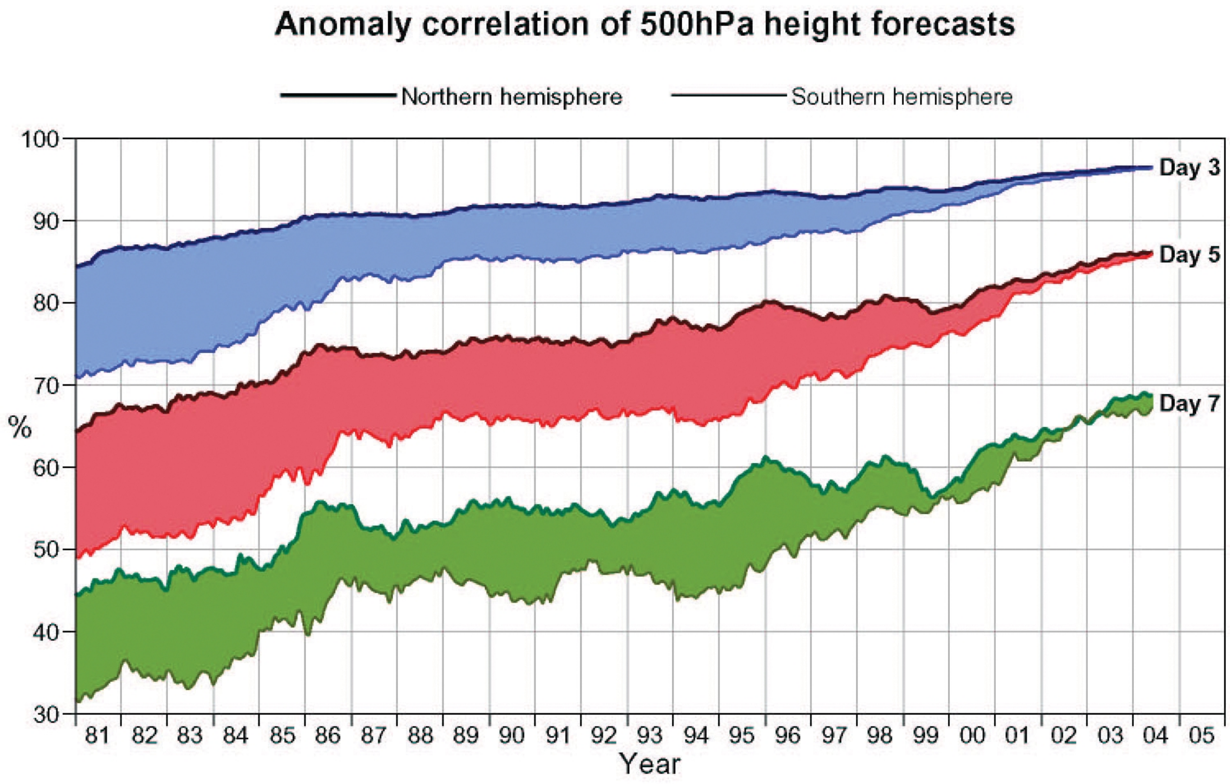

FIGURE D.1 The evolution of numerical weather prediction (NWP) skill in the Northern and Southern Hemispheres. Standard 500 hPa geopotential anomaly correlation derived from three observing system experiments, 1981 to 2004.

TABLE D.1 Snapshot of Current Data Count of European Centre for Medium-Range Weather Forecasts (ECMWF) Model: Data Ingested and Actually Assimilated

	Data Entering the Screening (percent)[a]		Data Assimilated (percent)[b]	
Synop	190,370	(0.27)	38,112	(1.06)
Aircraft	233,306	(0.33)	146,749	(4.07)
Satob	543,340	(0.78)	71,220	(1.97)
Dribu	15,081	(0.02)	4,381	(0.12)
Temp	110,998	(0.16)	63,763	(1.77)
Pilot	98,364	(0.14)	56,324	(1.56)
UpperSat	68,358,565	(97.97)	3,107200	(86.19)
PAOB	530	(0.00)	185	(0.00)
Scat	222,410	(0.32)	117,196	(3.25)
Total	69,772,964		3,605,130	

NOTES: Synop, traditional synoptic weather observations; Aircraft, measurements from aircraft; Satob, satellite observations; Dribu, drift buoys; Temp, temperature measurements other than synoptic; Pilot, commercial aviation observations; UpperSat, upper atmospheric measurements; PAOB, synthetic surface pressure data; Scat, scatterometer.

[a] Of screened data, 99.07 percent are satellite data.

[b] Of assimilated data, 91.41 percent are satellite data.

SOURCE: ECMWF.

There is now a stronger dependence on satellite data in the ECMWF system, and the influence of other, nonsatellite data types is becoming less important.

ECMWF's success as a satellite data user is evidenced by the fact that more than 99 percent of the data ingested by its NWP models is from meteorological and environmental satellites, and more than 91 percent of its model-assimilated data is satellite data (Table D.1).

Summary

The case study summary presented here[5] emphasizes ECMWF's ability to deal with the end-to-end aspect of the satellite data utilization in the NWP centers. The agency considers that each chain in the link is equally important and that they all matter:

- ECMWF has a talented, flexible, and agile operations department that is eager to deliver new data, both from operational satellites and from research satellites, to

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[5] This summary is provided largely by Tony Hollingsworth, retired head of research for the European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom.

the research department and then to implement the new data quickly into operations when the research and validation are mature.

- ECMWF has an equally capable research team of satellite, assimilation, modeling, and computer specialists who work closely and interactively and to the highest scientific standards to exploit new observational technologies that improve the ECMWF analyses, model, and forecasts.
- ECMWF has a powerful, flexible, theoretically well founded, and highly efficient four-dimensional variational data assimilation system, which was designed to use a wide range of nadir-scanning or conically scanning satellite data as well as all in situ data. The assimilation system is being extended to cope comfortably with new viewing geometries such as GPS and limb-sounding data.
- ECMWF has powerful computers and data-handling systems.
- ECMWF has a powerful data-monitoring capability in its operational and research assimilation systems, which compare engineering-calibrated, geolocated satellite measurements (measured radiances, scatterometer radar cross sections, and so on) with the model equivalent of the measurement. This is a powerful means of identifying anomalies in the measurements (and in the model). The data-monitoring results are an important element in ECMWF's active dialogue with all of its data providers, including NESDIS and NASA.
- ECMWF has strong support from EUMETSAT, ESA, and the EU in the form of fellowships and research contracts that fund postdoctoral research associates for work on satellite assimilation.
- ECMWF has strong support for its satellite work from its governing body, representing 18 European governments.

In summary, ECMWF has demonstrated that both operational and research satellite data are more important than nonsatellite data, are crucial for the success of weather forecasting, and can be optimally utilized from reception to end use. ECMWF relies on its visionary leadership, seamless partnerships, efficient administration, well-funded infrastructure, and expert teaming; on its intelligent data-monitoring, modeling, and processing system; and, most of all, on its willingness to take on challenges of finding ways to incorporate emerging satellite measurements to improve its mission objectives. And finally, "We [at ECMWF] must constantly make the case for the necessary resources (computing, personnel) to exploit the huge investments in satellite data."[6]

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[6] Statement by Tony Hollingsworth, from Tony Hollingsworth and Adrian Simmons, 2003, "ECMWF Experience in Using Environmental Satellites for Research and Operations," presentation to the Committee on Environmental Satellite Data Utilization at information collection meeting, June 2003, Madison, Wisconsin.

THE BILKO PROJECT: A CASE STUDY IN EDUCATING USERS

To facilitate and improve the use of environmental satellite data, education and/or training are needed to help users effectively address the following key issues:

- What environmental parameters are measured by satellite?
- For a desired parameter, how can data availability be determined?
- For those data, what are the coverage, sampling, and data storage characteristics?
- How can the data be obtained, from whom, in what form, at what cost, and with what delay?
- How can the data be worked with to produce desired products and information?
- What are the quality and accuracy issues with the data, and where are the techniques and associated calibration procedures summarized?

For the user seeking to learn generally what parameters are measured by satellites or to find out if a specific parameter is available, locating a comprehensive directory of satellite data is a challenge. Once the user learns, for example, that ocean surface temperature is measured by instruments onboard satellites, the next challenge is to determine whether the observations can be obtained, over what time and over what part of Earth there is coverage, whether the region and time of interest are included in the available data, and whether the time/space resolution of the data meets the user's needs. If there is coverage, the user must then determine how to obtain the data and then learn how to work with them: Are they image or digital files? How are the files to be manipulated? Have the data been geolocated and converted to engineering units? Is further calibration needed? Once work with the data begins and a path toward products or desired information is being followed, some users need to know more about how the measurements were made and about the accuracies and uncertainties of the data so that these characteristics can be reflected in the final products.

All of these problems—including the lack of centralized information about what satellite data are available and how they can be obtained, and the fact that working with the large data files is daunting for many, especially if the data need to be geolocated and processed to obtain useful fields—constitute impediments to the use of environmental satellite data. To deal with these challenges, a number of efforts have been made to provide education and hands-on training at various satellite data centers nationally and internationally. The Bilko project is such an effort within the oceanographic community. It is sponsored by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) with the goal of providing a "virtual global faculty for ocean and coastal remote sensing."[7]

The Bilko Web site[8] provides DOS and Windows software modules for a series of lessons. These lessons provide satellite imagery and take the user through the steps associated with using the images to address scientific questions. The images, the processing software, a tutorial in the use of the software, and lessons on oceanographic and coastal management applications of the software are provided in each module. The book developed to accompany the software is entitled *UNESCO Bilko Resource Book: An Index to Computer Based Learning Modules in Remote Sensing of Coastal-Marine Environment*.[9]

The Bilko software modules are quite extensive, each containing a number of exercises. The modules focus on various topics, including geographical areas (Atlantic, Pacific, Indian Oceans); thematic areas (coastal management, open ocean); data types (optical and infrared, microwave, airborne and in situ, numerical modeling); sea-surface temperature; ocean fronts; color scanner data; joint analysis of AVHRR and color scanner data; marginal seas; synthetic aperture radar data; seasonal variation of phytoplankton; coastal discharges; upwelling; coastal plumes and coastal management; sea ice; global winds; ocean eddies; bio-optical variability; coastal upwelling; dependence of AVHRR sea-surface temperature on satellite zenith angle; bathymetry; coastal ecosystems; red tides; coastal vegetation; acquiring images with appropriate scales and resolution; radiometric corrections; and marine vegetation.

DIRECT BROADCAST

The NOAA POES and GOES and NASA EOS satellites all currently provide direct-broadcast capability—direct broadcast here meaning that data acquired by satellite sensors are broadcast in real time to any ground station within range of the satellite's current position. The data are unencrypted and the signal characteristics are published, so the data are immediately accessible to any organization or individual with the wherewithal to deploy and operate a ground station. The cost of doing so is primarily a function of the broadcast signal strength (a weaker signal requires a larger antenna) and frequency (a higher frequency supports a higher data bandwidth but requires more expensive signal processing hardware). Polar-orbiting satellites (POES and EOS) additionally require an antenna that can be steered to track the satellite during data acquisition.

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[7] Available online at http://www.unesco.bilko.org. Accessed June 24, 2004.

[8] Available online at http://www.ncl.ac.uk/tcmweb/bilko/intro.shtml. Accessed June 24, 2004.

[9] Available online at http://www.ncl.ac.uk/tcmweb/bilko/bilko_resource_book.doc. Accessed June 24, 2004.

There are two principal rationales for direct broadcast. First, making the data publicly available in real time allows alternate processing chains to be independently developed and supported, adding considerable robustness to the overall system. Second, and more significant, because direct broadcast operates on a line of sight between the satellite and the ground station (as opposed to the playback of a signal recorded when the satellite is not visible), ground stations generally acquire local and/or regional data, which they may then customize for local and/or regional applications. Direct broadcast thus puts the data that much closer to the application.

A specific example is illustrative: Since 1994, the Institute for Computational Earth System Science (ICESS) at the University of California, Santa Barbara (UCSB) has operated an L-band ground station provided by the SeaSpace Corporation (one of several commercial vendors of ground station technology). A 1.2-m dish antenna mounted atop a six-story office building automatically tracks (using continuously updated orbit models) all currently operating NOAA satellites whenever they are above the horizon (Figure D.2(a)). An L-band receiver detects the high-resolution picture transmission signal from the AVHRR sensor. Analog data from the receiver are passed to a dedicated workstation, which decodes the multichannel digital image and initiates a standard processing sequence: reflectance/temperature retrieval, navigation to geographic coordinates, extraction of local and regional subsets, and archiving. Aside from the antenna, the entire system (antenna controller, receiver, workstation, and multiterabyte online archive) fits easily in the corner of an office (Figure D.2(b)). In 1993 the system cost approximately $50,000; today it would cost less than half that to replace it.

The ICESS ground station has been used to support both oceanic and terrestrial applications. In addition to contributing to research on long-term ocean processes in the Southern California Bight, the ground station's 10-year time series of consistently calculated sea-surface temperature has been exploited by local fishermen, even at the relatively crude resolutions available in false-color images delivered through a Web browser (see Plate 6). The availability of a similarly long-term data set of surface reflectance has been invaluable in operationalizing snow-covered-area algorithms developed by UCSB researchers (see Plate 7). Accumulating detailed time series over specific areas of interest, while at the same time accommodating real-time data needs (short-lived phenomena, field campaigns, and so on) would have been vastly more difficult, if not impossible, without a dedicated ground station.

Direct-broadcast processing software that can convert satellite signals to calibrated physical units and products is also provided by government-university collaborative efforts. For example, the International MODIS (Moderate-resolution Imaging Spectroradiometer) and AIRS (Atmospheric Infrared Radiation Sounder)


SeaSpace

FIGURE D.2 (top) Dish antenna of the high-resolution picture transmission (HRPT) ground station operated by the Institute for Computational Earth System Science (ICESS), University of California, Santa Barbara. (bottom) The HRPT ground station electronics (top unit, receiver; bottom unit, antenna controller, coffee mug for scale. Photos courtesy of the ICESS, University of California, Santa Barbara.

TABLE D.2 Summary of Algorithms for Current and Upcoming International MODIS (Moderate-resolution Imaging Spectroradiometer) and AIRS (Atmospheric Infrared Radiation Sounder) Processing Package (IMAPP) Products

Status	MODIS	AIRS/AMSU/HSB
Current	Geolocation/navigation	Geolocation/navigation
	Cloud mask	
	Cloud phase	
	Cloud top property	
	Clear temperature (T)/water vapor (q) sounding	
	Total precipitable water	
Planned	Cloud particle size	Clear/cloudy T/Q sounding
	Cloud optical thickness	Cloud detection
	Aerosol optical thickness	Cloud clearing
	Surface reflectance	Cloud height/emissivity
	Sea-surface temperature	Surface skin temperature
	Snow detection	Cloud liquid water
	Sea-ice detection	AMSU precipitation estimate
	Scene classification (clouds and land surface)	
	MODIS/AIRS collocation	

NOTES: AMSU, Advanced Microwave Sounder Unit; HSB, Humidity Sounder for Brazil.

Processing Package (IMAPP)[10] is a NASA-funded, freely distributed software package that allows any ground station capable of receiving direct broadcast from Terra or Aqua satellites to produce calibrated and geolocated radiances and a variety of environmental products.

IMAPP's capabilities, beyond providing rigorous sensor measurement calibration and geolocation, are summarized in Table D.2. These products range from atmospheric properties of clouds, sounding profiles, and precipitation, to surface properties of surface temperature, reflectance, and types. All of these products are designed to be available for direct broadcast in near real time (within 2 hours of data reception). Most important, the processing algorithms of IMAPP are validated to achieve the same quality as that of the official products produced by government-university teams.

The IMAPP software[11] has been ported to a variety of UNIX and personal computer platforms. The software has been well received by a wide variety of users

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[10] H-L. Huang, L.E. Gumley, K. Strabala, J. Li, E. Weisz, T. Rink, K.C. Baggett, J.E. Davies, W.L. Smith, and J.C. Dodge, 2004, "International MODIS and AIRS Processing Package (IMAPP)—A Direct Broadcast Software Package for the NASA Earth Observing System," *Bulletin of the American Meteorological Society* 85(2):159-161.

[11] Available online at http://cimss.ssec.wisc.edu/~gumley/IMAPP/. Accessed June 18, 2004.

and is currently in use at more than 75 ground stations around the world. IMAPP is also supplied as a standard feature by many commercial ground station vendors.

THE ADVANCED VERY HIGH RESOLUTION RADIOMETER (AVHRR) NORMALIZED DIFFERENCE VEGETATION INDEX (NDVI) PATHFINDER

Forward processing of the AVHRR sensor and producing the Normalized Difference Vegetation Index (NDVI) has been done by NOAA across five Television Infrared Observation Satellite (TIROS) platforms since 1981. The AVHRR NDVI, called the Pathfinder, is used operationally by many agencies, such as the U.S. Department of Agriculture's Foreign Agricultural Service, for global vegetation analysis. NOAA and NASA teamed up to reprocess the NDVI record from its inception, eliminating sensor and orbital degradation effects, and cross-walking the time series of five sensors to eliminate radiometric differences. The resulting consistently reprocessed data set has allowed the first clear detection of decadal trends in global biospheric vegetation.[12] The recent finding that global terrestrial net primary production has increased 6 percent between the 1982 and 1999 "greening of the biosphere" (Plate 8) was possible only by building a climate data record for NDVI based on the latest theory and algorithms applied to the full historical record.[13] The precision of this record, which was necessary to detect the climate trends, could not have been accomplished in an operational forward processing situation.

MODERATE-RESOLUTION IMAGING SPECTRORADIOMETER (MODIS) FIRE RAPID RESPONSE SYSTEM

A primary objective of the NASA Earth Observing System has been to deliver usable remote sensing data products to a wider array of less-sophisticated users. While it is still too soon to assess the overall success of this objective, there have been marked successes and failures during EOS's years of operation. The failures have been traced initially to technical problems—data being delivered in unfamiliar formats and geographic projections, overly complex user interfaces and ordering procedures, insufficient subsetting so that users were forced to deal with huge data files, poor documentation, and incomplete metadata. These problems have progressively been solved or alleviated, and now the larger test is whether the EOS data can actually provide important information to the user.

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[12] R.B. Myneni, C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani, 1997, "Increased Plant Growth in the Northern High Latitudes from 1981 to 1991," *Nature* 386(17):698-702.

[13] R. Nemani, C. Keeling, H. Hashimoto, W. Jolly, S. Piper, C. Tucker, R. Myneni, and S. Running, 2003, "Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999," *Science* 300:1560-1563.

The greatest EOS success has come from a user's identifying a clear data requirement and working directly with an EOS team to customize processing and delivery of the data to user specifications. This success story began shortly after launch of the Terra platform, when the U.S. Forest Service was involved with a summer of major wildfire management, in 2000. Wildfire management is a high-priority land management issue, consuming over $1 billion in costs in active years and with human safety and property risks attracting particular attention to the matter of improving procedures. During a major multiple-event wildfire conflagration in Montana and Idaho in August 2000, the Forest Service approached NASA and the University of Maryland to generate MODIS imagery to evaluate daily fire activity. The initial tests proved that MODIS data were timely, more objective, and cheaper than imagery generated from aircraft, and also that in severe conditions these data may help avoid human safety issues of pilots flying in smoke-obscured mountainous terrain (Plate 9).

During the summers of 2001, 2002, and 2003, the collaboration of NASA, the Forest Service, and the University of Maryland streamlined the direct reception, immediate processing, and distribution of 250 m MODIS data identifying fire activity and perimeters directly to the National Interagency Fire Center in Boise, Idaho, as well as to Regional Fire Coordination Centers. Through a network of fire intelligence specialists, these data were delivered to the incident commanders as part of a daily operational planning and fire assessment cycle (Plate 10 and Figure D.3).

Key to the success of this application has been the continuing interaction among the three partnering groups to identify exactly what remote sensing data are needed in exactly which format, processing the data to meet necessary deadlines, and delivering the data to a particular location for the individual to whom the information is valuable for specific decision making. The utility of MODIS data in broadscale fire assessment has now been well proven. Experiences from the 2003 wildland fire season showed that MODIS is also capable of providing much-needed intelligence at the incident level and that the fire community is able to incorporate satellite data into its daily planning and assessment cycle.

GEOSTATIONARY OPERATIONAL ENVIRONMENTAL SATELLITE (GOES) IMAGER AND SOUNDER

Two satellite orbits provide unique and complementary vantage points for observing the environment: Sun-synchronous and geosynchronous. Sun-synchronous satellites view the entire Earth twice per day (during the day and at night), passing over locations at the same local time every day. Geosynchronous satellites remain at a relatively fixed position, and rather than viewing the entire Earth, instead continuously image one large area of Earth's disk.

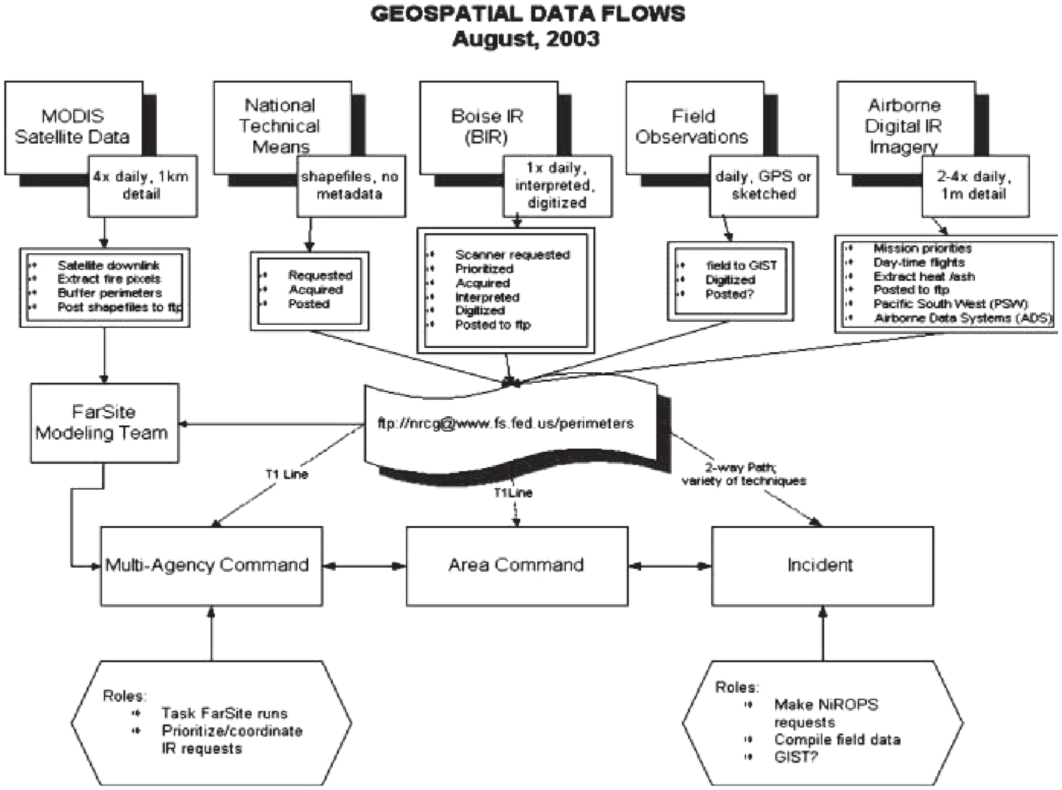

FIGURE D.3 Geospatial data flows from August 2003 fire control. NOTES: IR, infrared; GPS, Global Positioning System; GIST, Geographic Information Support Team; NiROPS, National Infrared Operations Program. SOURCE: Courtesy of Lloyd Queen, University of Montana.

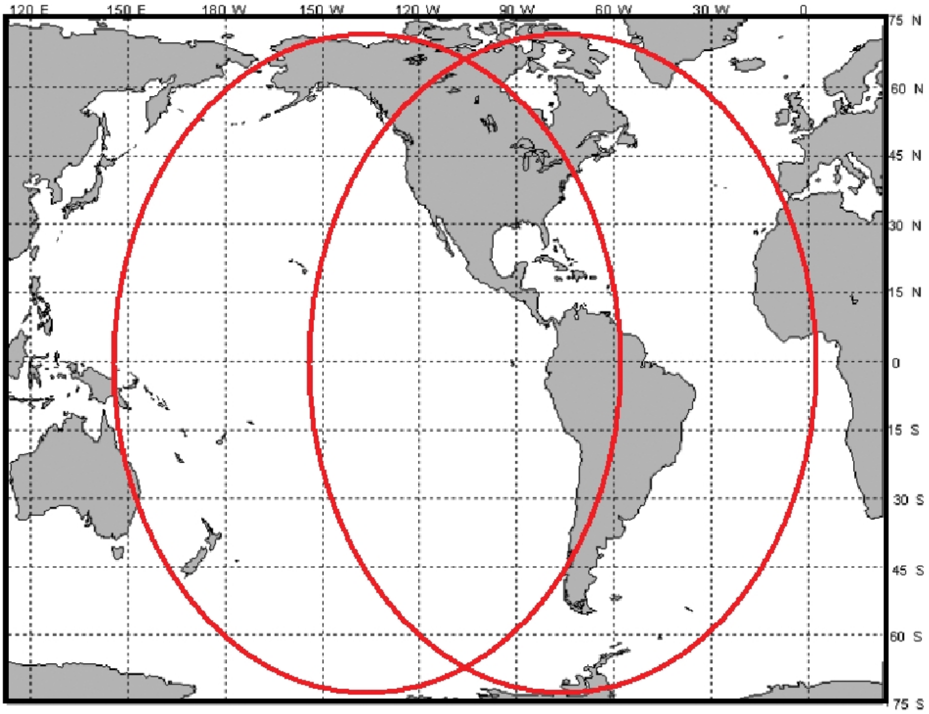

FIGURE D.4 Ground coverage of the Geostationary Operational Environmental Satellite (GOES)-West (left ellipse) and GOES-East (right ellipse) satellites. SOURCE: NASA Goddard Space Flight Center, *GOES Hyperspectral Environmental Suite (HES) Performance and Operation Requirements Document (PORD) draft*, Volume 0.5.3, September 12, 2003, NASA/GSFC, Greenbelt, Md., Figure 3.2.5, p. 45.

The United States operates two geostationary satellites in geosynchronous orbits, over fixed equatorial positions (Hyperspectral Environmental Satellite [HES] performance and operation requirements document [PORD]; see Figure D.4).[14] GOES-East sits at 75°E and best views the central and eastern United States, the Atlantic Ocean (for hurricane season, explosive winter storm developments, and so on), and Central and South America. GOES-West is located at 135°W, best viewing the

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[14] Additional information is available online at http://cimss.ssec.wisc.edu/goes/goes.html. Accessed June 18, 2004.

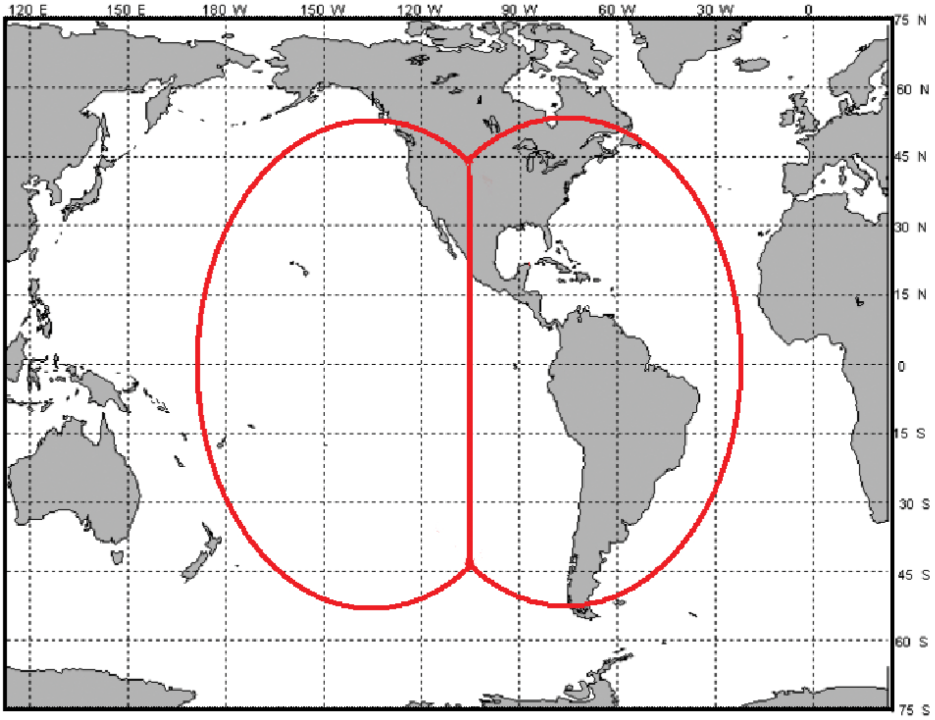

FIGURE D.5 Geostationary Operational Environmental Satellite (GOES)-West and GOES-East integrated coverage. SOURCE: NASA Goddard Space Flight Center, *GOES Hyperspectral Environmental Suite (HES) Performance and Operation Requirements Document (PORD) draft*, Volume 0.5.3, September 12, 2003, NASA/GSFC, Greenbelt, Md., Figure 3.2.6, p. 46.

United States from the Mississippi River west, and much of the Pacific Ocean (including tropical storms threatening Hawaii and weather systems approaching the Pacific Northwest). The best data are taken with local viewing zenith angles of 62° or less (see Figure D.4). Thus, the two GOES satellites together provide an optimal integrated view of the United States, Central and South America, and weather systems in the neighboring Atlantic and Pacific Oceans (Figure D.5).

The nation's need for improved geosynchronous observations with higher spectral, temporal, and spatial resolution becomes more critical as environmental data users both in operational areas (e.g., weather forecasters) and in research concentrate on improved monitoring and forecasting of rapidly evolving weather processes. NOAA's strategic goals support the operational needs of the GOES end users, who have demanded improved spatial resolution, spatial coverage, temporal resolution, spectral resolution, and radiometric accuracy. To keep pace with these growing needs, NOAA is continuing to evolve its geostationary environmental remote sensing capability. Satisfaction of significant operational requirements and improvement over today's systems are directly enabled through technology improvements and research demonstrations, for example, in NASA's EOS and Ice, Cloud, and land Elevation Satellite (ICESat). To enable NOAA to continue progress in improving its data utilization and forecast services, well-calibrated, well-characterized geosynchronous data must be available for numerical model assimilation and short-term forecasts at National Weather Service field offices. GOES-R sensors will collect significantly higher-quality environmental data and consequently more useful information (GOES-R Mission Requirements Document[15]). Benefits from the planned GOES-R instruments include the following:

- Improved understanding of the role of oceans in coupled geophysical and ecological processes,
- Cost savings and increased safety for marine transportation,
- Enhanced fisheries production and conservation through science-based knowledge, and
- Improved numerical-prediction (ocean, atmosphere, and coupled) models.[16]

For Earth environmental observations, perhaps the three most important sensors to be carried by GOES-R are the Advanced Baseline Imager (ABI), the Hyperspectral Environmental Satellite, and the Geostationary Lightning Mapper (GLM). Additionally, the Geostationary Microwave Imager (GMI), a six-band radiometer (a pre-planned product improvement) will provide time-resolved precipitation imagery and atmospheric vertical temperature and water profiles through cloud cover. In addition to improved sensors, GOES-R is positioned to help solve the greatest deficiencies of today's system: data latencies ranging from 5 to 40 minutes, several-hour interruptions during the spring and fall solar eclipse seasons, inability to conduct simultaneous global and mesoscale imaging, and degraded image quality owing to direct solar impingement.

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[15] "NOAA, 2004. Mission Requirements Document 2A (MRD-2A) for the GOES-R Series, version 2.3, March 23, 2004. Available online at http://www.osd.noaa.gov/goesr_arch_study/docs/MRD2A_03-19-04.pdf. Accessed on June 28, 2004.

[16] J. Gurka, T. Schmit, and R. Reynolds, 2003, "Highlights from the Second GOES Users' Conference: Recommendations for the GOES-R Series," presented to the American Meteorological Society.

TABLE D.3 GOES Imager Current and Upgraded Capability

Attribute	GOES Imager Today	GOES-R ABI	Implication
Horizontal resolution	VIS (1), IR (4-8) km	VIS (0.5), VNIR/SWIR (1), LWIR (2) km	Greatly improved spatial resolution and image quality to resolve severe weather.
Spectral channels	5	16	3 times more information, yielding diverse environmental products, not only weather.
NEdT	0.2 K	0.1 K	Lower noise.
Data rate	2.6 Mbps	25 to 50 Mbps	20 times increase in data rate.
Full disk refresh	26 min	5 min	Continuous imaging, plus mesoscale/full-disk simultaneity.
Quantization	10 bits	12 bits	Improved.

NOTES: GOES, Geostationary Operational Environmental Satellite; ABI, Advanced Baseline Imager; VIS, visible; IR, infrared; VNIR, very near infrared; SWIR, short-wave infrared; LWIR, long-wave infrared; NEdT, noise-equivalent-difference temperature.

ABI is the primary GOES-R cloud, land, and ocean imager. A significant upgrade to the capability of the current GOES imager, ABI is intended to provide enhanced spatial and temporal resolution and spectral capability to meet data product requirements described in the mission requirements document for atmospheric, oceanic, and land environmental sensing. These requirements include severe weather, fog, and nighttime low-cloud monitoring, volcanic cloud detection, microphysical cloud properties retrieval, thin cirrus detection, improved measurement of sea-surface temperatures, and observations of surface properties.[17] As illustrated in Table D.3, ABI will take full-disk images every 5 minutes, five times more rapidly than today's geosynchronous imagers, with the capability of monitoring severe weather events in 1,000 x 1,000 km boxes with 30-second reimaging (refresh).

As illustrated in Table D.4, HES will retrieve atmospheric vertical temperature (T) and water vapor (q) profiles, including hourly full-disk sounding, severe weather/mesoscale tasking with 2- to 4-minute refresh, and coastal waters (CW) imaging.[18] The principal HES improvement over today's GOES sounder is in its spectral separation performance. Instead of 19 discrete channels in the current sounder, HES will

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[17] T. Schmit and P. Menzel, 1999, "Spectral Band Selection for the Advanced Baseline Imager (ABI)." Available online at http://cimss.ssec.wisc.edu/goes/abi/ppt/abi_R&D.ppt. Accessed on June 24, 2004.

[18] HES Performance Operational Requirements Document. Available online at http://goes2.gsfc.nasa.gov/HEShome.htm. Accessed on June 24, 2004.

TABLE D.4 GOES Sounder Current and Upgraded Capability

Attribute	GOES Sounder Today	GOES-R HES	Implication
Scanning flexibility	Fixed scan area	Scan arbitrary-sized area within full disk on command	Increased flexibility to satisfy diverse simultaneous requirements.
Spectral channels	19 wide channels (1 VIS, 6 SWIR, 5 MWIR, 7 LWIR)	SWIR/MWIR/LWIR sounding: 1,700 to 3,400 channels. CW imaging: 14 channels (threshold)/hyperspectral	Increased sounder spectral resolution reduces T, Q, "V" retrieval uncertainty; new capability for high-resolution imaging of coastal ecosystems.
Coverage region/area	Full disk; local regions on command, including regional sounding	Full disk (10^8 km^2); CONUS (1.5×10^7 km^2); mesoscale (1.0×10^6 km^2); CW (2.4×10^6 km^2)	
Horizontal resolution	IR sounder (10 km), with 50-10 km retrievals	IR sounder/retrieval (4 km), CW imager (300 m)	Can sound between clouds, near fronts; able to resolve coastal gradients.

NOTES: GOES, Geostationary Operational Environmental Satellite; HES, Hyperspectral Environmental Satellite; VIS, visible; SWIR, short-wave infrared; MWIR, mid-wave infrared; LWIR, long-wave infrared; T, atmospheric vertical temperature; q, water vapor; "V," four-dimensional profiling of winds; CONUS, continental United States; CW, coastal waters; IR, infrared.

sense from 1,700 to 3,400 narrow channels using either dispersive (demonstrated by the AIRS instrument) or Fourier transform (demonstrated by aircraft instruments and the NPOESS Cross-track Infrared Sounder) spectroscopy. HES will also enable the four-dimensional profiling of winds ("V"). This increase in collected environmental data will yield a corresponding improvement in environmental information, enabling reductions in retrieval uncertainty while simultaneously improving the vertical resolution—for example, temperature inversions will be detectable.

Based in part on the success of the Tropical Rainfall Measuring Mission (TRMM) Lightning Imaging Sensor, the GLM will continuously map all forms of continental United States lightning discharges and measure total lightning activity over large areas of the Americas and nearby oceans on a continuous basis. GLM will help advance tornado warnings by 20 minutes, while enhancing lightning and intensity hazard alerts.

E

Biographical Information for Committee Members and Staff

COMMITTEE MEMBERS

Hung-Lung Allen Huang (*Chair*) is senior scientist at the Space Science and Engineering Center, University of Wisconsin-Madison. Dr. Huang is a member of the Cooperative Institute for Meteorological Satellite Studies and the principal investigator for the International MODIS/AIRS (Moderate-resolution Imaging Spectrometer/Atmospheric Infrared Radiation Sounder) Processing Package. He has more than 20 years of comprehensive experience in meteorological satellite data processing and applications, including 17 years of experience in remote sensing, geostationary and polar-orbiting meteorological satellite data applications, atmospheric radiation, meteorological profile retrieval, satellite instrument design performance analysis, information content analysis, and the use of high spectral resolution interferometer and microwave data. His experience also includes computer software development and maintenance for a real-time satellite image processing system.

Philip E. Ardanuy is director, Remote Sensing Applications, at Raytheon Information Solutions. A meteorology graduate of Florida State University, Dr. Ardanuy has 25 years of professional experience participating in National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and Department of Defense (DOD) remote sensing programs. He specializes in developing integrated mission systems leveraging the synergies of user requirements, science and sensor maturity, and data systems through government/industry/

academic partnerships. Dr. Ardanuy's research and development career extends across tropical meteorology, Earth's radiation budget and energy balance, satellite instrument calibration and characterization, research to operational science data systems, environmental observations validation, chief scientist for National Polar-orbiting Operational Environmental Satellite System Visible and Infrared Imager/Radiometer Suite, and the upcoming Geostationary Operational Environmental Satellite (GOES)-R mission.

John R. Christy is professor of atmospheric science and director of the Earth System Science Center at the University of Alabama in Huntsville. Dr. Christy began studying global climate issues in 1987. In November 2000, Governor Don Siegelman appointed him as the Alabama state climatologist. Dr. Christy has served as a contributor and lead author for the United Nations reports by the Intergovernmental Panel on Climate Change, in which satellite temperatures were included as a high-quality data set for studying global climate change. In addition, he has been a member of several committees of the National Research Council (NRC), including the Committee on Earth Studies (1998-2001) and the Committee to Review NASA's ESE [Earth Sciences Enterprise] Science Plan. Dr. Christy is a fellow of the American Meteorological Society.

James Frew is assistant professor in the Donald Bren School of Environmental Science and Management, University of California, Santa Barbara (UCSB). He is an adviser to NASA's New Data and Information Systems and Services) activity. Dr. Frew is a principal investigator in UCSB's Institute for Computational Earth System Science (ICESS). As part of his doctoral research, he developed the Image Processing Workbench, an open-source set of software tools for remote sensing image processing currently used for instruction and research at UCSB and elsewhere. He has served as both the manager and the acting director of the Computer Systems Laboratory (ICESS's predecessor) and as the associate director of the Sequoia 2000 Project, a 3-year, $14 million, multicampus consortium formed to investigate large-scale data management aspects of global change problems. Dr. Frew currently leads the Earth System Science Workbench project, part of NASA's Federation of Earth Science Information Partners.

Susan B. Fruchter is associate director for operations at the National Museum of Natural History, Smithsonian Institution. Prior to holding this position, Ms. Fruchter was extensively engaged at NOAA in satellite issues ranging from technology to policy: from 1994 to 2001, she was counselor to the Undersecretary of Commerce and was director of NOAA's Office of Policy and Strategic Planning in the Department of Commerce. She was responsible for leading the strategic planning efforts and process within NOAA and for coordination on a range of NOAA policy and interagency issues. Ms. Fruchter was also executive secretary for the Committee on Environment and Natural Resources of the National Science and Technology Council. Before serving at NOAA, she was director of administration and resources management at NASA's Office of Advanced Concepts and Technology.

Aris Georgakakos is a professor in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. He is also the school's associate chair for research, head of the Environmental Fluid Mechanics and Water Resources Program, and director of the Georgia Water Resources Institute. Dr. Georgakakos's areas of research include remote sensing of hydrologic variables, flood and drought management, hydropower scheduling, agricultural planning, regional groundwater management, and decision support systems for river basin planning, management, and conflict resolution.

Ying-Hwa (Bill) Kuo is senior scientist at the National Center for Atmospheric Research. He is also director of the Constellation Observing System for Meteorology, Ionosphere and Climate, a joint U.S.-Taiwan project using radio occultation (limb sounding) from space, and the head of Mesoscale Prediction Group/MMM Division. Dr. Kuo is a recognized leader in the field of mesoscale numerical modeling and data assimilation for weather forecasting. His scientific interests include mesoscale modeling, explosive marine cyclogenesis, mesoscale convective systems, heavy rainfall prediction, data assimilation, Global Positioning System/MET research, and model initialization. He served as the U.S. project director for the Taiwan Area Mesoscale Experiment. Dr. Kuo has been co-chief editor of *Monthly Weather Review* since 1998 and associate editor of *Terrestrial, Atmospheric and Oceanic Sciences* since January 1999.

David S. Linden is a private consultant at DSL Consulting and Massively Parallel Systems, Inc. Dr. Linden provides geographic information system (GIS) and remote sensing consulting services for corporate and government clients. He received a PhD in remote sensing/forestry from Colorado State University in 1995. He is a member of the GIS World Editorial Advisory Board, the American Society for Photogrammetry and Remote Sensing, the Society of American Foresters, and the International Society of Tropical Foresters.

Kevin Price is associate director of the Kansas Applied Remote Sensing Program, Kansas Biological Survey, University of Kansas, and an associate professor in the Department of Geography. Dr. Price is an ecologist and a geographer specializing in satellite remotely sensed imagery for studying Earth systems. His research focus is on land cover and use characterization and on Earth system studies using observations made from satellite remote sensing instruments. He is co-principal investigator for the Kansas Gap Analysis Program. His current research is on the grassland steppe of Inner Mongolia. He has ongoing research and educational activities in the U.S. Great Plains, Central Asia, Mexico, Central America, and South Central Africa. He serves on the NRC Committee for Agenda 21 and is helping draft recommendations to the U.S. State Department relative to sustainable development in Africa.

Steven W. Running is director of the Numerical Terradynamic Simulation Group, University of Montana. Professor Running's research focuses on terrestrial biogeochemical cycling and on integrating remote sensing, bioclimatology, and ecosystem modeling at multiple scales. His team currently produces a regular weekly data set of photosynthetic activity of the terrestrial biosphere. Dr. Running has served on numerous national and international committees, including the Scientific Committee of the International Geosphere-Biosphere Program; NASA Earth Observing System, Land Science Panel, chair, 1994-1998; the Terrestrial Observation Panel for Climate of the World Climate Research Program, World Meteorological Organization, 1995-1998; the NRC's BASC Climate Research Committee, 1996-1999; the SSB Committee to Review NASA's ESE Science Plan; and the NRC Committee on Earth Studies, 2004-2006. He is a lead author for the IPCC Fourth Assessment Report. He was elected a fellow of the American Geophysical Union in 2002.

Marijean T. Seelbach recently became vice president and deputy, business development, for Lockheed Martin Space Systems Company. Prior to this she was president and chief executive officer of QuakeFinder, LLC. Before holding that position, Dr. Seelbach was vice president of In-Q-Tel. From 1997 to 1999, she was senior vice president of engineering at SRI International, where she was responsible for major business segments that worked for such clients as the U.S. Department of Defense, Defense Advanced Research Projects Agency, U.S. Army, U.S. Navy, and U.S. Air Force. From 1989 to 1991, Dr. Seelbach was a professional member on the budget subcommittee of the House Permanent Select Committee on Intelligence of the U.S. Congress and was responsible for making budget recommendations for space-related programs.

Thomas H. Vonder Haar is University Distinguished Professor of Atmospheric Science at Colorado State University (CSU) and director of the Cooperative Institute for Research in the Atmosphere. His research interests lie in the areas of global energy budget, remote sensing from satellites, local-area forecasting, and biogeoscience. His present research activities include work on Earth's radiation budget and fundamental relationships with the climate system. His work has included some of the first results of the direct solar irradiance measurements from satellites and the exchange of energy between Earth and space. His studies on the interaction of clouds and radiation and the general circulation have formed a basis for national and international plans leading to the Global Energy and Water Experiment and programs related to global change. Dr. Vonder Haar developed and directs CSU's Satellite Earthstation to support research on storms at all scales. In February 2003, Dr. Vonder Haar was elected a member of the National Academy of Engineering.

Robert A. Weller is a senior scientist at Woods Hole Oceanographic Institution. Dr. Weller holds the Secretary of the Navy/Chief of Naval Operations Chair in Oceanography and is director of the Cooperative Institute for Climate and Ocean Research. His research interests include wind-forced motion in the upper ocean, mixed-layer dynamics, upper-ocean velocity structure studies, air-sea interaction, the role of the ocean in climate, and the development of upper-ocean and surface meteorological instrumentation and platforms for air/sea experiments. He is fellow and past president of the Ocean Sciences Section of the American Geophysical Union, and a member of the American Association for the Advancement of Science, the American Meteorological Society, and the Oceanographic Society. Dr. Weller served on the NRC's Committee Toward a National Collaboratory: Establishing the User-Developer Partnership and on its Committee on Radio Frequencies.

STAFF

Assistants to the Chair

Brian Osborne (through July 2003) received an MS from the University of Waikato, New Zealand, in 1995. His research topic was The Retrieval of Sea Surface Temperature from AVHRR (Advanced Very High Resolution Radiometer). Following enrollment as a PhD student at Curtin University of Technology, Western Australia, he spent 18 months as an honorary fellow at the University of Wisconsin-Madison's Space Science and Engineering Center. He subsequently served there as an assistant researcher until returning to New Zealand in 2003.

Rosalyn A. Pertzborn (from August 2003) is director for the Office of Space Science Education at the University of Wisconsin-Madison's Space Science and Engineering Center (SSEC). She has collaborated successfully with scientists at the SSEC and the Departments of Physics, Atmospheric and Oceanic Sciences, Geology, and Astronomy to design, implement, and evaluate education and public outreach (E/PO) programs. From 2001 though 2003, she was a program planning specialist at the Office of Space Science (OSS) at NASA Headquarters in Washington, D.C. She also served as lead on the TMCO (Technical, Management, Cost and Other) E/PO panel to support review and analysis of findings for mission concept study feasibility. She served as co-chair for the OSS/Education Division Working Group and principal liaison between OSS and the NASA Education Division. Ms. Pertzborn currently serves as co-chair for the June 2004 U.S./India Conference on Space Science, Applications and Commerce; co-convener for the April 2004 European Geoscience Union's, Education and Outreach Session; and as the lead E/PO consultant for the NASA Headquarters Mars Program Office.

National Research Council Staff

Claudette K. Baylor-Fleming has worked as a senior program assistant with the NRC's Space Studies Board since 1995, primarily as the program assistant to the director and administrative officer. She came to the NRC in 1988, first serving as senior secretary for the Institute of Medicine's Division of Health Sciences Policy, and then working for 7 years as the administrative/financial assistant for the NRC's Board on Global Change. In 2003, Ms. Baylor-Fleming completed two certificate programs, one at the Catholic University of America in Web technologies and the other at Trinity College of Washington in information technology applications. She is currently pursuing a BA in graphic design from American University.

Richard Leshner is a research associate for the Space Studies Board and a PhD 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.

Robert L. Riemer is a senior program officer with the Board on Physics and Astronomy and the Space Studies Board. Before joining the NRC in January 1985, Dr. Riemer was a senior project geophysicist for Gulf Oil Exploration and Production Company. He received a BS with honors in physics and astrophysics from the University of Wisconsin-Madison and a PhD with honors in physics from the University of Kansas-Lawrence. Dr. Riemer served as study director for the 1991 and 2000 decadal surveys of astronomy and has worked with many NRC committees, ranging in subject areas from various fields of physics and astronomy to mathematics and interdisciplinary research.

F

Committee Meeting Summaries

MARCH 11-12, 2003

The Committee on Environmental Satellite Data Utilization (CESDU) held its first meeting on March 11-12, 2003, at the National Academy of Sciences building in Washington, D.C. The committee heard from Ghassem Asrar, associate administrator, National Aeronautics and Space Administration (NASA); Gregory Williams, senior policy analyst, Earth Science Enterprise, NASA; Marie Colton, director, Office of Research and Applications, National Oceanic and Atmospheric Administration (NOAA), National Environmental Satellite, Data, and Information Service (NESDIS); Helen M. Wood, director, Office of Satellite Data Processing and Distribution, NOAA Satellite and Information Service; Gerald Dittberner, chief, Advanced System Planning Division, NOAA Satellite and Information Services; Thomas R. Karl, director, Satellite and Information Services, National Climatic Data Center, NOAA; Howard J. Singer, chief, Research and Development Division, NOAA Space Environment Center; Eric Webster, majority staff director, Subcommittee on Environment, Technology, and Standards, House Science Committee; James Dodge, program scientist, Research Division, Earth Science Enterprise, NASA; Stephen Mango, chief scientist, National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Project Office, NOAA; Edwin Sheffner, program manager, Applications Division, Earth Science Enterprise, NASA; and David Jones, president and CEO, StormCenter Communications, Inc.

The NRC report *Satellite Observations of the Earth's Environment: Accelerating the Transition from Research to Operations* was discussed by Richard Anthes, chair of the NRC Committee on NASA-NOAA Transition from Research to Operations (CONNTRO) and president of the University Corporation for Atmospheric Research (UCAR).

JUNE 17-19, 2003

The committee held its second meeting on June 17-19, 2003, at the Pyle Center on the University of Wisconsin-Madison campus. It heard from David Williams, head of Strategic Planning and International Relations, European Organization for the Exploitation of Meteorological Satellites; Hans-Peter Roesli, Swiss Federal Office of Meteorology and Climatology (MeteoSvizzera); Tony Hollingsworth, head of Research, European Centre for Medium-Range Weather Forecasts. A presentation on "Future Computing Capabilities" was given by Gurindar Sohi, University of Wisconsin. The committee also heard from Paul Menzel, chief scientist, Center for Satellite Applications and Research, NESDIS/NOAA; Gregory W. Withee, associate administrator for Satellite and Information Services, NOAA; Michael Mussetto, NPOESS Shared System Performance Responsibilities project scientist; Jeffrey Tu, NPOESS system architecture lead; and Gary Route, NPOESS Interface Data Processing Segment chief engineer. "Private Sector Data Use" was presented by Robert "Buzz" Bernstein, chief technology officer, SeaSpace, Inc.

SEPTEMBER 9-11, 2003

The committee held its third meeting on September 9-11, 2003, at the Keck Center of the National Academies, Washington, D.C. It heard from NOAA/NESDIS staff: on "NPOESS Data Exploitation" from James Silva, manager, NPOESS Data Exploitation Project and NPOESS implementation manager, Office of Systems Development; and from Mitch Goldberg, chief, Satellite Meteorology and Climatology Division, Office of Research and Applications; John J. Bates, chief, Remote Sensing Applications Division, National Climatic Data Center; and Richard G. Reynolds, chief, Ground Systems Division, Office of Systems Development, NOAA/NESDIS (also attending the session were Stephen Mango, Integrated Program Office (IPO); Stanley Schneider, IPO/NASA; Geoffrey Goodrum, NOAA/NESDIS; and Stanley Cutler, NOAA consultant/Mitretek); and on the "Comprehensive Large-Array Data Stewardship System" from Richard G. Reynolds, chief, Ground Systems Division, Office of Systems Development.

A presentation titled "Improved Utilization of Remotely Sensed Data" was given by John Townshend, chair, Geology Department, University of Maryland, College

Park. A talk on Department of Defense (DOD) environmental satellite data utilization was given by Robert Feden, chief of staff, Office of the Special Assistant, Office of the Assistant Secretary of Defense (Networks and Information Integration)/ Department of Defense, Chief Information Officer. Also presented were "Agricultural Monitoring for Global Food Security—Status of FAS (Foreign Agricultural Service) Satellite Crop Monitoring: From Legacy to Enterprise," by Bradley Doorn, remote sensing specialist, Production Estimates and Crop Assessment Division, Foreign Agricultural Service, U.S. Department of Agriculture (USDA); and on "Remote Sensing in the USDA Forest Service: Supporting Sustainable Natural Resources," by William Belton, assistant remote sensing program manager, USDA Forest Service.

"Satellite Data and National Weather Prediction: Progress, Problems, and Prospects" was presented by Ronald McPherson, executive director, American Meteorological Society; and a presentation on the Earth Science Data and Information System (ESDIS) Project was made by H.K. Ramapriyan, assistant project manager, ESDIS Project, NASA Goddard Space Flight Center. "The Role of Satellite Data in Environmental Modeling" was presented by Louis Uccellini, director, National Centers for Environmental Prediction, National Weather Service, NOAA. The committee was also provided with follow-up information from Dr. Ramapriyan: electronic copies of the reports "Goddard Earth Sciences (GES) Distributed Active Archive Center (DAAC) Lessons Learned from the Development of EOSDIS (Earth Observing System Data and Information System)," by Christopher Lynnes, systems engineer, Goddard Earth Sciences Distributed Active Archive Center; "The EOSDIS Core System (ECS) Science Data Processing System (SDPS) Lessons Learned," by Mike Moore (ESDIS Project), Dawn Lowe (ESDIS Project), Curt Schroeder (ESDIS Project), and Steve Fox (Raytheon); "NASA's Earth Science Data Systems—Past, Present and Future," by H.K. Ramapriyan, NASA Goddard Space Flight Center; "Science Investigator-Led Processing System (SIPS)—Lessons Learned," by H.K. Ramapriyan, R. Ullman, and K. McDonald, NASA Goddard Space Flight Center; and "EOSDIS User Base Numbers," by H.K. Ramapriyan, NASA Goddard Space Flight Center.

DECEMBER 2-4, 2003; FEBRUARY 17, 2004

The fourth and fifth CESDU meetings were closed writing sessions held at the National Academies' Beckman Center in Irvine, California, on December 2-4, 2003, and at the Keck Center of the National Academies in Washington, D.C., on February 17, 2004.

G

Acronyms

1DVAR	one-dimensional variational
3DVAR	three-dimensional variational
4DVAR	four-dimensional variational
ABI	Advanced Baseline Imager
ACRIMSAT	Active Cavity Radiometer Irradiance Monitor Satellite, an EOS satellite mission to measure total solar irradiance
ADEOS	Advanced Earth Observational Satellite
AFWA	U.S. Air Force Weather Agency
AIREP	aircraft report
AIRS	Atmospheric Infrared Radiation Sounder
AMSU	Advanced Microwave Sounder Unit
ASEB	Aeronautics and Space Engineering Board
ATMS	Advanced Technology Microwave Sounder
ATN	Advanced TIROS-N satellite
ATOVS	Advanced TIROS Operational Vertical Sounder
ATS	Advanced Technology Satellite
AVHRR	Advanced Very High Resolution Radiometer
AWIPS	Advanced Weather Interactive Processing System
BASC	Board on Atmospheric Sciences and Climate
BRDF	bidirectional reflectance distribution function

BUV	backscatter ultraviolet

CAIV	cost as independent variable
CAL/VAL	calibration/validation
CAPE	convective available potential energy
CBA	cost/benefit analysis
CDR	climate data record
CERES	Cloud and the Earth's Radiant Energy System, an instrument on the Earth Observing System's Terra spacecraft that measures the energy exchanged between the Sun; the Earth's atmosphere, surface and clouds; and outer space
CICE	Los Alamos Sea Ice Model
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CLASS	Comprehensive Large Array-data Stewardship System
CONNTRO	Committee on NASA-NOAA Transition from Research to Operations (NRC)
CONUS	continental United States
COSMIC	Constellation Observing System for Meteorology, Ionosphere, and Climate
CrIS	Cross-track Infrared Sounder
CW	coastal waters

DAAC	Distributed Active Archive Center
DISCOVR	Deep Space Climatic Observatory
DMSP	Defense Meteorological Satellite Program (Systems Program Office)
DOD	Department of Defense

ECMWF	European Centre for Medium-Range Weather Forecasts
ECS	EOSDIS Core System
EDR	environmental data record
EMC	Environmental Modeling Center of the National Weather Service's NCEP
ENVISAT	Environmental Satellite
EO-1	Earth Orbiter-1, a NASA-Goddard Space Flight Center satellite that demonstrated technology for the next-generation Landsat mission
EOR	environmental observation requirement
EOS	Earth Observing System
EOSDIS	Earth Observing System Data and Information System
EP	Earth Probe
EPA	Environmental Protection Agency

ERB	Earth radiation budget
ERBS	Earth Radiation Budget Satellite
ERBE	Earth Radiation Budget Experiment (NASA)
ERTS	Earth Resources Technology Satellite
ESA	European Space Agency
ESDIS	Earth Science Data and Information System
ESE	Earth Science Enterprise
ESSA	Environmental Satellite Services Administration
ETM+	Enhanced Thematic Mapper Plus, an instrument on the Landsat 7 spacecraft
EU	European Union
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
FCDR	fundamental climate data record
FEMA	Federal Emergency Management Agency
FNMOC	Fleet Numerical Meteorology and Oceanography Center (U.S. Navy)
FTP	File Transfer Protocol
GEO	geosynchronous Earth orbit
GIFTS	Geosynchronous Imaging Fourier Transform Spectrometer
GLM	Geostationary Lightning Mapper
GMES	Global Monitoring for Environmental Security
GMI	Geostationary Microwave Imager
GOES	Geostationary Operational Environmental Satellite
GOES-R	next-generation GOES
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GUI	graphical user interface
HES	Hyperspectral Environmental Satellite; Hyperspectral Environmental Suite
HIRDLS	High Resolution Dynamics Limb Sounder
HIRS	High-resolution Infrared Radiation Sounder
HRPT	high-resolution picture transmission
IASI	Interferometer Atmospheric Sounding Instrument
ICESS	Institute for Computational Earth System Science

IEOS	Integrated Earth Observing System
IMAPP	International MODIS and AIRS Processing Package
IORD	Integrated Operational Requirements Document
IP	Internet Protocol
IPO	Integrated Program Office
IR	infrared
IT	information technology
ITOS	Improved Television Infrared Observations Satellite
JCSDA	Joint Center for Satellite Data Assimilation
LEO	low Earth orbit
LORE	Limb Ozone Retrieval Experiment
LWIR	long-wave infrared
MLS	Microwave Limb Sounder
MODIS	Moderate-resolution Imaging Spectroradiometer
MRD	mission requirements document
MSU	Microwave Sounding Unit
MWIR	mid-wave infrared
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NDVI	Normalized Difference Vegetation Index
NEdT	noise-equivalent-difference-temperature
NESDIS	National Environmental Satellite, Data, and Information Service
NetCDF	Network Common Data Format
NEXRAD	Next Generation Radar, a network of Doppler radars operated by the National Weather Service
NIR	near-infrared
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NSDI	National Spatial Data Infrastructure

NSF	National Science Foundation
NWP	numerical weather prediction
NWS	National Weather Service
ODB	Observation Data Base
OLI	Operational Land Imager instrument (NASA)
OLS	Operational Linescan System
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
OSE	observing system experiment
PAOB	synthetic surface pressure data
PM	particulate matter
POES	Polar-orbiting Operational Environmental Satellite
PORD	Performance and operation requirements document
QuikSCAT	Quick Scatterometer (also called Seawinds General)
R&D	research and development
RDR	raw data record
SAGE	Stratospheric Aerosol and Gas Experiment
SAPC	Space Applications and Commercialization
SBUV	solar backscatter ultraviolet
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SDR	sensor data record
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOAP	Simple Object Access Protocol
SSB	Space Studies Board
SMS	Synchronous Meteorological Satellite
SST	sea-surface temperature
SSU	Stratospheric Sounding Unit
SWIR	short-wave infrared
TCDR	thematic climate data record
TES	Tropospheric Emission Spectrometer
TIROS	Television Infrared Observation Satellite
TMI	TRMM Microwave Imager
TOA	top-of-the-atmosphere measurements

TOMS	Total Ozone Mapping Spectrometer
TOMS/EP	Total Ozone Mapping Spectrometer, onboard an Earth Probe satellite (NASA)
TOPEX/ Poseidon	Ocean Topography Experiment
TOS	TIROS Operational Satellite
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
TRMM-PR	Tropical Rainfall Measuring Mission-Precipitation Radar
UARS	Upper Atmosphere Research Satellite
UCSB	University of California, Santa Barbara
UDDI	Universal Description, Discovery and Integration, protocol for Web services
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USAF	U.S. Air Force
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UV	Ultraviolet
VIIRS	Visible/Infrared Imager/Radiometer Suite
VIS	Visible
WMO	World Meteorological Organization
WSDL	Wireless Digital Subscriber Link, a high-speed Internet connection
WWW	World Weather Watch
XML	Extensible Markup Language

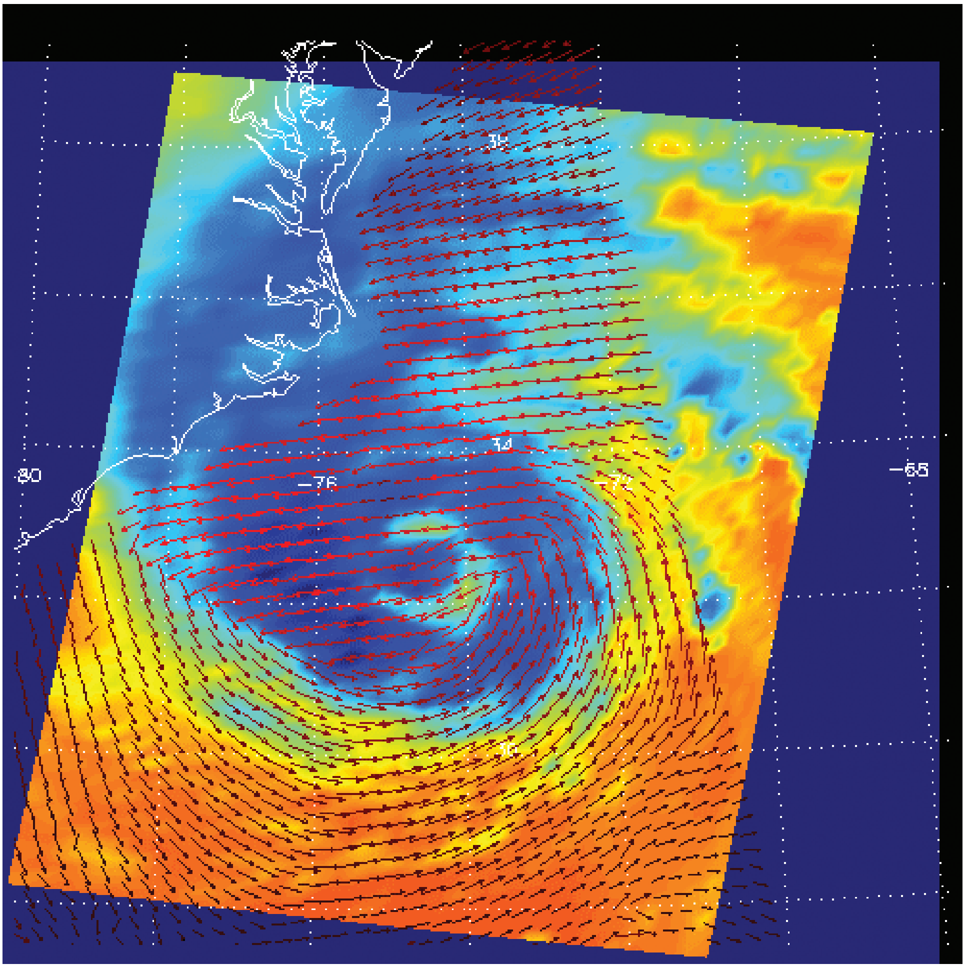

PLATE 1 Hurricane Isabel on September 13, 2003. The red vectors in the image show Isabel's surface winds as measured by the SeaWinds scatterometer on ADEOS-2, and the background colors show the temperature of clouds and surface, as viewed in the infrared by AIRS. Light blue areas show adjacent cold clouds' tops associated with strong thunderstorms embedded within the storm. SOURCE: Courtesy of NASA Jet Propulsion Laboratory.

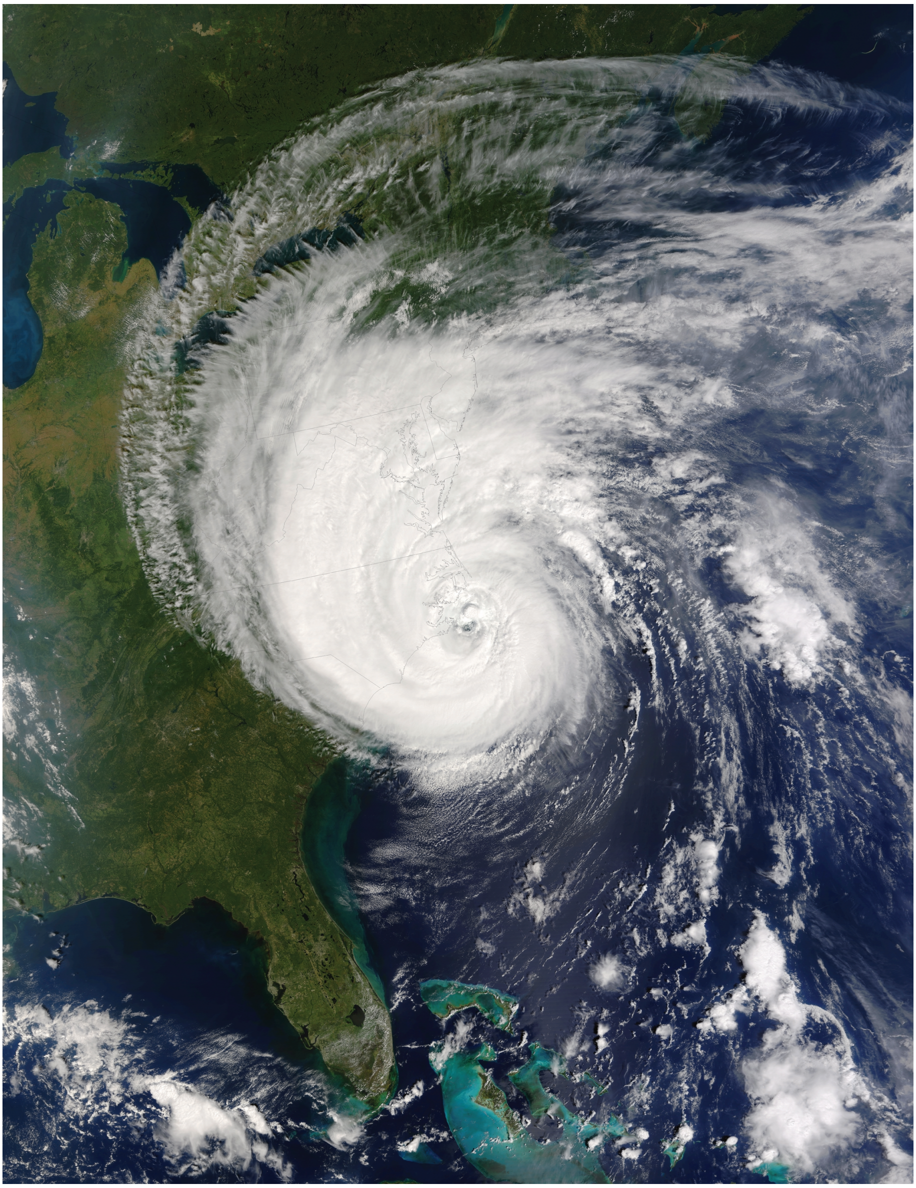

PLATE 2 Hurricane Isabel as it approached landfall on the outer banks of North Carolina on September 18, 2003. The image is a true-color (red-green-blue) NASA image taken by the Moderate-resolution Imaging Spectroradiometer (MODIS)—the research equivalent of the Visible and Infrared Imager/Radiometer Suite (VIIRS) to be flown on NPP and operationally by NPOESS in three orbit planes (with global coverage every 4 hours) beginning in 2009. SOURCE: Courtesy of NASA Goddard Space Flight Center.

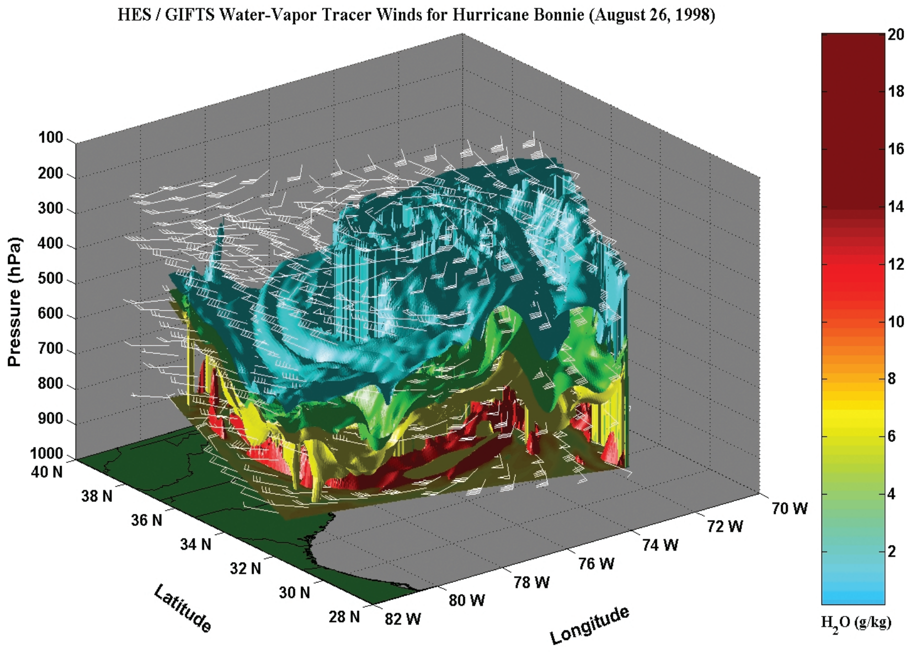

PLATE 3 Example of a future capability to be delivered with the Hyperspectral Environmental Suite (HES) on GOES-R in 2012: four-dimensional water vapor structure and wind profiling, in this case water-vapor tracer winds (the tracking of moisture features on constant-altitude surfaces determined by retrieval analyses) for Hurricane Bonnie (August 26, 1998). This simulation demonstrates the power of hyperspectral atmospheric profiling of temperature, moisture, and winds. Compared with the current operational system, the new capability will provide greatly improved spatial resolution, more rapid temporal refresh, and finer vertical resolution through increased spectral information content. SOURCE: Bormin Huang, University of Wisconsin-Madison.

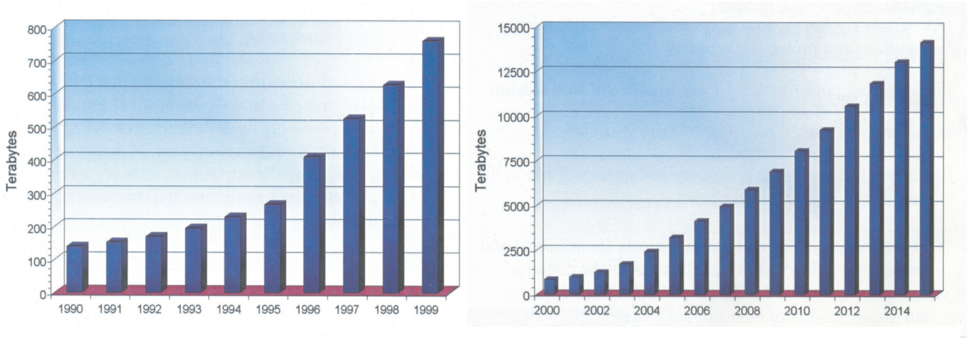

PLATE 4 Archive growth during the 1990s and 15-year projected archive growth. SOURCE: NOAA, 2001, *The Nation's Environmental Data: Treasures at Risk, Report to Congress on the Status and Challenges for NOAA's Environmental Data Systems* (A. Hittelman and I. Hakkarinen, eds.), U.S. Department of Commerce, National Oceanic and Atmospheric Administration, August 2001, p. viii. Available online at http://www.ngdc.noaa.gov/noaa_pubs/treasures.shtml.

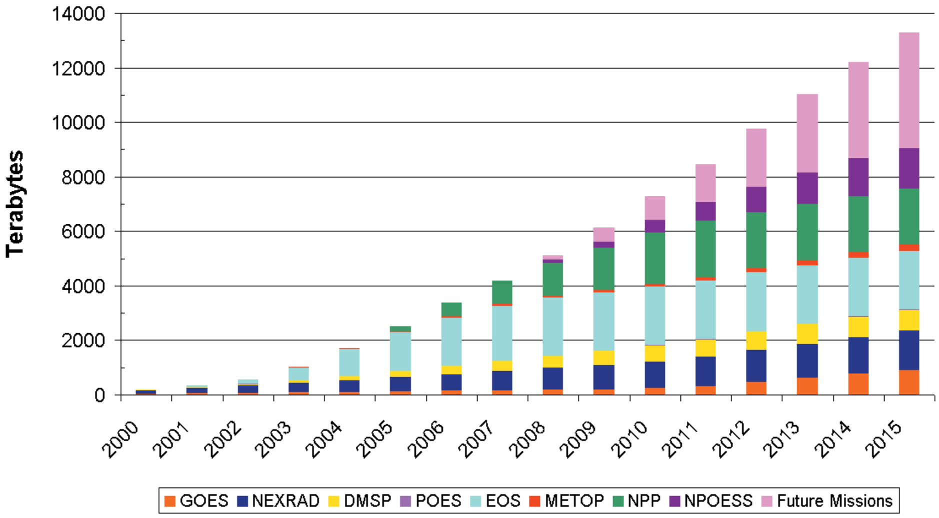

PLATE 5 Major systems archive growth from 2000 to 2015. SOURCE: NOAA, 2001, *The Nation's Environmental Data: Treasures at Risk, Report to Congress on the Status and Challenges for NOAA's Environmental Data Systems* (A. Hittelman and I. Hakkarinen, eds.), U.S. Department of Commerce, National Oceanic and Atmospheric Administration, August 2001, p. 16. Available online at http://www.ngdc.noaa.gov/noaa_pubs/treasures.shtml.

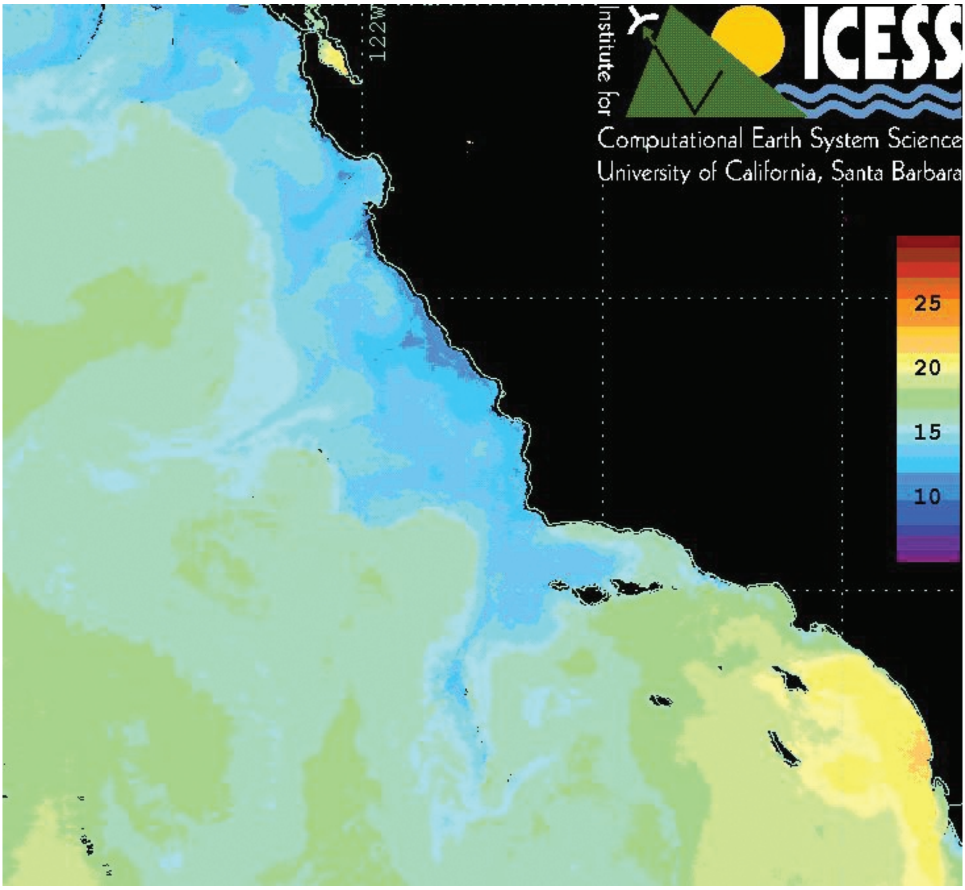

PLATE 6 Sample Advanced Very High Resolution Radiometer (AVHRR) composite (5-day) mean sea-surface temperature, Pacific Ocean, California, September 11, 2002 (the color bar is temperature in degrees Celsius). Image courtesy of the Institute for Computational Earth System Science (ICESS), University of California, Santa Barbara.

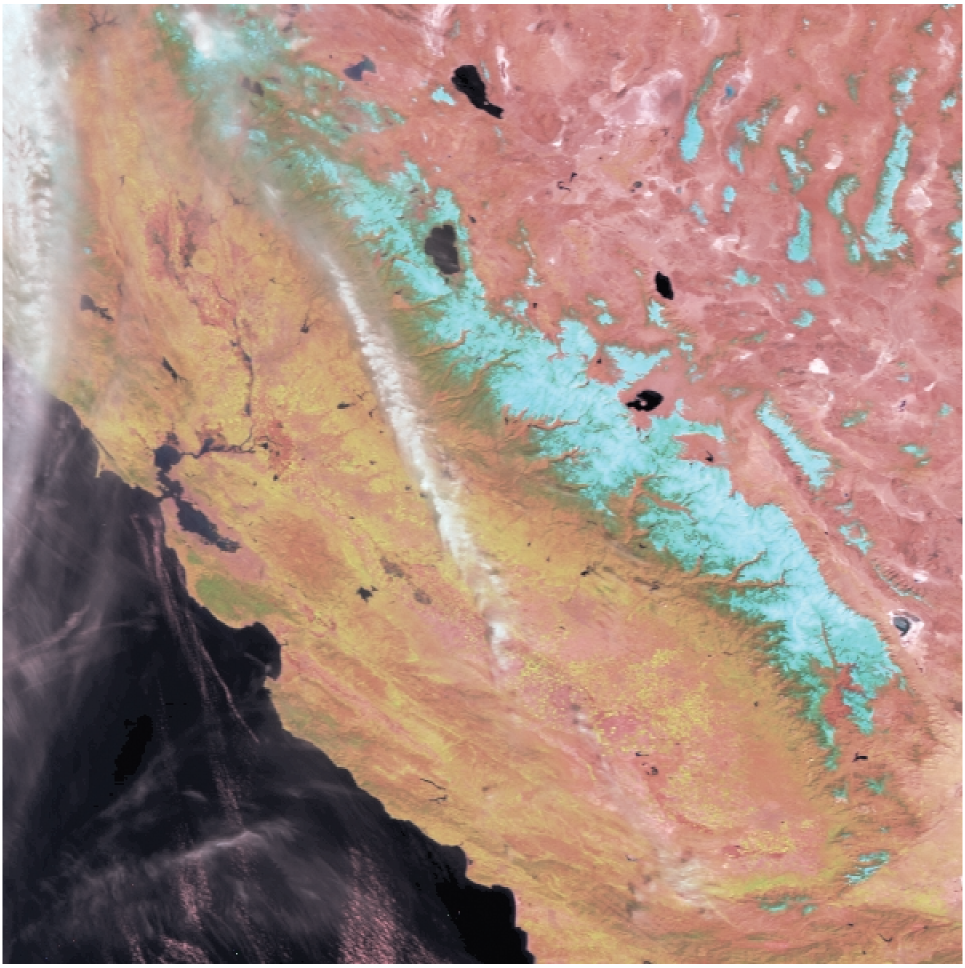

PLATE 7 Sample AVHRR snow-cover image, Sierra Nevada, California, March 19, 2003 (NOAA-17 satellite, channel 1,2,3A color composite, snow is cyan). Image courtesy of the Institute for Computational Earth System Science (ICESS), University of California, Santa Barbara.

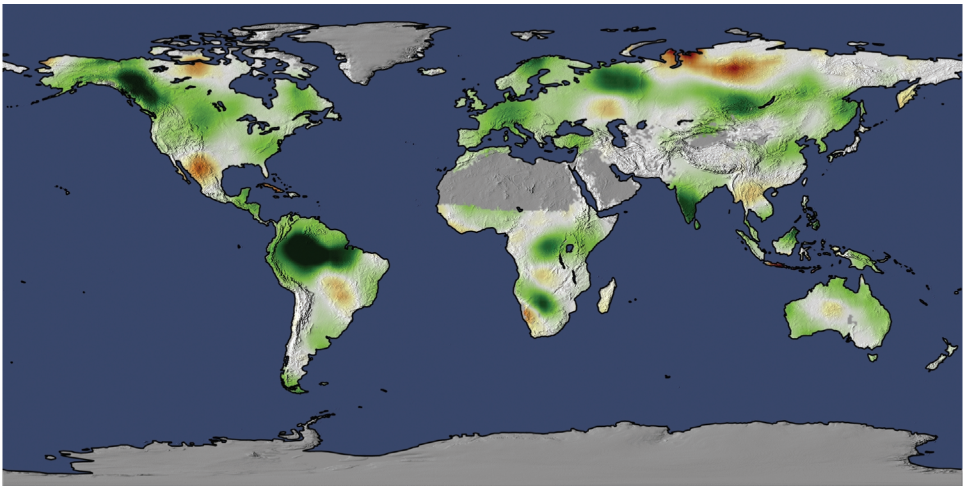

PLATE 8 Change in global terrestrial net primary production from 1982 to 1999. SOURCE: Reprinted with permission from R. Nemani, C. Keeling, H. Hashimoto, W. Jolly, S. Piper, C. Tucker, R. Myneni, and S. Running. 2003. "Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999," *Science* 300:1560-1563. Copyright 2003 AAAS.

PLATE 9 The MODIS Rapid Response system (http://rapidfire.sci.gsfc.nasa.gov/) has proven effective as a decision support tool for fighting large forest fires, such as the one pictured here in Montana. SOURCE: Courtesy of Lloyd Queen, University of Montana.

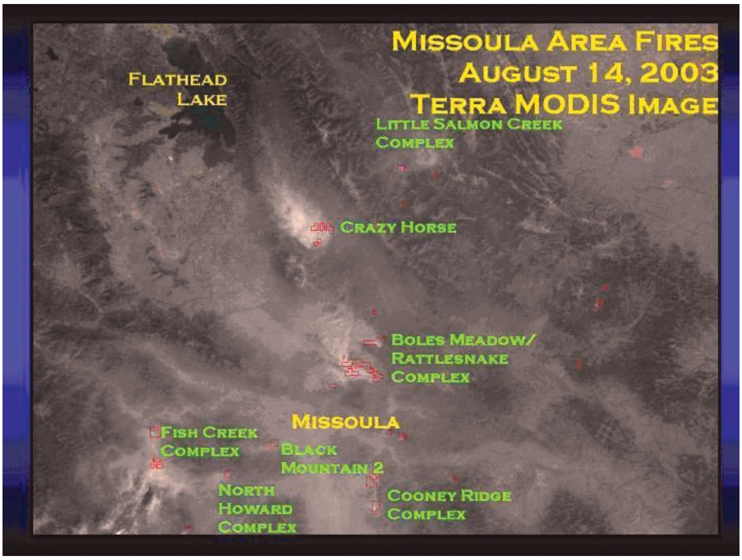

PLATE 10 Terra MODIS (Moderate-resolution Imaging Spectroradiometer) satellite image of fires in the area around Missoula, Montana, August 2003. SOURCE: Courtesy of Lloyd Queen, University of Montana.