FROM RESEARCH TO OPERATIONS IN WEATHER SATELLITES AND NUMERICAL WEATHER PREDICTION

CROSSING THE VALLEY OF DEATH

Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
National Research Council

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While the individuals listed above have provided constructive comments and suggestions, it must be emphasized that responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Preface

The term “Crossing the Valley of Death” is sometimes used in industry to describe a fundamental challenge for research and development (R&D) programs. For technology investments, the transitions from development to implementation are frequently difficult, and, if done improperly, these transitions often result in “skeletons in Death Valley.” Successful transitions from R&D to operational implementation always require: (1) an understanding of the importance (and risks) of the transition, (2) development and maintenance of appropriate transition plans, (3) adequate resource provision, and (4) continuous feedback (in both directions) between the R&D and operational activities. In the case of the atmospheric and climate sciences, inadequacies in transition planning and resource commitment can seriously inhibit the implementation of good research leading to useful societal benefits.

During the past generation, the atmospheric and climate sciences have experienced major improvements on various time and space scales in observational resources, scientific understanding, and forecasting capabilities applied to the characterization of the earth. Short-term synoptic forecasting, small regional scale forecasting, severe weather event warning, climate system analysis and modeling, and improved data and information processing and dissemination have all provided substantial societal benefits–especially in the 1990s. Even greater benefits (related to the pressing need to better understand and protect critical earth systems) can be achieved in the first decade of the 2000s, but only if the linkages among research, observation, forecasting, and information processing are adequately managed.

The Board on Atmospheric Sciences and Climate (BASC) recently completed a major review of the field of atmospheric sciences and published *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998a). As a follow-on to that effort, BASC identified almost 20 items from the report as potential subjects to examine more closely during the 1999 summer study. BASC selected the transition from research to operations as the first priority for more extensive study.

The federal agencies responsible for research, observing systems, information processing, and operational aspects of weather, climate, and related environmental activities asked BASC to address issues dealing with the transition of research results to the operational provision of services. As a result the following statement of task was developed for the study:

STATEMENT OF TASK

The BASC will convene a summer study in a workshop format to explore issues related to the transition from research and development to operations in the area of numerical weather prediction. Two case studies will form the nucleus of the effort:

1. The plans being developed by NOAA's NCEP to incorporate recent advances in atmospheric science research into the next generation of numerical weather prediction models.
2. The NPOESS Preparatory Program that will be used to transition the satellite sensors developed by NASA into operational capabilities on the NOAA operational weather satellites. Of particular interest are how sensor data are to be used operationally and how such data will be made available to the operational and research communities.

The board will summarize these plans, analyze their strengths and weaknesses, including any major barriers to their successful implementation, and recommend improvements.

Particular attention was directed to the ability of the major federal weather and climate prediction center, the National Centers for Environmental Prediction (NCEP), to implement the products of the research community and to the transition of research environmental satellite sensors to operational status. The NCEP readiness question was prompted by several internal government reviews of NCEP's responsibilities and capabilities and the apparent improvement in products and services that was being experienced in other prediction centers. The environmental satellite question was prompted by the 1998 NRC report *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1998c). This report recommended that the continued monitoring of climate variables be a specific mission of the operational satellite programs of NOAA, in contrast to the research satellite programs of NASA.

BASC conducted a summer study to review these two issues (see Appendix A), and this report is the result of that study.

In general, BASC was pleased with the health of the research community, but did identify some definite shortcomings in the ability of NCEP to exploit the fruits of the research community. Equally important, limitations at NCEP prevent optimal support to the academic and research communities in the form of data and tailored forecast products necessary to stimulate research. BASC noted that progress was being made in several areas that should lead to improvements. Plans for other short and long-term improvements were also evaluated.

BASC reviewed the progress of planning for the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Program (NPP) satellite mission which will assist in the transition of instruments from the NASA Earth Observing System (EOS) satellites to the operational NPOESS. Several BASC members had participated in earlier reviews of the NASA and NOAA plans and were generally pleased at the progress that was being made.

In its deliberations, BASC noted the improvements in the science of weather forecasting that have emerged in recent years and the increasing demand for additional products and services from many different sectors of the nation. BASC hopes that the recommendations in this report will enable the operational forecasting enterprise to meet these growing demands for service to the benefit of society.

Eric Barton and James Mahoney

Co-chairs, Board on Atmospheric Sciences and Climate

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Executive Summary

As the United States moves into the twenty-first century, individuals and organizations throughout the nation are reaping the rewards of more than a century of ever improving and expanding national weather and climate services. Accurate weather forecasts and climate projections are increasingly critical elements of any public and private decision-making process. Societal needs for new and improved products in such areas as water resources, air quality, and space weather are increasing. Improvements to forecast models and products will provide more accurate and timely forecasts, which can then be used by decision makers to better protect life and property, expand opportunities to stimulate economic activity, enhance national competitiveness, and improve environmental management.

This report examines the capability of two critical components of the forecast system for the efficient transfer of weather and climate research findings into improved operational forecast capabilities. The first component reviewed was the Environmental Modeling Center (EMC) of the National Weather Service's (NWS) National Centers for Environmental Prediction (NCEP). EMC's mission is to develop, enhance, and maintain numerical forecast systems in support of national and international forecast requirements (Lord, 1999). EMC operates numerical forecast systems for weather prediction (global and regional, 1-15 days), ocean prediction (global, daily to annual), and climate prediction (seasonal to interannual). This review was prompted by concerns of government officials that EMC funding was insufficient and working conditions adverse, resulting in compounded problems related to ineffective prioritization, insular operations, and failure to access the talent and resources required to adequately fulfill the EMC mission (Dorman, 1999).[1]

The second component of the forecasting system reviewed was the environmental observational satellite program. Even with the high utility of satellite observations, it was more than a decade from the launch of the first satellite before the benefits of satellite meteorology were being routinely used in the operations of the National Weather Service. Another five years passed before the satellite data were used in operational numerical weather prediction. In the first two decades of the environmental satellite program, NASA conducted a development program for new satellite sensors called the Operational Satellite Improvement Program (OSIP). These sensors were then transferred to NOAA for operational implementation. OSIP was cancelled in 1982.

Recent NRC reports have highlighted the problems facing the climate community arising from inadequate planning for transition between the research satellites of NASA and the operational monitoring satellites of NOAA (NRC, 1998c, 1999b). In response to the growing concern for the long-term monitoring of climate, NASA and NOAA have proposed a project to transfer instrumentation from the NASA Earth Observing System (EOS) to the NOAA National Polar-Orbiting Environmental Satellite System (NPOESS) operational satellites. This project, the NPOESS Preparatory Project (NPP), is a single satellite mission planned for 2005.

BASC FINDINGS

BASC found that the capability of NCEP and the environmental satellites needs to be improved or the transition from research to operations will likely be hampered as the forecasting system attempts to respond to

[1] The Dorman report resulted from a management review of the National Weather Service, led by Radm (Ret.) Craig Dorman, commissioned by the Department of Commerce to examine issues of technology infusion in the NWS. It provided documentation for various personnel, budget, and operational issues associated with the National Centers for Environmental Prediction and served as good background information for the summer study. The report is available from the Director, National Weather Service, and is also a part of the Public Access File maintained by the National Research Council for all reports.

society's needs for new, and better, forecast products. BASC recommends actions to enable the U.S. weather services to maximize the benefits from the nation's investment in weather and climate forecasting research.

While the overall atmospheric and oceanic research community in the United States is strong and forms the basis for expanding the quality and diversity of services provided to the nation, there is no concerted effort to address the societal benefits and economic impacts of various research and operational strategies. For instance, while the social science community is becoming engaged in the U.S. Weather Research Program (USWRP), few resources are being targeted for this activity.

When BASC examined the plans and capabilities for the transition of research to operations at EMC, several shortcomings were noted:

1. EMC does not possess the capability to test and evaluate new algorithms and new forecast models in parallel with the operational system or to obtain feedback from the user community[2]. There are insufficient computational resources to allow simultaneous testing of new model versions in parallel with the operational forecast computer runs.
2. In most cases, when new sensors are developed, insufficient budget is provided to develop the algorithms necessary to introduce those sensors into the operational system. There is limited capability to address the special needs associated with assimilation of a large volume of new satellite observations.
3. No one at EMC is clearly assigned the responsibility for technology transition.
4. Human resources at EMC receive only 47 percent of their funding from the base budget. The remainder is supported by *soft money* (funding that is not stable from year to year). Soft money poses difficulties in the planning that is required for an operational agency and can dilute the mission's effectiveness since the source of the soft funding frequently has objectives that may diverge from the operational mission.

Before its cancellation in 1982, the NASA Operational Satellite Improvement Program (OSIP) was a very effective mechanism for developing new sensors, proving their capability, and transferring them to the operational agencies for implementation. The NPP project offers a

[2] This term is used throughout the report to include various sectors of society that use weather and climate information. It includes various economic sectors (agriculture, transportation, industry, insurance, etc.) as well as emergency managers, the media, and the general public.

method for transitioning some of the recently developed sensors from NASA to NOAA. In some respects NPP fulfills some of the important characteristics of the former OSIP program; however, it is presently planned as a single mission. BASC reviewed the NPP project plans, and several of the BASC members who participated in earlier studies (NRC, 1998c, 1999b) were able to identify the favorable progress that had been made in planning for the NPP. However, additional effort is still required for an effective national program of transition. BASC also recognizes that programs such as NPOESS, as currently planned, are not solutions to all climate and weather observational needs.

Many of the research to forecast product transition issues discussed in this report in the context of weather and climate will also be encountered as NOAA and other organizations define and produce forecasts of air quality, water quantity and quality, ultraviolet radiation, space weather, and other environmental properties. If they are to succeed, planning for these forecast products must be thorough and involve the relevant research and user communities. The following recommendations would enhance NOAA's ability to coordinate the plans for developing and producing forecasts of environmental properties with these communities. Relevant researchers and users would also be provided with the mechanisms to continuously improve these forecast products.

KEY RECOMMENDATIONS RELATING TO EMC

RECOMMENDATION EMC-1

NOAA should implement a development, testing, and integration facility at EMC. It should have the following characteristics:

- Adequate computer resources
- Adequate personnel with the proper understanding of user needs, as well as technological capabilities, including communications expertise
- A model archiving system
- Improved visitor programs
- Expertise in parallel processing and efficient code development

The inability to evaluate and test new algorithms while maintaining current operational forecasts is a major limitation (Emanuel and Kalnay, 1996).

RECOMMENDATION EMC-2

NOAA should determine the staffing levels required to perform EMC's operational mission and support these critical staff through base funding.

This will eliminate the planning uncertainties and other negative impacts of soft money for an operational organization.

Added Requirements to Serve Future Needs

RECOMMENDATION EMC-3

NWS should seriously consider co-locating EMC with other appropriate institutions.

Operational predictions of weather, water, and climate should be integrated in order to make optimal forecasts to serve the nation. The NWS has already recognized that co-location of forecasting centers with universities and research centers has led to faster progress through synergy.

RECOMMENDATION EMC-4

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 (NRC, 1999c). 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.

As we enter the twenty-first century, it will be impossible to meet tomorrow's needs with yesterday's technology. An annual budget, designed around life cycle costs should enable forecasting system capabilities to be in place to meet the evolving needs of the nation for weather and climate forecasts.

RECOMMENDATION EMC-5

EMC should actively participate in the USWRP to ensure that research objectives are consistent with operational needs and to enable the effective transition of more promising results to operation. EMC should collaborate with other appropriate parties in the development of community prediction models.

The USWRP has been justified in terms of transferring research into improved products for the nation, so it is appropriate that USWRP activi ties be structured to enable this transition. The community prediction model approach enables rapid assimilation of new research results.

RECOMMENDATION EMC-6

Recognizing the importance of the ocean in weather and climate forecasting, EMC leadership should be cognizant of the ocean-related research conducted outside the framework of the USWRP by the National Science Foundation, the Office of Naval Research, etc., and seek opportunities for the transition of appropriate results from research to operations.

NSF, NOAA, Navy, and NASA funded research and research communities that have little to do with the USWRP can be key players and partners with EMC. The air–sea interaction and coupled ocean–atmosphere–land climate communities can contribute research results to the EMC mission.

RECOMMENDATION EMC-7

NCEP and EMC, under broad NWS guidelines, should institutionalize the transition process, assigning clear responsibility for continuous evaluation of its effectiveness and for the identification of bottlenecks and opportunities.

With the important exception of DOD, the nation's forecasting enterprise lacks a clear delineation of responsibility for the transfer of research to operations, although there does exist clear responsibility for both research and operations.

Examples of the development of new technologies without concomitant improvements in operational products are identified in Chapter 3 and Chapter 4.

KEY RECOMMENDATIONS FOR THE ENVIRONMENTAL SATELLITE PROGRAMS

RECOMMENDATION SATELLITE-1

NASA and NOAA should implement a replacement to the Operational Satellite Improvement Program (OSIP) having the following characteristics:

- A planned path for the transition of instruments from research to operations
- A commitment to algorithm development commensurate with hardware development
- Calibration and validation of derived geophysical parameters
- Close linkage to the development, testing, and integration facility at NOAA's EMC as recommended in Chapter 3

A robust program of technology development, exploratory sensor development, and research missions ensures a continuous push toward improved capability in environmental remote sensing to improve weather and climate forecasting.

RECOMMENDATION SATELLITE-2

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 and 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

The objective is to develop a feedback and advanced planning component of the NPOESS process that ensures a more rapid transition of new observations to operational use.

RECOMMENDATION SATELLITE-3A

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.

RECOMMENDATION SATELLITE-3B

NASA and NOAA should evaluate the potential savings that would result from an interagency commitment to archive NPOESS satellite data through EOSDIS.

NASA's EOSDIS has demonstrated the complexities and costs associated with the development of an accessible data archive. Given that EOSDIS is currently the only data system with the potential to address the large-scale problems described here, careful assessment of its suitability for NPOESS archival is appropriate.

RECOMMENDATION SATELLITE-4

NOAA and NASA should begin to explore the potential of integrating in situ and satellite observation networks in support of both research and operational needs.

NPOESS has begun the process of convergence in national satellite systems, but the issues being addressed by NPOESS for satellite systems are equally applicable to the entire observational network. Similar integration is appropriate for in situ networks and for combined satellite-in situ measurement systems. This will facilitate the data assimilation process and therefore accelerate the use of disparate and complex data into operational weather forecasting.

RECOMMENDATION SATELLITE-5

NASA and NOAA should work together to ensure that the continuity of critical climate and weather observations is maintained.

BASC reiterates the recommendations contained in several NRC reports (NRC, 1998a, 1998c, 1999a, 1999c) stressing the need for more effective planning and execution of the observing systems for climate and weather.

RECOMMENDATION BALANCE-1

NOAA should adopt the philosophy in which new sensor development would incorporate plans for the inclusion of funds for the transition of the data into operational products at the appropriate stage of the development process.

RECOMMENDATION BALANCE-2

It is clearly preferable to add the necessary resources to EMC without negatively impacting the nation's weather and climate research enterprise. However, if that is not possible, then BASC recommends that some of the nation's weather and climate research resources be shifted to EMC-related enterprises and the USWRP.

Finally, BASC recommends that NOAA study the balance of its efforts in weather and climate with the goal of establishing an organization that efficiently balances the task of performing research and transferring this research into operations.

This study should also take into account the research provided by other agencies, most notably NSF and NASA. Such agencies should also help in providing prototype capabilities to transform their research into the applications for which they were intended. Study of the balance between research and operations should occur continuously, or imbalances will quickly re-establish themselves.

1

Introduction

In 1900, the head of the weather forecast office in Galveston, Texas, assured citizens that an approaching storm posed no threat. Eight thousand went to the beach and barrier island to watch the rising tide and perished in “Isaac's Storm.” Almost four decades later, the “38 Hurricane” roared up an unwarned Narragansett Bay into New England, killing more than 200 people. In 1992, Hurricane Andrew was closely monitored from space and earth, and its track was correctly forecast as it moved into Homestead, Florida, and across the state. Although Andrew's property damage amounted to $30 billion—one of the most costly natural disasters in the United States—the loss of life was less than 1 percent of that sustained in the Galveston disaster 90 years earlier.

The United States experiences a greater variety of extreme weather events than does any other country.[3] Because of this variety and the societal impacts of these events, great demands are placed on forecast

[3] The unique geographic structure of the North American continent accounts for this. The continent has a major north-south mountain range, but no east-west range of any significance. As a result, the warm moist air from the Gulf of Mexico can clash with the cold air from the polar regions, releasing the energy to fuel the severe weather activity experienced by the United States. Almost 1,000 tornadoes occur in this country during an average year; they are almost unheard of in Europe.

models to predict weather events, and substantial interest is focused on the causes and effects of climate variability.

As the United States moves into the twenty-first century, both individuals and organizations throughout the nation are reaping the rewards of, and are ever more dependent on, more than a century of ever improving and expanding national weather and climate services. The Bureau of Economic Analysis (Department of Commerce) estimates that activities sensitive to weather and climate account for 42 percent of the U.S. Gross Domestic Product (NRC, 1998a). For this reason, accurate weather forecasts and climate projections continue to be an increasingly critical component of most public and private decision-making processes. There is strong evidence that improvements to forecast models and products will provide more accurate and timely forecasts, which can be used by decision makers to better protect life and property and expand opportunities to stimulate economic activity, enhance national competitiveness, and improve environmental management (Pielke and Kimpel, 1997).

This report focuses on two important aspects of the weather forecasting system in the United States: the National Centers for Environmental Prediction (NCEP) with its Environmental Modeling Center (EMC) and the meteorological satellite programs of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). The study from which this report results is described in Appendix A. The purposes of this report are:

1. to examine issues related to the efficient transfer of weather and climate research findings into improved operational forecasts,
2. to review agency plans for the transition process at EMC and NPOESS, and
3. to recommend actions that will improve the transition process, thereby enhancing the utility of the nation's investment in weather and climate research and associated observational systems.

The nation has invested considerable resources in the development of research and technologies to meet the present demands [4]of its citizens for

[4] The term *demand* is not used in this report in the strictest economic sense. The government provides the basic weather services in this country and therefore the usual demand–price relationship does not exist. The many *customers* of weather services express their needs and desires for information that will improve their operations. For example, the emergency manager of a coastal community *demands* greater accuracy in the hurricane forecast to enable better performance in the evacuation of the community as the storm approaches. These are real needs and the government, in carrying out its mandate for the protection of life and property of the citizenry, needs to respond. Several examples of these expanding needs or *demands* are discussed in this chapter, but for a more detailed discussion of the many users of weather services and their needs, the reader is referred to NRC, 1998a, and NRC, 1999c.

improved forecasts. These investments include ongoing meteorological research programs sponsored by the National Science Foundation (NSF), NOAA, NASA, major elements of the U.S. Global Change Research Program (USGCRP), including NASA's Earth Observing System (EOS) satellites, as well as technological improvements such as the modernization of the National Weather Service (USGCRP, 1999; NRC 1998a, 1998c, 1999c). However, current weather and climate forecasting services are under considerable stress just to meet daily demands and have limited capabilities and resources for efficient integration and exploitation of new research results. Thus, many potential benefits to the nation promised by the research breakthroughs are as yet unrealized.

The outputs of the forecast system are products that guide decisions about future actions. The decision maker may be an individual, a private business, a non-governmental organization, or a government agency. The information may be based on past, present, or future climate and weather. In general, past information is used to define the context (climatology) in which climate information affects a decision. Present weather and climate information is used to define short-term actions. Simple statistical inference about future weather or climate or predictions based on dynamic models can be used to guide decisions about future actions to be taken by users sensitive to weather and climate.

EXPANSION OF THE FORECASTING FAMILY

>As a result of the significant improvements in forecast capability achieved during the past decade, the demand for other specialized forecast applications—and the potential for substantial new public benefits—has grown rapidly in recent years. The public has become accustomed to ever improving forecast products that are incorporated more frequently into daily decision-making. Weeklong forecasts, not viewed as credible two decades ago, are now an indispensable part of our planning processes. New products have also shown their worth. For instance, solar

ultraviolet radiation forecasts, developed by the Environmental Protection Agency (EPA) and the NWS, alert beach goers to the need for sunscreen and other precautions against harmful exposure to the sun.

The National Weather Service Modernization Committee of the NRC described the future requirements for services in the report *A Vision for the National Weather Service: Road Map for the Future* (NRC, 1999c):

> Environmental information, both global and local, will become a part of the international information infrastructure that individuals and organizations use on a daily basis. Business customers will use worldwide environmental information to plan operations in the global marketplace. At the same time, customers will also require information for specific times and places. Location-specific business decisions, such as when to start pouring concrete in a construction project or whether to shut down operations in response to tornado or hurricane warnings, will be made with the help of decision support systems that include environmental data targeted for a specific place and time.

It will soon be possible to deliver several new forecast products that will, at first, be unfamiliar to the public, but will become as indispensable as our present weeklong weather forecasts. A detailed discussion of the various scientific areas supporting these products is contained in the technical chapters of the report *The Atmospheric Sciences Enteringthe Twenty-First Century* (NRC, 1998a). Examples of new products include the following:

1. Threats to life and property and the costly and disruptive nature of evacuations are resulting in demands for improved hurricane forecasts of storm track, intensity, and precipitation. It is estimated that the evacuation of the southeast and mid-Atlantic coastal area, in the face of approaching Hurricane Floyd in September 1999, had an economic impact of approximately $2 billion (Pielke, 1999). Improved forecasts of hurricane track and intensity will reduce the necessity and attendant cost of overwarning.
2. While lightning poses one of the greatest dangers to life and property in the United States, at the present time only general forecasts of lightning likelihood are produced (e.g., 60 percent chance of thunderstorms in the evening) (NWS, 1994). With increasing accuracy of small-scale weather system forecasting and better understanding of the physics

of lightning, soon it will be possible to provide specific forecasts of lightning occurrences (i.e., the probability of lightning strikes at specific times and places). This will not only be useful to those scheduling outdoor activities, but it will also allow electric utilities to prepare for disruptions that may accompany a serious lightning storm.

3. Increasing concern over the consequences of energy production will result in demand for improved planning and operations in power production. Improved temperature forecasts will result in significant savings in fuel costs and a more efficient electric industry (Keener, 1997).
4. Not only will the energy industries need improved short-term forecasts for near-term operations and plans, the improvements in seasonal to interannual forecasting are increasing the demand for products and services on that time scale. The accurate seasonal outlook prior to the 1997–98 El Niño event allowed utilities to realize savings of about $500 million (Changnon, 2000).
5. For reasons not completely understood, the occurrence of asthma is increasing. Certain combinations of humidity and air pollution aggravate asthma. With substantial progress being made in understanding atmospheric chemistry and modeling transport of atmospheric chemicals and aerosols, setting the stage for operational forecasting of atmospheric chemical composition (NRC, 1998a, 1998c), it should be possible to produce useful forecasts of pollution levels that might trigger asthma attacks. The strong ties between air temperature and air quality and the associated negative impact of poor air quality on all aspects of human respiratory health are creating demands for a whole new suite of air quality forecasts.
6. Space weather hazards are becoming increasingly important to the performance and reliability of space-borne and ground-based communication and observation systems because of the increased sophistication of the deployed systems. The demand for space weather forecasts will grow as large constellations of satellites are launched in low earth orbit over the next several years. With the development of increasingly sophisticated technologies and the expansion of human activities into near-earth space, there will be an increasing need to forecast the changing fluxes of energetic particles, geomagnetic fluctuations, short wavelength solar radiation, and other upper atmosphere/near space conditions (NRC, 1998a). Fortunately, an unprecedented armada of spacecraft is providing the required data, and there has been tremendous progress in research modeling of space weather phenomena. The

National Space Weather Program now seeks to implement operational space weather forecasting based on these advances.

7. Clean, safe water is essential to human well-being. Recent research has uncovered some remarkable results that have significant implications for requirements for forecasting products. For instance, cholera outbreaks have been shown to be related to oceanic physical conditions and the resulting algal types and concentrations. Thus, we are now in a position to forecast the conditions leading to cholera outbreaks around the world. Other water-related forecasts dealing with water availability and quality will also be possible and will complement current drought and flood forecasts.
8. The potential links between climate variability and ecosystem impacts (food, forage, timber, fiber, water) are being enumerated currently in the first U.S. National Assessment of Climate Change Impacts. This linkage is expected to result in a growing demand for improved projections of future climate conditions.

The potential is enormous. The demand for new and diverse forecasting products will continue to grow and, with implementation, these expanded products will promote increased human safety and stimulate economic benefits in the United States and elsewhere. The foundation for these products is NOAA's forecasting capability, which can improve by capitalizing on U.S. investments in weather and climate research and technology.[5] Just as NOAA's traditional weather forecasting products have spurred the growth of private companies that provide tailored weather products for their clients, this increased demand will also facilitate more rapid growth of private sector enterprises structuring specific products for their clients or customizing or extending government-provided products.

However, until current research advances are incorporated effectively into operational forecasts, the nation will not realize the attendant benefits of its research investment. It is important to understand the transition process and to ensure its efficient operation. Otherwise, impediments that may exist now will become more problematic in the future as a consequence of anticipated expanded demands on the nation's weather and climate forecasting.

[5] Atmospheric Research Recommendations 2 (Extend a Disciplined Forecast Process to New Areas) and 3 (Initiate Studies in Emerging Issues) from the ‘Twenty-First Century Report' urge the necessary activity to meet the new and increasing demands for weather and climate products and services.

In order to focus attention on the transition issues, Chapter 2 further defines and describes the linkages between the research and operational communities required to effect transitions across the ‘Valley of Death.' Chapter 3 and Chapter 4 then focus on critical elements of the U.S. weather and climate forecasting enterprise. The first critical element discussed in Chapter 3 is the Environmental Modeling Center (EMC) of the National Centers for Environmental Prediction (NCEP). The second critical element, highlighted in Chapter 4, involves environmental satellites and related data systems. The transition from research to operational satellites is of major importance, as both climate and weather communities are highly dependent on satellite information.

2

Transition from Research to Operations in Weather Satellites and Numerical Weather Prediction

Weather sensitive sectors of society include those involved with energy generation, agriculture, forestry, fisheries, construction, recreation, tourism, transportation and navigation, public utilities (energy purchase, electricity distribution, and capacity planning), retail trade distribution and stocking, finance, insurance and re-insurance, recreation, and real estate (NRC, 1998a). The utility of this information is diverse—it impacts military operations and staging; commercial airline scheduling, operations and flight planning; space launch scheduling; agriculture crop selection, planting, cultivation, and harvest timing; water resource management; and a wide range of commercial industries that schedule outdoor activities (e.g., construction, transportation). Information about extreme weather, especially that which puts life and property at risk, is essential for all sectors, but particularly for the emergency management, preparedness, and disaster relief communities. Both the public and private sectors exhibit a growing demand for accurate information about and prediction of extreme weather and climate events.

To meet this demand the federal government organizes the nation's weather prediction responsibilities into two related areas. First, *operations* are the basis for production and dissemination of official forecasts and warnings. (Operational services are also divided between public sector predictions, both civilian and military, and private sector, value-added dissemination and prediction services.) Second, research, systems development, and technology development and implementation are supported to improve the skill of weather forecasts. These activities are in some cases tightly coupled to operational efforts, while others have a weaker connection. Research is carried out in both federal laboratories and universities. Research and development, whether in federal laboratories or universities, is largely supported by the federal government, and amounts to about $500 million each year (OFCM, 1998).

A challenge facing the meteorological community is to reduce impediments that limit the efficient transfer of weather and climate research findings into improved operational forecast capabilities that will benefit a wide group of users in the United States and countries that rely on U.S. forecasting leadership. To place the report's subsequent discussion of numerical weather prediction and satellite technology into a broader context, this chapter discusses the relation of research and operations in the meteorological community.

The operational forecast system is responsible for collecting and assembling data and for using that data, in conjunction with models, to produce forecast products in a timely fashion. Consequently, the system encompasses many elements, from the instruments on land, on the ocean surface, in the atmosphere, and in space, to the computational resources required to create, display, and disseminate the products. All elements of the system can be improved, and both the private sector and the academic research and development communities can contribute to that improvement. There are prohibitive impediments to improvement, however. Because the system is operational and is required to provide service 24 hours a day, 7 days a week, it cannot be taken off line for improvements to be made. Therefore, testing of changes in parallel to the operational forecasts is an essential precursor to adopting improvements to ensure that the changes introduced do not degrade the forecast skill. Yet EMC lacks the computational resources to conduct parallel testing.

IMPROVING THE FORECAST SYSTEM

Improvements in observational capabilities, assimilation techniques, and forecast models have the potential to increase the timeliness and accuracy of the forecast products. Both private sector and academic research and development organizations have driven such improvement in the past, and can be expected to do so in the future. These organizations do not have to remain on line to provide an operational flow of observational data and forecast products; therefore they are free to concentrate on advancing the state of the art, raising effectiveness and skill in observing, assembling observations, and making predictions.

Strong interaction between the research and operational communities can improve the transition process. If the research community produces new science, one would expect opportunities to improve operations to exist. But without effective transitions from research or a dialogue between research and operations about system performance, improvements to the skill of the operational forecast system will be slow. The potential forecast skill based on current research understanding, state-of-the-art sensors, and computers is expected to be higher than that of the operational system. Verification of forecast skill and ongoing dialogue about performance should guide operational practices toward improvement.

Key issues for an operational forecast system are to ensure that transitions do indeed result in improvements and that the effort required for the transition is not disruptive. Improvements have been noted in the past such as the development of numerical weather prediction (1948), the first climate forecast of warm sea surface temperature in the tropical Pacific (1986), and the realization that chlorofluorocarbons photodissociate in the stratosphere depleting the ozone layer (1974). Feasibility must be demonstrated for the entire operational process, and production of additional climate and weather information must be accompanied by considerations of its dissemination, use, and impact. Impact may be related to demand, which depends on visibility of the information and recognition of its value. In certain cases (e.g., human health) public perceptions of hazards might result in demands for new products even though the ability to accurately forecast and quantify health hazards may be limited. The private sector also is capable of visualizing new products that, when advertised to the public, will generate demand.

Transition to Operations

If the new information has sufficient value, then a transition to operational status is desirable. The major challenges in accomplishing such a transition are institutional. Observations, modeling and prediction, and information dissemination to users should be tightly linked, and financial support of the operational system requires long-term commitment.

The transition plan should be sensitive to the research community that developed the system. Ideally, the new system should serve a dual purpose by continuing to serve the needs of the research community and continuing to promote advances in data analysis and use. To that end, the research community should be involved as advisors, and sufficient resources should remain available for continued exploration.

Not only should the operational structure include sufficient commitment to maintain critical observations, modeling, prediction, and information dissemination, but it should also include a continued interaction with the research community to promote the opportunities to maintain a state-of-the art capability[6]. The continued dialogue between the research and operational communities is needed to guarantee that the latest techniques and current knowledge are available to the operational services. This linkage will ensure that the latest research continues to be available for operational use. The operational services will be able to keep abreast of the latest research, to continuously assess the observing and simulation systems, to persistently determine how the information can be improved, and to consistently interface with the user community in the design of new useful products. The dialogue should include interested members of the research and user communities, and ongoing surveys should continually assess changing user needs.

GUIDELINES FOR THE TRANSITION PROCESS

BASC has selected the following criteria as key to an effective transition for the field of weather and climate prediction:

- A strong research program, including understanding of the role of the operational community in the broader context of the weather prediction system (NRC, 1998a, 1999c).
- A healthy infrastructure for transition. The forecasting system needs an observation, technology, and modeling capability that serves as a foundation for research and permits the demonstration of the potential for useful new products without drawing resources away from the operational forecast system. There is a need for a long-term commitment of adequate resources to maintain the research or operational programs. Mechanisms should be developed to enable continuous development and

[6] For a discussion of the changing paradigm for research to operations transition, see “Beyond Basic and Applied” (Pielke and Byerly, 1998).

maintenance of state-of-the-art capabilities (Recommendation 4, NRC, 1999c).

- Strong interface with the user community (Pielke and Byerly, 1998).
- International observation and data access partnerships (NRC, 1998a; Recommendation 8, NRC, 1999c).
- Continuous evaluation processes of each of the components of the weather prediction system as well as its subcomponents (NRC, 1998a).

In order to focus attention on the strengths and weaknesses of current U.S. efforts, the following two chapters apply the principles contained in these guidelines to two critical aspects of the U.S. weather and climate forecasting enterprise.

3

Developing, Enhancing, and Maintaining Numerical Forecast Capability in the U.S.

Operational weather forecasting in the United States has evolved considerably since the formation of the U.S. Weather Bureau in 1870 as a component within the U.S. Army Signal Service. From an initial effort that was largely observational, increasing scientific understanding and technological advances have permitted the development of a forecast system that is based on models that incorporate physical understanding of the earth's coupled atmospheric and oceanic system. As a result, the nation's weather services now have the ability to forecast weather and climate events and patterns. Until the end of World War II, the federal government provided virtually all weather services. Since then, however, the demand for specialized meteorological services has led to the development of effective private sector organizations that offer forecast products and services.

The U.S. National Weather Service (NWS) still plays the central role in the provision of operational weather data and services in this nation. It is responsible for the maintenance of the fundamental observing networks, the core forecasting infrastructure, and the provision of severe weather and flood warnings necessary for the protection of life and property. The NWS consists of a network of 120 Weather Forecast Offices spread more or less uniformly across the country, 13 River Forecast Centers covering the major river basins, and the National Centers for

Environmental Prediction (NCEP) providing guidance products[7] for the rest of the NWS, other government agencies, and the private sector.

NCEP is composed of several centers that provide specialized products to the meteorological community (see Appendix B for a description of the NCEP structure and the functions of its major units). This chapter focuses on linkages, actual and potential, between research and operations at NCEP's Environmental Modeling Center (EMC), which has the major responsibility for implementing and operating the numerical weather and climate prediction models that serve as the basis of modern forecasting operations. Both government and private sector activities use EMC products.

CURRENT SITUATION AT EMC

The mission of EMC is to "Develop, enhance, and maintain numerical forecast systems in support of national and international forecast requirements" (Lord, 1999). EMC operates numerical forecast systems for weather prediction (global and regional, 1-15 days), ocean prediction (global, daily to annual) and climate prediction (seasonal to interannual). It is responsible for enhancing numerical forecasts through improvements in data assimilation techniques, model physics, and numerical methods. EMC is also responsible for adapting the production programs to new hardware systems. It must remain responsive to changes to the quality and quantity of the input data and to the changing operational requirements for products and services. EMC's mission is accomplished through a blend of in-house research and development and cooperative alliances with the external research community. Forty-seven percent of the funding for the EMC staff is provided by the base budget, and 53 percent comes from soft money.[8]

[7] Guidance products are those analyses and forecasts that are intended for use by meteorologists in the preparation of specific products for the public or other specific users. They may consist of NWP output, special analyses of specific parameters, or technical discussions.

[8] Base funding is that funding level that is expected to continue from year to year to support a certain level of activity. The amount is usually changed only if there is a substantial change in the program activities. Soft money refers to funds that are one-time in nature, provided by another agency, and are not stable from year to year. Consequently, the increasing reliance of an agency on soft money hampers the effective planning of future activities and requires increasing efforts on the part of that agency to secure the temporary funding.

Although the mission appears well defined, previous reports, as well as presentations to BASC, reveal prioritization and staffing issues that indicate EMC capabilities are already stressed, and therefore, the task of meeting society's growing expectations of the forecasting enterprise is already compromised[9]. These concerns were pointed out as major shortcomings in the Dorman report:

> The danger signs at EMC include lack of effective prioritization processes, insufficient base funding which compounds the work allocation problem, and an insular concept of operations that fails to adequately access the national talent and resource base (Dorman, 1999).

NCEP management clearly recognizes the value of the Dorman report recommendations, and they indicated to BASC that many of the criticisms are being addressed. For example, EMC activities have been prioritized to permit a rational framework for resource allocation decisions (Lord, 1999). EMC also is now a major player, with other institutions, in the development of the next generation of mesoscale forecast models (Lord, 1999). The fact that the base funding for EMC still covers less than half of the EMC staff, however, creates extreme stress on the system. Soft money funding may be appropriate for some research activities, but not for operational organizations. The increasing difficulty in continuing to collect the soft money necessary to operate the center has been a major concern for EMC leadership. The lack of stable base funding makes it difficult to plan the ongoing operations. At the same time, the organizations that serve as the sources for the soft money may have interests that differ from the principle mission of EMC and may place conditions on the receipt of the funding resulting in tensions in priority setting. The solution to this problem may well lie at levels in NOAA considerably above EMC or NCEP.

Advances in computer power play an important role in NWP accuracy increases as noted in Figure 3.1. Computer power, as measured by

[9] Several BASC members have personal experience with the situation at EMC, having spent time there in various capacities. One member recently visited on a cooperative research project and described to the rest of the board the situation from his perspective. There was no disagreement with the views expressed by the Dorman report.

millions of floating point operations per second (MFLOPS), is depicted in Figure 3.2 for NCEP (Lord, 1999) and the European Center for Medium Range Forecasting (ECMWF) (ECMWF, 1999). Note that the scale for computing power is logarithmic. Although both centers have benefited from a rapid increase in computer power, the disparity between EMC and ECMWF increased during the 1990s. One important consequence of the disparity is that, relative to ECMWF, EMC lacks adequate resources to conduct experiments to test and evaluate model improvements and work effectively with external users to build a more effective analysis and forecast system. Likewise, these computational limitations hinder EMC's ability to develop new products and services (NRC, 1999c). However, improvements are being made in this situation with the recent acquisition of a new IBM system for NCEP. The planned increase for 2000 and 2001 is currently in the NCEP budget, and this addition should provide EMC with the computer power necessary for improved operations. There is no plan at this time for a system on which to perform parallel testing and demonstrations (Lord, 1999)[10].

The lack of resources affects EMC's ability to adequately interface with the user community to evaluate and improve the operational prediction models. The value of cooperation among interested user groups has been demonstrated by the National Center for Atmospheric Research (NCAR) community climate model (CCM) and the Penn State/NCAR mesoscale model, version 5 (MM5). The MM5 model is now used not only at NCAR, but also at 44 U.S. universities, 28 federal and state agencies, 60 foreign organizations, and 28 private sector companies. In the past decade, the CCM user group has grown to over 200 individuals and organizations. These community models benefit from the number of scientists that are using, evaluating, and making suggestions for improving them. EMC has not used the MM5 for operations, but instead developed an independent model, the ETA[11]. Although the ETA model has some advantages, it is not widely used in the community. EMC needs to benefit more from the active involvement of the community in the design, testing, implementation, and evaluation of new models, something that EMC management has recognized from their ongoing work with the broader meteorological community in generating the next generation weather prediction model (Lord, 1999).

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[10] An excellent discussion of the computational needs of the National Weather Service is provided in the National Weather Service Modernization Committee's ‘Road Map Report' (NRC, 1999c). The report also contains a strong recommendation for the provision of state-of-the-art supercomputer capability on an ongoing basis to EMC.

[11] The ETA model is the operational mesoscale numerical weather prediction model used at EMC. It derives its name from the coordinate system used in the model architecture.

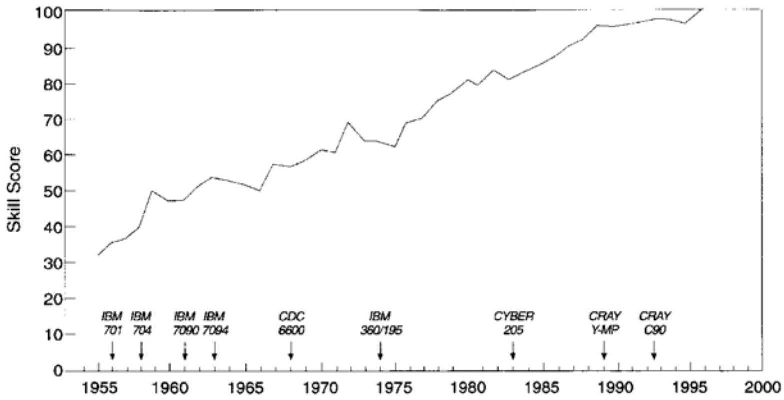

Figure 3.1. The skill score, an objective measure of accuracy of the numerical forecasts, of the NCEP 500-hPa 36-hour forecast has been tracked from the beginning of operational numerical weather prediction in 1955. The major improvements in accuracy were associated with the major changes in computational power available for the models. The complete history of the model results is presented in a review article by Kalnay et al., 1998.

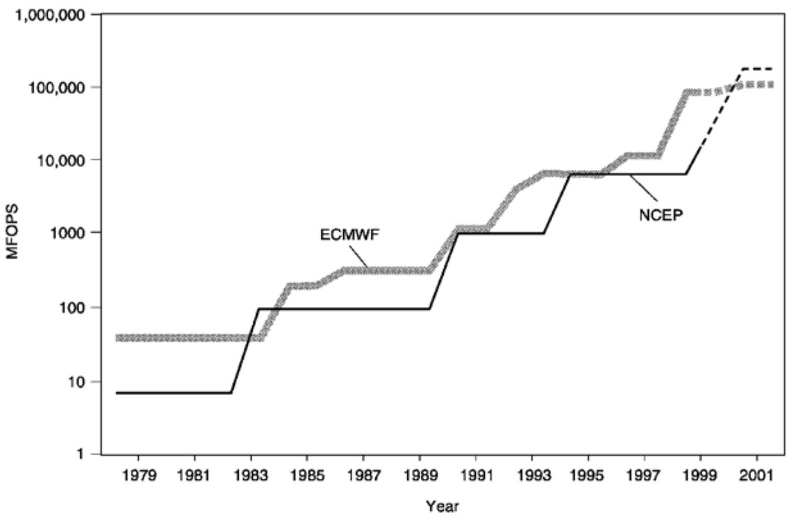

Figure 3.2. The capability of the computers available for numerical weather prediction at NCEP and ECMWF are presented in terms of MFLOPS (millions of floating point operations per second). Note the logarithmic scale. The values for 2000 and 2001 are current plans under contract with computer vendors. (Source: NCEP and ECMWF)

The ability to encourage researchers from other agencies to spend periods of weeks to months at EMC is important in leveraging national investments in research. Such visits have been shown to be a significant component of the success enjoyed by ECMWF. Discussions with EMC personnel indicated that, currently, these visits are seriously hindered by the lack of adequate EMC facilities. Space is so limited that there is no room to accommodate visitors, and adequate temporary lodging is not readily available in the vicinity.

EXAMPLES OF TRANSITIONS AT EMC

Mechanisms exist to implement obvious improvements in forecasting capability to an operational mode. For example, NSF supported the doctoral dissertation of a student from the University of Oklahoma for several years through the NSF/NCEP Joint Program, yielding an advanced prognostic cloud scheme for the operational ETA model. Post degree, the student became a Visiting Scientist at NCEP/EMC, where he spent two additional years developing and testing his scheme for a wide variety of meteorological situations in the operational environment. The scheme was implemented operationally, resulting in significant improvement in the operational prediction of precipitation. This outcome was the result of NSF's support to enable the interaction and EMC's support for testing and implementation.

Such cases, however, appear to be relatively unusual rather than part of a systematic process. Several recent specific examples involving the transition from research to operations illustrate the problems associated with this inadequacy. Each case was discussed by the EMC representatives at the summer study.

- As part of their ongoing research program, scientists at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) developed an advanced model for hurricane prediction. NWS agreed that EMC would implement the GFDL model after a planned supercomputer upgrade (it was too computationally expensive for the computer then in use). The transfer to operations took place over three years. While testing using the diverse examples characteristic of operational use revealed some areas of weakness, the new model resulted in a major improvement of operational hurricane forecasts with the largest reduction in track prediction error obtained in many years. However, this transition is far from complete. The GFDL research staff is still occasionally maintaining the program and is now working on converting the model code to run on a new computer system. Even though it is a vital part of the operational run-stream, there is a lack of sufficient programmer staff at EMC to effect fully the code transition.

- Over many years, NOAA's Forecast Systems Laboratory (FSL) developed a system designed to produce a quick, accurate analysis and short range forecast over the continental United States. Following an agreement between FSL and EMC, this model was implemented operationally at EMC, a major effort requiring about two years of joint development and operational testing. The model provides a rapid (1 to 3 hours) update of the atmospheric evolution essential for severe weather forecasting. While the outcome of this transition was a success, the process was not expedient because of the difficulty in incorporating capabilities developed outside of EMC. A formal management agreement and considerable time were required to ensure cooperation.
- In December 1992, EMC and ECMWF were the first centers to implement operational ensemble predictions which provide useful guidance to the forecasters about forecast reliability. When the ensemble members are very different from each other, the forecast is very uncertain. This observation led to the development of the adaptive observation concept in which additional observations are taken to reduce uncertainty. Two sets of research experiments, FASTEX and NORPEX, demonstrated both the moderate cost and the success of this approach in improving severe storm forecasts. Despite the success, the transition to operations has not occurred because funding necessary for aircraft operations to implement the adaptive observational process has not materialized.
- Almost $1 billion has been invested in a national Doppler weather radar network as part of the modernization of the weather service. At the heart of the network is the NEXRAD radar that provides critical information needed for severe weather warnings issued by the NWS. Although the radars have been in existence for nine years, the detailed data from the radars, which include radar reflectivity, precipitation rate and characterization (e.g., rain/hail/snow), and wind velocities,

have not been incorporated into data assimilation models routinely used at EMC for operational numerical weather prediction. The lack of new resources and higher priority demands on available staff time at EMC have created an impediment to the development of an assimilation algorithm that would enable enhanced predictions and have prevented researchers from evaluating the inclusion of the radar data (NRC, 1999d).

- Accurate observations and model output are central to both the research and operations enterprise and critical for advances in research and improvements in operations. There are many examples of this, including use of model output as observational surrogates in those regions where the observational network does not permit detailed analysis of weather, use of gridded surface meteorology over the ocean in deploying instrumented buoys and ships, and use of atmospheric variability measures to assess changes in the temperature, salinity, and velocity structure of the upper ocean. The NWP model output permits exploration of new, improved methodologies and applications by the research community. However, resource limitations have prevented these data from being made available routinely to the research community. The lack becomes a major obstacle in linking operations and research.
- The observations that are currently used in weather forecasting are taken from airborne, ground-based, and satellite platforms. In general, planning for each set of observations or platform is done independently. This design inadequacy sometimes results from difficulties in assembling a national network of observational instrumentation across many federal agencies. Some progress has been made in developing a national plan for an integrated observing system for weather observations (NRC, 1998a); however, with respect to climate, a national integrated observing network is not in place (NRC, 1999a). With the anticipated suite of future forecast products, the need for a national plan for the required observation network is critical. Such a plan would require consideration of the necessary hardware, maintenance and operation, and assessment of methods to assimilate the measurements into the models. EMC is beginning to address a portion of this requirement through computer-based studies, but again, the lack of sufficient computer resources for parallel testing of data assimilation scenarios and measurement and sampling strategies is slowing the efforts.
- For the last two decades, EMC's computational resources have been a small fraction of the capability at other international facilities

such as the ECMWF (Figure 3.2). This lack of resources has had a demonstrated negative impact. For example, specific cases have occurred in which upgrades to the U.S. forecasting capability could not be executed simultaneously with the existing operational forecast codes in order to provide careful assessment, debugging, and systematic changes in the newly developed code. As a consequence, at the appearance of a problem, new model versions have been replaced by older model versions to prevent an interruption in service. In contrast, ECMWF is capable of simultaneous execution of test and operational codes.

- Computational power is not the only computational issue. EMC purchased an alternative architecture based on parallel processing that computer experts predict will be the architecture of choice in the future (a Department of Commerce ruling prevents the sale of advanced vector processing capability from foreign suppliers even though U.S. suppliers are not competitive in terms of performance [NRC, 1998b, 1998c]). By "adapting to the future early" it is hoped that while the U.S. capability may lag for a period, it will then leapfrog current vector machine capability. However, the EMC transition to this architecture occurred before the software and model programming expertise required to ensure efficient utilization was available. Consequently, the transition to a new architecture is likely to result in significant stress to an understaffed facility. This issue will affect many U.S. laboratories in addition to EMC, arguing for community model infrastructure as well as programming and software alliances (Reed et al., 1999).

These examples were discussed at the summer study and contribute to the following assessment.

BASC ASSESSMENT OF THE TRANSITION PROCESS

BASC's assessment of the strengths and weaknesses in the current transition from research to operations follows from the criteria described in Chapter 2:

A Strong Research Program

1. BASC considers that the overall atmospheric and oceanic research community in the United States is strong (NRC, 1998a). Improvements in weather and short-term climate forecasting will involve

leveraging this research strength to expand the quality and diversity of services provided to the nation.

2. Some major research programs are taking steps to link research activities and forecast products to society's needs. For example, the national and regional assessment programs under the USGCRP are addressing the societal impacts of climate variability and the resulting potential environmental changes (USGCRP, 1999).
3. BASC could find no evidence of a comprehensive effort to address the societal benefits and economic impacts of various research and transition strategies. For instance, while the social science community dealing with societal benefits and economic impacts is becoming more fully engaged in the USWRP, few resources are being targeted for this activity. There is also little USWRP funding that promotes transition to operational products (NRC, 2000b).

A Healthy Infrastructure

1. EMC does not have the ability to test and evaluate new algorithms and forecast capabilities and obtain feedback from the user community. Insufficient computational resources prevent simultaneous testing of new model versions while operational forecasts proceed. Computational capability that allows simultaneous testing and operational execution of model codes does not exist. The ability to address the special needs associated with assimilation of a large volume of new satellite observations is limited.
2. Several aspects of the U.S. weather observational capability have improved considerably in the past decade. The NEXRAD weather radar system, the new Geostationary Operational Environmental Satellite (GOES), and the increased number and quality of moored and drifting ocean buoys all add to the potential for significant improvements to the forecasting enterprise.
3. Human resources at EMC receive only 47 percent of their funding from the base budget; the remainder is supported by soft money. Although EMC has been successful despite this limited base funding, BASC is concerned that the level of base funding is too low for an operational agency.
4. When new sensors are developed, the budget to develop the algorithms and tests to introduce those sensors into the operational system is frequently inadequate.

5. EMC is located in a substandard and unsafe facility. The building is not suitable for hosting quality technical activities with modern computer and communications requirements. Muggings in the parking lot and bullet holes in the windows create an environment that is not conducive to the recruitment of scientific talent on a short- or long-term basis.
6. EMC is not co-located with any other forecasting enterprise, data assimilation facility, or research and/or operational team. It is geographically isolated from the supporting NOAA laboratory structure, such as GFDL and FSL, and from the other national capabilities such as NCAR and NASA Goddard. While NCEP recognizes the advantages of co-location with complementary research facilities and has developed plans for co-location with NASA Goddard, these plans have never materialized.
7. EMC lacks a clear delineation of responsibility for the transfer of research results to operations. No one at the EMC or the weather-related NOAA labs is specifically assigned the responsibility for this linkage.
8. The NWS model development process is becoming more open to the research community. EMC is participating with other organizations to develop a community mesoscale prediction model that will enable greater participation by a large number of researchers in the process of incremental improvements in the model performance. With its present computer and human resources, EMC cannot rerun a forecast situation to evaluate the cause of major forecast errors in an attempt to improve the performance.
9. EMC does not have a capable and accessible data and model archiving system that would enable the research community to address ways of improving EMC's forecasting models.

Strong Interface with the User Community

1. Limitations on resources have forced the elimination of routine forecast verifications at EMC (Lord, 1999), adding to the difficulties in making improvements and limiting the information on the expected improvements in forecast capability.
2. The lack of greater understanding of societal benefits and economic impacts of forecast products limits effective decisions in resource allocations.

International Observation and Data Access Partnerships

The international data exchange experience tends to be mixed. Some international programs, such as TOPEX/POSEIDON and TRMM, are quite effective in exchanging data. However, commercialization issues within the national meteorological services are increasingly hampering the exchange of more conventional meteorological data, resulting in a reduction of the amount of data archived in the World Data Centers (NRC, 1998a). If it continues, this trend could have a considerable detrimental effect on both research and forecasting operations.

Continuous Evaluation Process

There is limited capability at EMC for continuous evaluation of operational effectiveness. The NCEP director acknowledged at the BASC summer study that forecast products are no longer routinely verified because of personnel and resource limitations.

RECOMMENDATIONS FOR EMC

The United States has a strong atmospheric and oceanic research community. However, resources designed to enhance the delivery of products useful for society have not fully supported this investment. There is an impressive opportunity to leverage a small investment into great accomplishments if key issues and problems that limit the transfer of knowledge and capability are addressed. Improved leveraging of this investment is essential to providing services and to expanding the forecasting products provided to the nation. The sense of the recommendations that follow is very similar to that of Recommendation 4 from the ‘Road Map report' of the National Weather Service Modernization Committee; however, they focus on NCEP and EMC rather than the more general NWS-wide nature of the Road Map recommendation (NRC, 1999c).

The recommendations are divided into three elements: (1) improvements needed to ensure that the United States avoid degradation or failure of current capabilities, (2) improvements needed to ensure that the nation can address future product demands and needs, and (3) management changes that have little associated costs, but will facilitate needed improvements. Alternate mission definitions or organizations were not considered by BASC.

Improvements Required to Ensure Continuation of Current Capabilities

1. *A credible development, testing, and integration facility within EMC with a strong connection to the research community.* The inability to evaluate and test new algorithms while maintaining current operational forecasts is a major limitation (Emanuel and Kalnay, 1996).

RECOMMENDATION EMC-1

NOAA should implement a development, testing, and integration facility at EMC. It should have the following characteristics:

- Adequate computer resources
- Adequate personnel with the proper understanding of user needs, as well as technological capabilities, including communications expertise
- A model archiving system
- Improved visitor programs
- Expertise in parallel processing and efficient code development

The facility personnel would test, within a quasi-operational environment, ideas that have already been developed and shown to be promising in an academic environment. They would collaborate with outside researchers on tasks such as routine forecast verification, code conversion, and optimization. Such tasks cannot be handled by an individual researcher and constitute major barriers for the transition from research to operational implementation. Adequate computer resources should be provided to support this testing and to test new algorithms needed for massively parallel computers. The test facility could also facilitate the archiving of operational products in real time, make them available to researchers, and transition successful experimental projects such as Reanalysis, Seasonal to Interannual Prediction, and the GEWEX/GCIP Land Data Assimilation System into regular operational execution.

Such a test facility would require proper understanding of the user needs, as well as technological capabilities including communications expertise. A model archiving system should be closely connected to this model testing facility. From the initial creation of NCEP, the development and implementation of atmospheric (and eventually ocean) models and analysis systems has been conducted primarily within the organization, at first using civil servants, and later supplemented by contractors and visitors. The pace of progress is slow in meeting the requirements of the National Weather Service. The complexity of model and analysis systems science and technology has outgrown the single-site development methodology that has been in place for the past 40 years. No single center anywhere in the world can afford the staff necessary to permit internal development of all the upgrades required to continue improving models and analysis systems at the required pace. Even ECMWF relies on the meteorological research capabilities of its member states for partnership activities (ECMWF, 1999). Resources should be identified that ensure active collaboration and participation. Methods that will effectively open the NWS model development process to the research community outside EMC are required. Improved visitor programs, graduate fellowship programs, and funded collaborative efforts using designated funds are essential.

Currently, EMC modeling plans are presented and reviewed annually by the NWS users (the NCEP Service Centers and representatives of the forecasters in the NWS regions). This is a very comprehensive procedure that has led to better communications and faster response to forecasters' needs. NCEP should expand this review to include external users as well.

NOAA should provide the computational resources on the development side to simultaneously perform test simulations, reprocessing, and ongoing operational forecasts. Expertise in parallel processing and efficient code development should be a part of the facility. Collaborative partnerships to address the programming challenges of new computer architectures will be essential to the success of the enterprise and should be developed. Necessary staff should be added to enable archiving of data and model products and to interface with researchers. Both space and sufficient workstations should be available to enhance research collaboration. The capability to increase the number of long-term visitors (5 to 10 senior researchers, young investigators, and graduate fellows) is required to open the NWS process to the research community.

Staff should be budgeted to assist and support visiting researchers. Designated funds are needed to support mission-related research projects.

2. *Staffing requirements.*

RECOMMENDATION EMC-2

NOAA should determine the staffing levels required to perform EMC's operational mission and support these critical staff through base funding.

Many of the issues and bottlenecks involve a lack of staff at EMC. The NWS and NCEP cannot even sustain their present level of development activity, and this level is viewed by BASC as inadequate. It is interesting to note that other agencies are willing to provide funds to EMC for certain activities, demonstrating the importance of NCEP for NOAA and other federal agencies. Yet this requirement for extensive outside funding (soft money) also clearly defines the nature of the human resource problems in an operational enterprise, an issue which will be exacerbated with any expansion of the forecast products.

Added Requirements to Serve Future Needs

3. *Co-locate forecasting capabilities.*

RECOMMENDATION EMC-3

NWS should seriously consider co-locating EMC with other appropriate institutions.

Operational predictions of weather, water, and climate should be integrated in order to make optimal forecasts to serve the nation. The NWS has already recognized that co-location of forecasting centers with universities and research centers has led to faster progress through synergy. The benefits of co-location or formal interaction are clear. For example, the institutional and physical separation of EMC, which devel ops operational atmospheric and ocean forecast models, and the NWS Office of Hydrology, which develops operational river models for the River Forecasting Centers, has hampered this integration. Similarly, the NWS Techniques Development Laboratory develops user products through techniques such as Model Output Statistics, which improve the utility of the forecasts by correcting error bias and relating model output variables to variables of user interest such as visibility. The integration of the atmospheric, water, and climate forecasting functions is important to allow for improvements in the usefulness of the forecasts.

Several options for co-location are available, including co-location with NASA Goddard Space Flight Center, with universities with strong atmospheric science capabilities, or with other national laboratories. If resources offered by NASA and/or universities are leveraged, this could result in net savings to the government over a period of 5 to 10 years. Further, prompt action should be taken to improve the safety and adequacy of the EMC facilities. The current location is viewed as unacceptable for attracting staff or visitors or for expansion of capability. NSF, NASA, and NOAA should support visits by university and other researchers to EMC under improved site conditions to accelerate the transition from research to operations, as is so successfully done in Europe.

4. Continued modernization and improvement.

RECOMMENDATION EMC-4

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 (NRC, 1999c). 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.

NOAA's National Weather Service (NWS) began a major modernization program in 1989. Before the modernization, the NOAA weather radars were using vacuum tubes that were no longer manufactured in the United States and replacements were being obtained from the former Soviet Union. $4.5 billion has been spent on this modernization—all new radar equipment has been installed, all field offices staffed, and the forecasting and warning operations have been modernized throughout the NWS. Given the pace of technological change, however, it will not be long before this current equipment becomes obsolete. As we enter the twenty-first century, it will be impossible to meet tomorrow's needs with yesterday's technology. An annual budget designed around life cycle costs should enable the forecasting system capabilities to be in place to meet the evolving needs of the nation for weather and climate forecasts.

5. *National and international research potential in the atmospheric sciences.*

RECOMMENDATION EMC-5

EMC should actively participate in the USWRP to ensure that research objectives are consistent with operational needs and to enable the effective transition of more promising results to operations. EMC should collaborate with other appropriate parties in the development of community prediction models.

The USWRP provides one mechanism to improve the balance of resources involved with the transfer of research to operations via its joint agency grants program. The program has been justified in terms of transferring research into improved products for the nation, so it is appropriate that USWRP activities are structured to enable this transition (NRC, 2000b). The community prediction model approach, as illustrated by the experience with the MM5 community model, enables the rapid assimilation of research results into the operational systems.

6. *National and international research potential in the ocean sciences.*

RECOMMENDATION EMC-6

Recognizing the importance of the ocean in weather and climate forecasting, EMC leadership should be cognizant of the ocean-related research conducted outside the framework of the USWRP by NSF, the Office of Naval Research (ONR), etc., and seek opportunities for the transition of appropriate results from research to operations.

It is important to recognize that the USWRP is not the only user community engaged in research applicable to the NCEP mission. BASC noted how poorly EMC's model verifies over the oceans. Forecast improvement could come from improvement of model performance over the oceans. Some NSF, NOAA, Navy, and NASA funded research and research communities have little to do with USWRP but should be key players and partners with EMC. The air–sea interaction and coupled ocean–atmosphere–land climate communities can contribute research results to the EMC mission.

Management Changes with Little Associated Costs

7. *Clear responsibility for transition.*

RECOMMENDATION EMC-7

NCEP and EMC, under broad NWS guidelines, should institutionalize the transition process, assigning clear responsibility for continuous evaluation of its effectiveness and for the identification of bottlenecks and opportunities.

With the important exception of DOD[12] the nation's forecasting enterprise lacks a clear delineation of responsibility for the transfer of research to operations, although there does exist clear responsibility for both research and operations. In NOAA, this transfer responsibility is currently assigned in an ad hoc fashion, a situation that frustrates effective transfer both within NOAA and between other agencies and NOAA. In contrast, DOD designates responsibility for transfer to a particular person in its research and development process. NOAA has in the past utilized a process called the “troika” to facilitate the transfer of research to operations. This process, while important, is outside the formal institutional lines of authority and budgeting. Transition responsibility requires an end-to-end advisory involvement, from involving operations people in the planning of research agendas and research people in operational planning.

[12] The DOD has requirements for the identification of a plan for the transition of research to operations as a part of the planning and budgeting document. An ONR representative briefed BASC at the summer study on the U.S. Navy's version of this mechanism.

4

Environmental Satellites

Environmental satellites serve as a major component of the forecasting system, both from the standpoint of capabilities and of costs. The launch of the first meteorological satellite in April 1960 opened up an important new vantage point for observing the atmosphere and eventually the entire earth system. Even with the new potential of satellite observations, it took over a decade before the benefits of satellite meteorology were being routinely used in the operations of the National Weather Service. Another half decade passed before the satellite data were used in operational numerical weather prediction.

In the 1970s, in an effort to assist in the transition of satellite observational data from research to operations, NASA conducted the Operational Satellite Improvement Program (OSIP) that was responsible for developing new instruments for environmental satellites. In this program, NASA developed the prototype instruments, flew them frequently on high altitude aircraft missions for a preliminary checkout, and then deployed them on research spacecraft for a complete evaluation. Successful instruments were then available for transition to the operational NOAA satellite series (Fleming, 1996).

For budgetary and mission clarity reasons, NASA canceled the program in 1982. NOAA never developed a replacement for OSIP; instead, it continued with a procurement practice of specifying the instrument performance and having the contractor deliver the instrument for flight on the operational satellites. This procedure did not allow for the iterative development process that was so successful in the OSIP program (Fleming, 1996).

Because environmental satellites currently provide the only effective means of covering the entire globe in a short period of time, the climate research community depends on satellite coverage for many of the studies of climate processes and overall climate monitoring. The NRC Committee on Global Change Research suggested that NASA's Earth Science Enterprise (ESE) may not be able to fulfill the needs of the climate community, particularly with respect to the long-term monitoring needed for studies of detection and attribution of climate change and recommended that the task of monitoring climate variables be assigned to the operational satellite systems of NOAA (NRC, 1999a). A recent review of the ESE mission plans confirmed that concern and stressed that the planning for the transition from research to operational satellites must be carefully accomplished to ensure the successful support of all users of satellite data (NRC, 1999b). BASC learned that both the Administrator of NASA and the Administrator of NOAA have recognized these problems in mission definition, requirements process, and related issues in separate letters to the President's Science Advisor and are presently working on policy papers to clarify these issues.

In response to the growing concern for the long term monitoring mission for climate, NASA and NOAA have proposed a National Polar-Orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) which will serve as a bridging mission, enabling the near-term evaluation of some of the EOS instruments to determine their suitability for implementation on NPOESS operational satellites. In some respects, the NPP fulfills some of the important characteristics of the former OSIP program. However, it is presently planned as a single mission to bridge the time between the present NOAA and DOD polar orbiters and the initiation of the converged NPOESS system and does not serve as an ongoing mechanism for the development and testing of new instruments.

BASC has reviewed the NPP program plans. Several of the BASC members participated in earlier NRC studies (NRC, 1998c, 1999b) and were able to compare and evaluate the progress that had been made in the planning process for the NPP. The NPOESS program has a clearly articulated objective to meet the operational satellite requirements of NOAA and the Department of Defense (DOD) and to couple this program with the efforts to achieve NASA's mission. However, the process for promoting the transition from research to operations has not been clearly articulated.

RESEARCH SCIENTIST INVOLVEMENT IN NPOESS

Research satellites are often justified in terms of benefits to society through potentially improved products or services. At other times, they are justified in terms of obtaining better understanding of environmental processes through a single experiment, with little intent for the satellite system to become operational. In many cases data that were originally intended only for research purposes also prove to be extremely valuable in the preparation of useful operational products. For example, the TOPEX mission has produced new radar scatterometer data that has demonstrated its usefulness for determining sea state, from which one can infer the surface wind velocity, a measurement that had been extremely difficult to obtain. These measurements are now being considered by ECMWF for assimilation into operational prediction models. A similar situation is now developing with several of the projected EOS suite of measurements having the potential to become an operational set of measurements on NPOESS.

However, little evidence was presented to BASC illustrating dedicated efforts to examine new uses of satellite data. Further, instrument development programs for operational satellite programs typically do not include funding for development of the necessary assimilation algorithms. Lack of such funding often impedes the timely use of the new data products by the operational forecasting community.

After a new observing system is developed and deployed operationally, the taxpayer does not benefit by receiving improved forecasts until the new observations are included in the forecast preparation process. This inclusion is, in general, very complex, and requires close collaboration between the instrument designers and the data assimilation scientist. It requires the development of *observation models* that transform atmospheric model variables into *model observations* (e.g., satellite radiances) and quality control procedures that take advantage of information from the data and the model, etc. Experiences at ECMWF, EMC, the United

Kingdom Met. Office (UKMO), and other centers indicate that this preparation for implementation requires two or more scientists for two to five years before launch if the new instrument is to be used efficiently shortly after launch. Observing System Simulation Experiments (OSSE) can help to create all the necessary software and can begin using the new data soon after launch. When this does not happen, there is a gap of several years when the data is collected, but not used efficiently in the EMC models. During that period, the cost of the observing system, which may be on the order of $100 million per year, does not produce a direct forecast benefit to the user. With advanced planning and a full science team employed early in the new sensor development, the users of the new data can begin operations immediately after launch and sensor checkout, greatly extending the effective lifetime of the instrument. The science team should include experts in instrumentation, algorithm development, operational forecasting, and the end user requirements. BASC believes that proper planning for transition, with full stakeholder participation, is likely to be very cost effective in the long run.

ACCESSIBILITY OF ENVIRONMENTAL SATELLITE DATA

The return on the nation's investment in remote sensing systems depends on data utilization for the public good. Utilization depends on public and private access to, and exploitation of, these new sources of weather, climate, and other environmental data. NASA's EOSDIS program, although facing many technical and budgetary difficulties, was conceived with this purpose in mind. Now that the conversion of some of the long-term measurements from NASA satellites to NOAA satellites seems inevitable, the accessibility of both NOAA and NASA data should be addressed. Current plans do not appear adequate to ensure reasonable accessibility of archived NPOESS data. Several NRC reports have also expressed concern regarding a national commitment for ensuring that long-term monitoring of earth from space takes place (NRC 1998c, 1999b). Current plans include a transfer of key earth observations from the research-based EOS to the operational-based NPOESS. While plans are being developed for the sensors and ground processing, it appears that only limited consideration has been given to the requirements for data archiving (Withee, 1999).

An efficient, robust data archiving system is at the core of the transition from the research to operations processes and the generation of advanced forecast products. It provides the case studies necessary to develop and evaluate new forecasting techniques. A major challenge for the data system is the huge size of the projected data archives. It is necessary, but difficult, to ensure that data are quality controlled, accessible, and reprocessed as necessary for a long enough period of time (years to decades) to serve as climate monitoring data. One way to handle this challenge is to use and, if necessary, add to EOSDIS. In the future it is reasonable to anticipate that a considerable number of weather and climate related forecast products will need to be captured and archived into a data system. These products will be used by EMC to make operational forecasts, but the business sector and the research community will also use them. Thus the model data archive is a resource for research and application that should be readily available to these diverse communities. Given the advances in the private sector with Internet data webs, NASA and NOAA need to be more forward looking with respect to incorporating advances in data base systems for the delivery of data to users.

COORDINATION AMONG OBSERVATIONAL SYSTEMS

The transition to the NPOESS satellite observational system has focused on the difficulty of combining the mission and research requirements of NOAA, DOD, and NASA. The coordination across observational systems, including both in situ and satellite observations, has not been a part of the satellite convergence charge (NRC, 2000a). Better coordination of the data availability from satellite and in-situ observational systems has considerable potential. Such coordination is critical to evaluate the NPOESS sensors through calibration/validation activities, to improve the efficiency of data assimilation through better utilization of all data sources, and to enable research in weather and climate and development of user-specific advanced forecast products through *one-stop* data shopping.

BASC ASSESSMENT OF TRANSITION PROCESS

Based on the discussions and presentations at the summer study, BASC assessed the transition process for the environmental satellites using the template developed in Chapter 2.

A Strong Research Program

The research programs in support of the environmental satellites are strong and offer the operational community opportunities for improvement.

A Healthy Infrastructure

The NASA Operational Satellite Improvement Program (OSIP) was a very effective mechanism for developing new sensors, proving their capability, and handing them over to the operational agencies for implementation. The present NASA efforts, including the Instrument Incubator program and the New Millennium missions, address part of this process and are to be commended (NRC, 1999b). The NPP program offers a method for transferring some of the sensors from NASA to NPOESS. BASC also recognizes that programs such as NPOESS are not a solution to all climate and weather observational needs.

A strong research and exploratory program in advanced technologies and sensor development, recognizing modernization as a continuing requirement, has not been formulated.

Strong Interface with the User Community

There are deficiencies in the interface with the user community, particularly with respect to the data archival needs of the various users of the satellite data and products (NRC, 1998c, 1999b).

International Observation and Data Access Partnerships

BASC believes that an efficient, robust data archiving system is at the core of effectively linking research to operations, the generation of advanced forecast products, and continual data utilization for the public good. The size of the observational and forecast data archives presents a considerable challenge that has not yet been met. The recent track record of the U.S. environmental community has not been encouraging. For instance, the Earth Observing System Data and Information System (EOSDIS) has attempted to meet the archival needs of NASA's Mission to Planet Earth, but, despite large expenditures, has yet to prove its capability to fulfill that need. The NPOESS planning process has not yet addressed the need for archiving the resulting data, and there is little effort being devoted to the process of integrating in situ and satellite observations to create a more efficient observational system. NASA's Tropical Rainfall Measuring Mission (TRMM) satellite program, while a relatively modest effort, did an excellent job in planning for data archival and access and could serve as a model for future activities.

Continuous Evaluation Process

There is a limited capability within the present program to examine the impacts of the various sensors. Part of this is tied to the deficiency identified in Chapter 3 dealing with the lack of system infrastructure to run parallel operations to evaluate the impact of new sensors and forecasting techniques.

RECOMMENDATIONS FOR THE ENVIRONMENTAL SATELLITE PROGRAMS

Several NRC reports expressed considerable concern about the U.S. plans for NPOESS (NRC, 1998c, 1999b, 2000a). BASC members involved in these earlier assessments concluded that, based on the agency plans for the NPP presented at the study, the program is moving in the right direction to address many of these earlier concerns, including the acceptance of the climate monitoring mission by NOAA as evidenced in the NPP plans. BASC encourages the transition of research achievements into long-term environmental monitoring and applications. There is a growing need for an operational global climate and environmental monitoring system to meet the requirements for public safety and economic development. BASC encourages NOAA, NASA, and DOD to continue the strong cooperation required to ensure success in this effort. At the same time, the transition from research to operations cannot be viewed as simply a sensor or instrument transition.

1. *Replacement for the Operational Satellite Improvement Program (OSIP).*

RECOMMENDATION SATELLITE-1

NASA and NOAA should implement a replacement to the Operational Satellite Improvement Program (OSIP) having the following characteristics:

- A planned path for the transition of instruments from research to operations
- A commitment to algorithm development commensurate with hardware development
- Calibration and validation of derived geophysical parameters
- Close linkage to the development, testing, and integration facility at NOAA's EMC as recommended in Chapter 3

NPOESS will not satisfy the full spectrum of research or operational needs of the nation, particularly for the study of longer-term issues such as climate change, nor is it likely to generate an impetus for technologic innovation. Robust programs of technologic development, exploratory sensor development, and research missions at NASA are needed to enable a continuous push toward improved capability and innovative product development. In turn, a continuing process similar to the former OSIP can assess the state of research and operational technology and update NPOESS as needed to accomplish its national mission. This requires a more coordinated plan for research and technologic innovation that includes coherent budget and timing links for a transition to operations. The modernization of operational sensors should be a continuous process.

2. *Enable EMC to utilize new satellite observations in improving forecast capability.*

RECOMMENDATION SATELLITE-2

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 and 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.

The objective is to develop a timely feedback and advanced planning component of the NPOESS process that ensures a more rapid transition of new observations to operational use. Within NOAA, these efforts could be closely linked to the development, testing, and integration facility at NOAA's EMC that was recommended earlier in this report (see Chapter 3).

3. *Plan for archiving NPOESS data.*

RECOMMENDATION SATELLITE-3A

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.

Data are central to both the research and operation enterprise, and its availability is critical for advances in research and improvements in operations. For major studies of the atmosphere, upper air data are crucial. While radiosonde data are archived at a number of centers around the world in accordance with international agreements through the World Meteorological Organization, no such mechanism is in place for satellite data. There is little incentive for operational forecasters to keep satellite data either for climate studies or for advanced operational research. During the summer study, the Assistant Administrator for NESDIS acknowledged that archiving plans for NPOESS are insufficient. Early planning and assessment is essential and requires a very skilled working group whose members are collectively able to foresee how technology will advance over the next decade and how these advances might make this huge data archiving and accessibility task more tractable with the human and dollar resources available. The NPOESS program has set up a variety of review teams related to science, algorithm performance, etc. The team in Recommendation Satellite-2 can assist the NPOESS program in developing the archiving requirements for the NPOESS user communities.

RECOMMENDATION SATELLITE-3B

NASA and NOAA should evaluate the potential savings that would result from an interagency commitment to archive NPOESS satellite data through EOSDIS.

NASA's EOSDIS has demonstrated the complexities and costs associated with the development of an accessible data archive. Given that EOSDIS is currently the only data system with the potential to address the large-scale problems described here, careful assessment of EOSDIS suitability for NPOESS archival is appropriate. Additionally, NASA's Tropical Rainfall Measuring Mission (TRMM) satellite program, although much smaller than NPOESS, established an excellent archival program and could be studied for best practices.

4. *Integrating across observation networks.*

RECOMMENDATION SATELLITE-4

NOAA and NASA should begin to explore the potential of integrating in situ and satellite observation networks in support of both research and operational needs.

NPOESS has begun the process of convergence in national satellite systems, but the issues being addressed are equally applicable to the entire observational network. Similar integration is appropriate for in situ networks and for combined satellite-in situ measurement systems. This is a key issue that is likely to expand as the forecasting family expands to include atmospheric chemistry, health, and other variables. To facilitate the data assimilation process and therefore accelerate the transition of the use of disparate and complex data into operational forecasting, the first steps might focus on national and international sounding capabilities and the importance of developing a consistent, high-quality, long-term observational capability (NRC, 1998a).

5. *Continuity of measurements for climate studies.*

RECOMMENDATION SATELLITE-5

NASA and NOAA should work together to ensure that the continuity of critical climate and weather observations is maintained.

Several recent NRC reports have recommended that careful attention be paid to the climate observing system. *Global Environmental Change: Research Pathways for the Next Decade* (NRC, 1998c) specifically recommended that the spaced-based operational systems be developed to also meet the climate observing needs. *Adequacy of Climate Observing Systems* (NRC, 1999a) identified needs with the entire range of observing systems and identified several principles that should be implemented to ensure viable climate data for the future. BASC reiterates the recommendations of these and other NRC reports stressing the need for more effective planning and execution of the observing systems for climate and weather.

5

Concluding Remarks

Great demands are placed on the forecast capability of the United States because of the great variety of weather events that are experienced and the impacts of the major weather events on the nation's citizens and economy. In addition, there is growing public interest in better projections of climate variability and climate change and in expanding the forecast family to better serve the needs of our nation. As examples, better forecasts of air quality, health hazards, space weather, lightning, and water availability and quality are possible. The potential is enormous and the demand for new and diverse forecasting products will continue to grow. If the forecasting system can satisfy this demand, the result will be increased protection of human health and safety and improved economic benefit. However, BASC's assessment of U.S. efforts indicates that current demands stress the present resources and capability and that U.S. weather services are failing to take advantage of our nation's research accomplishments to improve operational forecasts. This deficiency is limiting realization of national benefits.

As recommended in *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998a), BASC reiterates the need for the establishment of a public discussion procedure involving the NWS users, the research community, and the private sector. Such a discussion should balance the push of science from the research community and the pull of national needs for new forecast products.

BASC recognizes the need for the private sector to have greater access to government facilities. Indeed, *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998a) recommended the close collaboration of the private sector, the public sector, and the academic community. BASC, in cooperation with the Federal Committee on Meteorological Services and Supporting Research, is maintaining an awareness of the issues and will address these roles with respect to climate at the planned 2000 summer study that deals with climate services.

RECOMMENDATION BALANCE-1

NOAA should adopt the philosophy in which new sensor development would incorporate plans for the inclusion of funds for the transition of the data into operational products at the appropriate stage of the development process.

There are numerous examples of the development of new technologies without concomitant improvements in operational products. The NEXRAD implementation is a case in point. NEXRAD data are used successfully for short-term severe weather prediction, but NEXRAD radar data assimilation algorithms have not been sufficiently developed and tested for input into EMC's operational NWP forecast models. Satellite sensors are a second case in point. If valuable, the assimilation of new observations should become part of the operational suite of measurements used in predictions. Agency managers at the summer study suggested that 10 percent of the cost of a new sensor should be budgeted for research and transition of the data into operational forecasts.

The path forward is obviously constrained by resource availability. BASC believes that at the present time many segments of the weather and climate community, including research and operations, could use more resources, but the transition from research investment to operational capability is especially critical to address. The operational environmental satellites operated by NOAA are critical to weather and climate prediction, yet no mechanism exists for effectively incorporating the benefits from the NASA research instruments into the operational systems. Almost all of the nation's operational weather and climate guidance products come from EMC, which does not presently possess the necessary resources to transfer many of the U.S. advances in observations and modeling to operations. Thus, there is a built-in inefficiency in which many of the advances that have had their funding justified through improved weather and climate forecasting cannot find their way into U.S. operations because of personnel and computational resource limitations at EMC. In fact, many of the U.S. research advances are incorporated into foreign products first. If this is allowed to continue, the United States will be at a competitive disadvantage in many areas, including private sector forecast services development and even national security.

RECOMMENDATION BALANCE-2

It is clearly preferable to add the necessary resources to EMC without negatively impacting the nation's weather and climate research enterprise. However, if that is not possible then BASC recommends that some of the nation's weather and climate research resources be shifted to EMC-related enterprises and the USWRP.

Finally, BASC recommends that NOAA study the balance of its efforts in weather and climate with the goal of establishing an organization that efficiently balances the task of performing research and transferring this research into operations.

This study should also take into account the research provided by other agencies, most notably NSF and NASA. Such agencies should also help in providing prototype capabilities to transform their research into the applications for which they were intended. Study of the balance between research and operations should occur continuously, otherwise, imbalances will quickly re-establish themselves.

References

Changnon, S. A., ed., 2000. *El Niño 1997–1998: The Climate Event of the Century*. New York: Oxford University Press.

Dorman, C., 1999. Technology Infusion Panel - Summary Report, Memorandum to Jack Kelly, 15 March, 1999, National Weather Service, Silver Spring, Maryland.

Emanuel, K., and E. Kalnay, 1996. Observations In Aid Of Numerical Weather Prediction For North America Report Of The Prospectus Development Team #7, U.S. Weather Research Program Office, National Center for Atmospheric Research, Boulder Colorado. {Available at http://uswrp.mmm.ucar.edu/uswrp/PDT/PDT7.html}

ECMWF (European Center for Medium Range Forecasting), 1999. The Scientific and Technical Foundation of the ECMWF Strategy, 1999–2008. ECMWF, Reading, United Kingdom, 36 p.

Fleming, J. R., ed., 1996. *Historical Essays on Meteorology, 1919–1995*. Boston: American Meteorological Society.

Kalnay, E., S. J. Lord, and R. McPherson, 1998. Maturity of Operational Numerical Weather Prediction: Medium Range. *Bull. Amer. Meteor Soc.* 79:2753-2769.

Keener, R., 1997. Impacts of weather and potential use and value of improved forecasts for one electric power utility. In: Societal Aspects of Weather: Report of the Sixth Prospectus Development Team of the U.S. Weather Research Program to NOAA and NSF, p. 869. *Bull. Amer. Meteor. Soc.* 78:867-876 .

Lord, S., 1999. The Environmental Modeling Center, Present Status and Future Plans, a presentation to the BASC summer study, National Centers for Environmental Prediction, Camp Springs, Maryland.

NRC (National Research Council), 1998a. *The Atmospheric Sciences Entering the Twenty-First Century*. Washington, D.C.: National Academy Press.

NRC, 1998b. *Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities*. Washington, D.C.: National Academy Press.

NRC, 1998c. *Global Environmental Change: Research Pathways for the Next Decade*. Washington, D.C.: National Academy Press.

NRC, 1999a. *Adequacy of Climate Observing Systems*. Washington, D.C.: National Academy Press.

NRC, 1999b. *Assessment of NASA's Plans for Post-2002 Earth Observing Missions*. Washington, D.C.: National Academy Press.

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

NRC, 1999d. *Enhancing Access to NEXRAD Data, A Critical National Resource* Washington, D.C.: National Academy Press.

NRC, 2000a. *Issues in the Integration of Research and Operational Satellite Systems*. Washington, D.C.: National Academy Press.

NRC, 2000b. *Assessment of the Current Status of the U.S. Weather Research Program*. Washington, D.C.: National Academy Press.

NWS (National Weather Service), 1994. Thunderstorms and Lightning, the Underrated Killers! A Preparedness Guide. U.S. Department Of Commerce, National Oceanic and Atmospheric Administration National Weather Service. Washington, D.C.

OFCM (Office of the Federal Coordinator for Meteorology), 1998. *The Federal Plan for Meteorological Services and Supporting Research for Fiscal Year 1999*. FCM-P1-1998. Washington, D.C. (OFCM).

Pielke, Jr., R. A., and J. Kimpel, 1997. Societal Aspects of Weather, Report of the Sixth Prospectus Development Team of the U.S. Weather Research Program to NOAA and NSF. *Bull. Amer. Meteor. Soc.* 78:867-876 .

Pielke, Jr., R. A., and R. Byerly, Jr., 1998. Beyond Basic and Applied. *Physics Today*, February 1998, pp. 42-46 .

Pielke, Jr., R. A., 1999. Floyd, the fire drill. Web site editorial in *WeatherZine,* Edition 8, October, at: {http://www.esig.ucar.edu/socasp/zine/18/editorial.html}

Reed, D. A., P. Woodward, T. Dunning, L. Johnsson, M. Simmons, G. Karniadakis, R. Hirsh, and C. Leith, Jr.. 1999. Report of the National Center for Atmospheric Research Code Assessment Panel, National Science Foundation, Washington, D.C., 12 p.

USGCRP, 1999. Our Changing Planet, the FY2000 U.S. Global Change Research Program. A Supplement to the President's Fiscal Year 2000 Budget. U.S. Global Change Research Program Office, Washington, D.C., 100 p .

Withee, G. 1999. NPOESS Transition Issues, a presentation to the BASC Summer Study, National Environmental Satellite, Data, and Information Service, Silver Spring, Maryland.

Acronyms and Abbreviations

BASC	Board on Atmospheric Sciences and Climate
CCM	community climate model
DOD	Department of Defense
ECMWF	European Center for Medium Range Forecasting
EMC	Environmental Modeling Center
EOS	Earth Observing System (NASA)
EOSDIS	EOS Data and Information System
ESE	Earth Sciences Enterprise
FASTEX	Fronts and Atlantic Storm-Track Experiment
FSL	Forecast Systems Laboratory
GCIP	GEWEX Continental-scale International Project
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GOES	Geostationary Operational Environmental Satellite
MFLOPS	millions of floating point operations per second
NASA	National Aeronautics and Space Administration

NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NESDIS	National Environmental Satellite, Data and Information Service (NOAA)
NEXRAD	Next-Generation Weather Radar systems
NOAA	National Oceanic and Atmospheric Administration
NORPEX	North Pacific Experiment
NPOESS	National Polar-Orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Program
NRC	National Research Council
NSF	National Science Foundation
NWP	Numerical Weather Prediction
NWS	National Weather Service
ONR	Office of Naval Research
OSIP	Operational Satellite Improvement Program
OSSE	Observing System Simulation Experiment
R&D	research and development
TOPEX/ POSEIDON	Ocean Surface Topography Experiment (Joint U.S. France research program)
TRMM	Tropical Rainfall Measuring Mission (NASA)
UKMO	United Kingdom Met. Office
USGCRP	U.S. Global Change Research Program
USWRP	U.S. Weather Research Program

Board Members' Biographies

Eric J. Barron (*Co-chair*) is Director of the EMS Environment Institute and Distinguished Professor of Geosciences at Pennsylvania State University. He received his Ph.D. in geophysics from the University of Miami. His professional experience encompasses fellow and scientist at the National Center for Atmospheric Research, associate professor of marine geology and geophysics at the University of Miami, and director of the Earth System Science Center at Penn State. His specialty is paleoclimatology/ paleoceanography. His research emphasizes global change, specifically numerical models of the climate system and the study of climate change throughout Earth history. Dr. Barron is a fellow of the American Geophysical Union and the American Meteorological Society.

James R. Mahoney (*Co-chair*) is the principal of Mahoney Environmental Consultants in McLean, Virginia. He received his Ph.D. in meteorology from the Massachusetts Institute of Technology. He has served on the faculty at Harvard University School of Public Health and as senior vice president of the I T Group, Inc., co-founder and senior vice president of Environmental Research and Technology, Inc., and manager of the Environmental Services Group at the Bechtel Group, Inc. Dr. Mahoney was also director of the National Acid Precipitation Assessment Program (1988-1990), coordinating the completion and reporting of the 10-year $550 million federal research and assessment program, and was awarded the Gold Medal for his accomplishments by the Secretary of Commerce. He served as president of the American Meteorological Society from 1990-1991.

Susan K. Avery is Director of the Cooperative Institute for Research in Environmental Sciences and Professor of Electrical and Computer Engineering at the University of Colorado, Boulder. She received her Ph.D. in atmospheric science from the University of Illinois. She has served on the faculty in the Department of Electrical Engineering, University of Illinois, and as associate dean of research and graduate education, College of Engineering, University of Colorado. Her specialty is atmospheric dynamics; her fields of research are wave dynamics, including the coupling of atmospheric regions and interactions between scales of motion, precipitation studies using ground-based radar; and the use of ground-based Doppler radar techniques for observing the neutral atmosphere. Dr. Avery is a fellow of the American Meteorological Society and the Institute of Electrical and Electronics Engineers, as well as a member of the American Geophysical Union. She is the past chair of the United States Committee to the International Union of Radio Science and a past officer of the University Corporation for Atmospheric Research.

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

Lance F. Bosart is a professor in the Department of Earth and Atmospheric Sciences at the University at Albany/State University of New York, where he has served since 1969. He received his Ph.D. in meteorology from the Massachusetts Institute of Technology. His research specialty is synoptic-dynamic meteorology. He works on a variety of observational problems in the tropics and middle latitudes from the large scale to the mesoscale and on operationally oriented research problems through cooperative research projects with staff members of the National Weather Service under the auspices of the Cooperative Meteorology Education and Training (COMET) program. Dr. Bosart is a member of the American Meteorological Society (AMS) and the Royal Meteorological Society. He was the recipient of the Jule Charney award (AMS). He is a past editor of the journal *Monthly Weather Review* and presently an associate editor of the journal *Weather and Forecasting*. Currently he holds an affiliate scientist appointment at the National Center for Atmospheric Research.

Steven F. Clifford is director of the Environmental Technology Laboratory (NOAA). He received his Ph.D. in engineering science from Dartmouth College. One of his research goals is to develop a global observing system using ground-based, airborne, and satellite remote sensing systems to better observe and monitor the global environment and use these observations as input to global air-sea circulation models for improving forecasts of weather and climate change. Dr. Clifford is a member of the National Academy of Engineering. He is also a fellow of the Optical and Acoustical Societies of America, a senior member of the Institute of Electrical and Electronics Engineers, and a member of the American Physical Society, the American Geophysical Union, and the American Meteorological Society. He was the recipient of the 1998 Meritorious Presidential Rank Award.

George L. Frederick is Business Development Manager, Meteorological Systems and Services, Radian Electronic Systems, and Principal Scientist/ Senior Project Manager, Radian International LLC. He received his M.S. in meteorology from the University of Wisconsin, Madison. Mr. Frederick is responsible for managing atmospheric projects which include design, installation, and data processing of atmospheric measurement systems employing both in-situ and remote sensing techniques. He is working with government, state, and private industry to better employ remote sensing technology for the enhanced monitoring of atmospheric pollutants. Mr. Frederick is a fellow and past president (1999-2000) of the American Meteorological Society.

Marvin Geller is a Professor of Atmospheric Science and the Dean and Director of Stony Brook's Marine Sciences Research Center (State University of New York). He received his Ph.D. from the Massachusetts Institute of Technology. Dr. Geller is a well-known researcher in atmospheric dynamics and serves on several important national and international committees. He is co-chair of the World Climate Research Programme's SPARC (Stratospheric Processes and Their Role in Climate) project, president of the American Geophysical Union's Atmospheric Sciences section, chair-elect of NASULGC's Board on the Oceans and Atmosphere, president of ICSU's SCOSTEP (Scientific Committee on Solar-Terrestrial Physics), and a fellow of the American Meteorological Society. He has also served on and chaired several NRC panels and committees, including the BASC Committee on Solar-Terrestrial Research.

Charles E. Kolb is President and Chief Executive Officer of Aerodyne Research, Inc. He received his Ph.D. in physical chemistry from Princeton University and joined Aerodyne as a senior research scientist in 1971. His research interests have included atmospheric and environmental chemistry, combustion chemistry, materials science, and the chemistry and physics of rocket and aircraft exhaust plumes. Dr. Kolb is a fellow of the American Physical Society, the Optical Society of America, and the American Geophysical Union, where he served as the atmospheric sciences editor of *Geophysics Research Letters* (1996-1999). He is also a member of the American Association for the Advancement of Science and the American Chemical Society, which honored him with its Award for Creative Advances in Environmental Science and Technology in 1997. He has served on a number of NRC committees, including the BASC Committee on Atmospheric Chemistry.

Judith L. Lean is a research physicist at the Naval Research Laboratory. She received her Ph.D. in Atmospheric Physics from the University of Adelaide, Australia. She specializes in the study of the variability of solar radiation. The focus of her current research is the mechanisms, models, and measurements of variation in the sun's radiative output, and the effects of this variability on the earth's global climate and space weather. Dr. Lean is a member of the American Geophysical Union and the American Meteorological Society.

Roger A. Pielke, Jr. is a scientist at the Environmental and Societal Impacts Group at the National Center for Atmospheric Research in Boulder, Colorado. With a B.A. in mathematics and a Ph.D. in political science from the University of Colorado, he focuses his research on the relation of scientific information and public and private sector decision making. His current areas of research are societal responses to extreme weather events, domestic and international policy responses to climate change, and United States science policy. In 2000, he received the Sigma Xi Distinguished Lectureship Award. He currently chairs the American Meteorological Society's Committee on Societal Impacts and serves on the Science Steering Committee of the World Meteorological Organization's World Weather Research Programme among other advisory committees. He is a co-author or co-editor of three books, most recently (with D. Sarewitz and R. Byerly) *Prediction: Decision making and the future of nature* (2000).

Michael J. Prather is a professor in the Earth System Science Department at the University of California, Irvine. He received his Ph.D. in astronomy from Yale University. His research interests include the simulation of the physical, chemical, and biological processes that determine atmospheric composition, specifically ozone and other trace gases. Dr. Prather has authored chapters in the World Meteorological Organization's Ozone Assessments (1985-1994) and the IPCC's assessments of climate and aviation effects (1995-2000). He is a fellow of the American Geophysical Union and a foreign member of the Norwegian Academy, and has served on several NRC committees, including the BASC Panel on Climate Variability on Decade-to-Century Time Scales.

Robert T. Ryan is Chief Meteorologist at WRC-TV (NBC 4) in Washington, D.C. He received his Masters in atmospheric sciences from the State University of New York, Albany. Prior to his career in broadcasting, he was a research associate in the Physics Section at Arthur D. Little, where his work involved various cloud physics projects with the Department of Defense. He was also involved in various meteorological field experiments for NASA and the U.S. Army. Mr. Ryan is nationally and internationally recognized for his outreach and educational activities in meteorology and atmospheric sciences. He was the first broadcast meteorologist elected to serve as president of the American Meteorological Society (AMS). He has also served the AMS as Councilor, Commissioner of Professional Affairs, and Chairman of the Board of

Broadcast Meteorology. In 1997, Mr. Ryan received the Charles Franklin Brooks Award for service to the Society. He has also served on various AMS, NASA, and NOAA study groups, testified a number of times before Congress, and is the winner of nine Emmy awards for his television productions and service to the community. He is a fellow of the AMS and a member of the American Association for the Advancement of Science.

Mark R. Schoeberl is a senior atmospheric scientist at NASA's Goddard Space Flight Center. He received his Ph.D. in physics from the University of Illinois. He has also served as a scientist at Science Applications, Inc., and at the Naval Research Laboratory. His fields of research include atmospheric dynamics, stratospheric physics and chemistry, and numerical modeling. He is the EOS-Aura Project Scientist. Dr. Schoeberl has received many NASA awards, including the Group Achievement Award in 1988, 1989, 1991, 1994, 1995, and 1998, and the Education and Outreach Award in 1999. In addition he was awarded the Scientific Achievement Medal in 1991, the Distinguished Service Medal in 2000, and the William Nordberg Award for Earth Sciences in 1998. He is a fellow of the American Geophysical Union (AGU) and the past president of the AGU's Atmospheric Sciences section. He is also a fellow of the American Association for the Advancement of Science and the American Meteorological Society.

Joanne Simpson is Chief Scientist for Meteorology and Senior Fellow at NASA's Goddard Space Flight Center. She received her Ph.D. from the University of Chicago and an honorary D.Sc. from the State University of New York, Albany. She has served on the faculty at the University of California, Los Angeles, and at the University of Virginia. She was also head of the atmospheric physics and chemistry laboratory at ESSA, director of NOAA's Experimental Laboratory, and head of the severe storms branch at NASA Goddard. Her areas of research include atmospheric convection, tropical meteorology, weather modification, and satellite meteorology. Dr. Simpson was elected to the National Academy of Engineering in 1988. She is a fellow and honorary member of the American Meteorological Society (AMS). She has received many awards, including the Charles Franklin Brooks Award and the Meisinger Award from the AMS, the Rossby Research Medal, the Silver and Gold Medals from the Department of Commerce, and NASA's Exceptional Scientific Achievement Medal and William Nordberg Award. She has served on several NRC committees and is currently a member of the BASC Committee on Climate, Ecosystems, Infectious Diseases, and Human Health.

Nien Dak Sze is Chairman and Founder of Atmospheric and Environmental Research, Inc. (AER), in Cambridge, Massachusetts. Dr. Sze received his doctorate from Harvard University. He is one of the original developers of 1- and 2-D stratospheric models that simulated ozone depletions and enabled industry/government to assess the environmental acceptability of alternative CFCs. Dr. Sze predicted the increase in global methane concentration in the mid 1970s before its upward trend was observed. He was among the few theorists who participated in the Airborne Antarctic Ozone Experiment (AAOE) that provided the unprecedented data set relating the Antarctic Ozone Hole to CFCs emissions. Dr. Sze has served as a panel member of the U.S. EPA's Science Advisory Board. He has also served on a panel of the National Academy of Sciences Committee for Scholarly Communication with the People's Republic of China. Other recent appointments include membership on the Harvard University Committee on Environment and the Central Policy Unit of the Government of Hong Kong. He has received three NASA Group Achievement Awards.

Thomas F. Tascione is Vice President, Weather Systems Operations, Sterling Software (U.S.), Inc. In this position he oversees the development of a state-of-the-art weather forecasting technology for the Defense Department. In addition, he manages a commercial space weather forecasting service to support the commercial satellite and electric power industries. Another focus area is advanced weather visualization technology for aviation including a patented system to extract and apply weather information along a route a flight using a simple web-browser. His prior professional experience was with the Department of Defense (1972-1993), during which he held numerous weather and space weather forecasting positions. He was the architect of the Air Force space weather forecast models program, and he co-chaired the interagency committee that initiated and developed the National Space Weather Program (NSWP). Dr. Tascione received his Ph.D. in space physics from Rice University.

Robert A. Weller is a Senior Scientist at Woods Hole Oceanographic Institution, where he holds the Secretary of the Navy/CNO Chair in

Oceanography and is Director of the Cooperative Institute for Climate and Ocean Research. He received his Ph.D. in Physical Oceanography from the University of California, San Diego, Scripps Institution of Oceanography. 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. Dr. Weller received the James B. Macelwane Award from the American Geophysical Union (AGU) in 1986. He is a fellow of the AGU and president of the Ocean Sciences section. He is also a member of the American Association for the Advancement of Science, the American Meteorological Society, and the Oceanographic Society.

Eric F. Wood is Professor of Civil and Environmental Engineering at Princeton University, where he has taught since 1976. He received his Sc.D. in civil engineering from the Massachusetts Institute of Technology. His areas of research include hydroclimatology with an emphasis on land-atmospheric interaction, hydrological remote sensing, modeling the terrestrial water and energy budgets over a range of scales and hydrologic impact of climate change. Dr. Wood is a member of the NRC Board on Water Science and Technology and the BASC Climate Research Committee. He is a member of the Council and a fellow of the American Meteorological Society (AMS) and a fellow of the American Geophysical Union (AGU). He has received the AGU Robert E. Horton Award, the AMS Horton Lectureship, and the Princeton Rheinstein Award.

Appendix A

Summer Study Background

The origin of the summer study was a discussion of the issues in atmospheric sciences at the fall 1998 BASC meeting. The NASA representative at the meeting, while describing the program development in the Earth Sciences Directorate, noted that a major problem as he saw it was the lack of capability to hand over to the operational community (NOAA) the capabilities that were developed in the Earth Observing System program. He noted that sensors were developed without regard of the future operational possibility and that the operational NOAA program frequently developed sensors with characteristics almost identical to those in the NASA EOS program. He highlighted this as an area that presented an opportunity for more rapid and cost effective advances if cooperation between the two agencies could be improved.

At the same meeting the NOAA representative identified the apparent mismatch between the research opportunities that were being developed in the NOAA laboratories and the universities and the ability of the operational systems within the National Weather Service (NWS) to incorporate the new science and technology. This was particularly disturbing to the agency representatives and the BASC members because much of this research was being accomplished in response to the NWS stated needs for improvement in various areas. There was some discussion of the reasons for this disconnect, but the discussion at the BASC meeting was not detailed enough to clarify the issues or identify areas of potential improvement. The NOAA representative subsequently identified to BASC the study that had been chartered by NOAA to examine the needs and opportunities for technology infusion in the NWS. This study, led by RAdm (U.S. Navy, Ret.) Craig Dorman, was provided to BASC as input into the summer study. BASC was considering the necessary follow up to the major review of the field, *The Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998a). Twenty potential areas from the report were under consideration for greater study by the BASC, but because of the importance of the issues raised by the NASA and NOAA liaisons to the board, the BASC accepted the topic of transition from research to operations in the weather satellites and numerical weather prediction for the 1999 summer study.

Discussions with NOAA and NASA liaisons to BASC developed the plan for the BASC summer study that would address the technology transfer issues that were identified at the BASC meeting. The agencies requested a focused study concentrating on the areas they felt presented the greatest problems. NASA representatives requested a look at the mechanisms for transition of research satellite sensors to operational systems. NOAA representatives were interested in concentration on the capability of the NWS's National Centers for Environmental Prediction (NCEP), and specifically on the NCEP's Environmental Modeling Center (EMC) to implement the research results into operational numerical weather prediction within the NWS.

At its spring 1999 meeting BASC discussed the summer study with the agency representatives and developed the following statement of task:

STATEMENT OF TASK

The BASC will convene a summer study in a workshop format to explore issues related to the transition from research and development to operations in the area of weather prediction. Two case studies will form the nucleus of the effort:

1. The plans being developed by NOAA's NCEP to incorporate recent advances in atmospheric science research into the next generation of numerical weather prediction models.

2. The NPOESS Preparatory Program that will be used to transition the satellite sensors developed by NASA into operational capabilities on the NOAA operational weather satellites. Of particular interest are how sensor data are to be used operationally and how such data will be made available to the operational and research communities.

The board will summarize these plans, analyze their strengths and weaknesses, including any major barriers to their successful implementation, and recommend improvements.

The summer study did not address any potential reorganization of the weather forecasting activities in the nation.

Even though NOAA and NASA were the major agencies involved, the NSF also played a very important role in the preparation and in the study itself. BASC approved the plan and the agencies began to provide the material that would serve as the review material. To facilitate the summer study, BASC reviewed all relevant materials prior to the meeting.

The study was conducted at the Jonsson Center in Woods Hole, Massachusetts, from June 28 through July 2, 1999. In addition to the BASC members, the following also participated:

- Thomas Cuff, Deputy Technical Director, Office of the Oceanographer of the Navy
- Geoff DeMego, NOAA/NCEP
- Richard Greenfield, Director, Division of Atmospheric Sciences, NSF (presently Director, Atmospheric Public Policy Program, American Meteorological Society)
- Jamison Hawkins, Requirements Division, NOAA/NESDIS
- William Hooke, Director, U.S. Weather Research Program Office, NOAA/OAR
- Eugenia Kalnay, Commission on Geosciences, Environment, and Resources liaison to BASC, University of Oklahoma (presently Chair, Atmospheric Sciences, University of Maryland)
- Jack Kelly, Director, National Weather Service, NOAA

- Stephen Lord, Acting Director, Environmental Modeling Center, NOAA/NCEP
- Alexander (Sandy) McDonald, Director, Forecast Systems Laboratory, NOAA
- Craig Nelson, NPOESS Integrated Program Office, NOAA
- Cynthia Nelson, Office of the Federal Coordinator for Meteorological Services and Supporting Research, NOAA
- Richard Rood, Office of Data Assimilation, Goddard Space Flight Center, NASA
- Edward Sarachik, University of Washington
- Robert Schiffer, Office of Earth Sciences, NASA
- Louis Uccellini, Director, National Centers for Environmental Prediction, NOAA/NWS
- Greg Withee, Assistant Administrator for Satellite and Information Services, NOAA/NESDIS

AGENDA FOR THE 1999 BASC SUMMER STUDY

Note: Specific time allotments were not assigned to topics or presenters in order to facilitate the discussion and allow sufficient time for each topic.

The first day covered the overview of the EMC and satellite situations and gave BASC the opportunity to examine the major issues with senior management from NWS, NESDIS, and NASA. Subsequent sessions examined the details of the two areas and sought to clarify what the major factors were that impeded the transition from research to operations. All sessions were open to all participants except the last day when BASC developed the draft report outline and identified writing assignments. All issues to be addressed in the report were discussed fully in the open sessions to ensure that the agency information had been properly understood and to permit the BASC members to question the agency representatives in detail.

Monday, June 28 OPEN SESSION

- Welcome and Introductions (Barron and Mahoney)

- Logistics for the meeting (Friday and Gustafson)
- Scope of the study (Barron, Mahoney)
- Context of the national needs and priorities for weather and climate forecasting, including *The Atmospheric Sciences Entering the Twenty-First Century*(Barron, Pielke, Ryan)
- Strategic objectives of NOAA/NWS/NCEP for meeting the needs.
  NWS Perspective (Kelly)
  OAR Perspective (Macdonald)
  NCEP Perspective (Uccellini)
- Discussion of current environment at NCEP. The discussion should include the barriers to moving forward to meet the needs of the various users.
  A view from Lance Bosart (Presented by Barron/Mahoney)
  A view from Joanne Simpson (Presented by Barron/Mahoney)
  (Bosart and Simpson could not attend but provided comments in advance.)
  Identification of issues (NCEP)
  A view from the laboratory perspective (MacDonald)
  A view from someone who has been there (Kalnay)
- A look at other centers:
  Comparison of the U.S. centers (Cynthia Nelson)
  A Look at the Navy (Cuff)
  A Look at the ECMWF (Discussion of a paper by Tony Hollingsworth)

Tuesday, June 28 OPEN SESSION

- NCEP plans for the future (Lord)
- Resource plans for NOAA with respect to computational capability (MacDonald)

- Issues in supercomputing (Rood)
- Research plans to meet the demands for the need for improved weather and climate forecasts (MacDonald)
- The ECMWF Model. What could work in the U.S.? What could not? Do we need to move in that direction? (Discussion of a paper by Tony Hollingsworth)

Wednesday, June 30 OPEN SESSION

- Satellite transition discussions:

  Current NASA Earth Science Enterprise (ESE) plans, the ESE planning process, and NASA research to operations transition issues (Schiffer)

  Principles and issues being developed in response to the Goldin and Baker letters (Schiffer)

  NRC review of the NASA Post 2002 study, NASA's response to the report and issues still remaining (Geller, Barron, Sarachik, Schiffer)

  Progress of the BSD, BASC, and CGCR Chairs' review of the EOS - NPOESS transition issues (Barron)

  NOAA NPP program: Plans, mechanisms for infusing research requirements, and methods of balancing the demand pull and technology push (Withee)

  NOAA readiness for ‘shepherding' the “EOS” type data (Withee, Kelly, NCEP)

  NCEP capabilities for exploitation of new satellite data (NCEP)

Thursday, July 1 OPEN SESSION

This will be an open discussion during which the issues that have been presented during the previous days will be discussed and crystallized. This will be an opportunity for clarification of the material presented and BASC's understanding of the material and issues.

Friday, July 2 CLOSED SESSION

Report Preparation: Discussion of conclusions and recommendations, development of annotated outline, and identification of writing assignments.

Appendix B

National Weather Service Organization

(Source, NWS)

GENERAL DESCRIPTION

The NWS is composed of a headquarters, regional offices, and national centers with field offices for meteorological and hydrological services. The NWS mission is supported through the activities of the organization on a 24 hour a day 7 day a week basis at the field offices under the leadership of the regional offices. There are six regional offices. They are Alaskan Region (Anchorage) with 4 forecast offices, Pacific Region (Honolulu) with 2 forecast offices, Western Region (Salt Lake City) with 24 forecast offices, Central Region (Kansas City) with 37 forecast offices, Southern Region (Fort Worth) with 31 forecast offices, and Eastern Region (Bohemia) with 23 forecast offices.

There are 13 River Forecast Offices located around the United States with one located in Alaskan Region, two in Central Region, three in Eastern Region, four in Southern Region, and three located in Western Region. Products are provided in the form of alphanumeric observations, forecasts, warnings, advisories, outlooks (covering their geographical areas of responsibility), and graphical products of various types.

The National Centers for Environmental Prediction

The National Centers for Environmental Prediction (NCEP) was established in 1958 as the National Meteorological Center. Since the center's beginning, operational weather forecasting has transformed from an infant discipline into a mature science.

NCEP is comprised of nine specialized centers for analyzing and forecasting the atmosphere on a global scale with some geographically separated centers having a specialized service focus on portions of the overall national warning and forecasting process.

1. Aviation Weather Center (AWC), Kansas City, Missouri. The AWC has the responsibility of providing aviation weather warnings and forecasts for all domestic air routes and those areas of the globe for which the United States has international responsibility.
2. Climate Prediction Center (CPC), Washington D.C. area. The CPC is responsible for the seasonal to interannual climate forecasts for the United States and well as general climate diagnostic and outlook information.
3. Environmental Modeling Center (EMC), Washington, D.C. area. The EMC has the responsibility to develop, enhance and maintain numerical forecast systems in support of national and international forecast requirements. This report concentrates in large part on the activities of this center. It develops the models and provides the quality control and verification of them.
4. Hydrometeorological Prediction Center (HPC), Washington, D.C. area. HPC produces the guidance forecast products of sensible weather and precipitation for use throughout the field office structure of the NWS. The products are also used extensively by the private sector and broadcast meteorologists.
5. NCEP Central Operations, Washington, D.C. area. Central Operations are responsible for the operation of the computer and communications equipment used by NCEP centers. Central Operations is not responsible for the applications that are run on the systems.
6. Marine Prediction Center (MPC), Washington, D.C. area. The MPC produces the marine weather forecast and real time oceanographic products to meet the national and international requirements.
7. Space Environment Center (SEC), Boulder, Colorado. The SEC monitors solar activity and produces forecasts of space weather that may affect satellite, power, and communications systems.
8. Storm Prediction Center (SPC), Norman, Oklahoma. The SPC is responsible for the nationwide severe storm forecasting program. It produces outlooks for convective activity and issues watches for severe weather events, except hurricanes.

9. Tropical Prediction Center (TPC), Miami, Florida. The TPC, formerly known as the National Hurricane Center, is responsible for tropical weather forecasts that satisfy the United States' international obligations, as well as the warnings and forecasts for tropical storms and hurricanes in the Atlantic and the Eastern Pacific.

Each center has a specific responsibility for a portion of the NCEP products and services suite, yet they all work together toward the common goals of saving lives, protecting property, and creating economic opportunity. Seven of the centers provide direct products to users, while two of the centers provide essential support through developing and running complex computer models of the atmosphere.

Weather Service field offices, other government agencies, and private meteorological services rely on NCEP's products. Many of the forecasts that reach the public via media outlets originate at NCEP. In addition to weather, NCEP meteorologists prepare seasonal forecasts that extend out to a year in advance.

Further details regarding NCEP can be found at:
<http://www.ncep.noaa.gov/>.

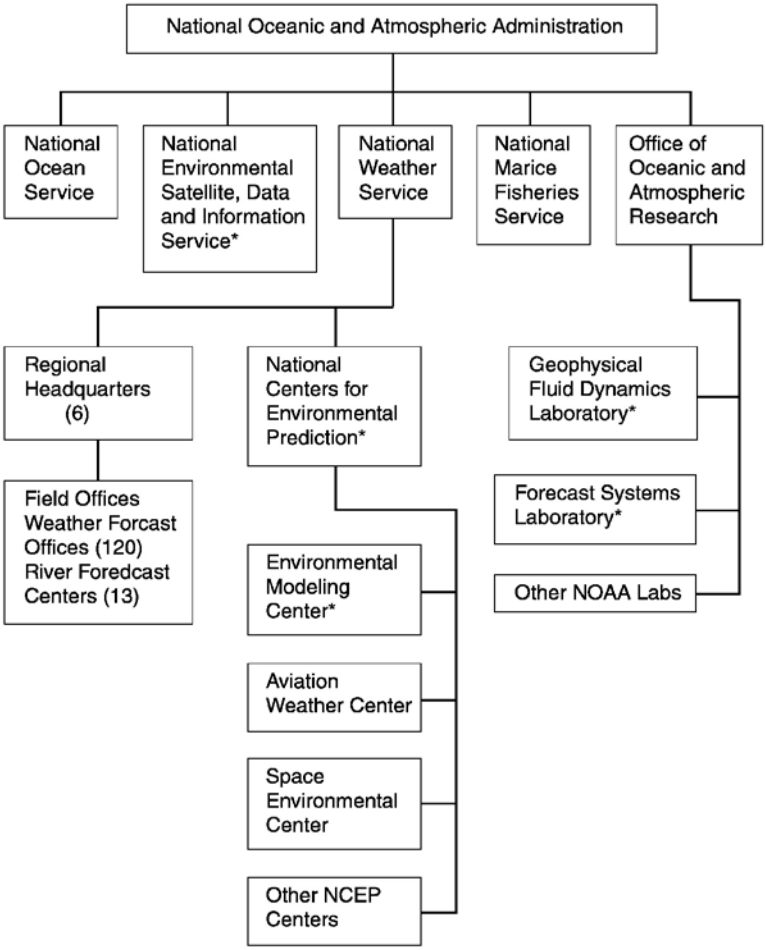

Figure B.1. Organizational structure of NOAA. An “*” indicates those organizations that are discussed in this report.