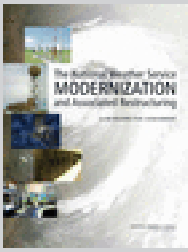

# The National Weather Service Modernization and Associated Restructuring: A Retrospective Assessment

ISBN
978-0-309-21798-9

140 pages
8 1/2 x 11
PAPERBACK (2011)

Committee on the Assessment of the National Weather Serviceâ€™s Modernization Program; National Research Council of the National Academies

# The National Weather Service MODERNIZATION and Associated Restructuring

## A RETROSPECTIVE ASSESSMENT

Committee on the Assessment of the
National Weather Service's Modernization Program

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

NATIONAL RESEARCH COUNCIL
*OF THE NATIONAL ACADEMIES*

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

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

This study was supported by the National Oceanic and Atmospheric Administration under contract number DG133R08CQ0062, Task Order #8. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the sponsor or any of its sub agencies.

International Standard Book Number-13: 978-0-309-21798-9
International Standard Book Number-10: 0-309-21798-9

Copies of this report are available from the program office:
Board on Atmospheric Sciences and Climate
500 Fifth Street, N.W.
Washington, DC 20001
(202) 334-3512

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



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# Preface

The Modernization and Associated Restructuring (MAR) of the National Weather Service (NWS) was a large and complex reengineering of a federal agency. The process lasted a decade and cost an estimated $4.5 billion. The result was greater integration of science into weather service activities and improved outreach and coordination with users of weather information. It was responsible for a marked increase in the accuracy and timeliness of forecast and warning services provided to the nation by the NWS. The modernized NWS was achieved through the development and deployment of new observational and computational systems and redefining the NWS field office structure to best utilize the investment in the new technologies.

The MAR was both necessary and generally well executed. However, it required revolutionary, often difficult, changes. The procurement of large, complex technical systems presented challenges in and of itself. The MAR also affected the career paths and personal lives of a large portion of the field office workforce. The MAR created a new, modernized NWS, and, significantly, it created a framework that will allow the NWS to keep up with technological changes in a more evolutionary manner. In addition to this new framework, the MAR also resulted in many "Lessons Learned" for the NWS. It is our hope that the NWS will apply the lessons we have identified in this report as they map their future direction.

This report contains the first part of the committee's work, a retrospective assessment of the MAR with a focus on lessons learned from the effort to plan, deploy, and oversee the MAR. The second phase of our work will apply the lessons learned from the MAR to advise NWS on how best to plan, deploy, and oversee future improvements, and will be presented in a second report.

This congressionally requested report presents the first comprehensive assessment of the execution of the MAR and its impact on the provision of weather services in the United States. This assessment would not have been possible without the assistance of many of our colleagues in the weather enterprise. The committee would like to acknowledge the many individuals who briefed us, provided written information, or other technical information. They include Carl Bjerkaas, Gary Carter, Valery Dagostaro, Joe Facundo, George Frederick, Joe Friday, Mary Glackin, Richard Hallgren, Jack Hayes, Rick Heuwinkel, Richard Hirn, Fiona Horsfall, Jack Kelly, Chuck Kluepfel, Ken Kraus, Sandy MacDonald, Lauren Marone, Frank Misciasci, Joel Myers, Vickie Nadolski, Tim Owen, Maria Pirone, Bill Proenza, Barry Reichenbaugh, Buddy Ritchie, Jae-Kyung Schemm, Bob Serafin, John Sokich, Margaret Spring, Louis Uccellini, Rich Vogt, Glenn White, and Doug Young.

The committee is particularly grateful to the NWS staff who hosted committee member Weather Forecast Office (WFO) site visits. They include Pat Baye, Eric Boldt, Dave Carpenter, Brad Coleman, Glenn Field, Michael Foster, Bob Glancy, Gene Hafele, Robert Hopkins, Mark Jackson, Jayme Laber, Jim Lee, Harold Opitz, Robin Radlein, David Reynolds, Nezette Rydell, Glen Sampson, Susan Sanders, Pablo

Santos, Robert Thompson, Steve Todd, David Vallee, and Steve Zubrick.

We would also like to acknowledge the NWS staff who assisted with our survey of WFOs collocated with academic or other research institutions. They include Peter Ahnert, Jonathan Blaes, Bruce Budd, Dave Carpenter, Tony Hall, Ray O'Keefe, Rhett Milne, David Reynolds, Nezette Rydell, Glen Sampson, Dennis Staley, Ray Tanabe, and Mark Tew.

Our sincerest thanks are extended to Edward Johnson and John Sokich for providing information and helping with access to NWS staff and facilities. The committee is greatly indebted to Study Director Maggie Walser and to Senior Program Assistant Ricardo Payne for their expert support.

John A. Armstrong, *Chair*
Committee on the Assessment of
the National Weather Service's
Modernization Program

# Acknowledgments

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

- Leo Andreoli, Retired, Northrop Grumman Aerospace Corporation, Torrance, California
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- William Hooke, American Meteorological Society, Washington, DC
- Roger Pielke Sr., Colorado State University, Fort Collins
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- Robert Serafin, National Center for Atmospheric Research, Boulder, Colorado
- George Smith, Riverside Technology, Inc., Moneta, Virginia
- Warren Washington, National Center for Atmospheric Research, Boulder, Colorado
- Joseph Yura, Retired, University of Texas, Austin

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Margaret LeMone, National Center for Atmospheric Research, Boulder, CO. Appointed by the Report Review Committee, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Institutional oversight for this project was provided by

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# Contents

# Summary

Weather information, specifically forecasts and warnings, has a great impact on the U.S. economy and is critical for the protection of life and property. The National Weather Service (NWS) serves as the nation's authoritative source of such information, providing routine public, marine, and aviation forecasts, as well as advisories and warnings when conditions warrant. Under its operating model, the NWS provides these services as well as atmospheric and hydrological data free of charge to other agencies, the research community, the private sector, and the public. The NWS also provides seasonal climate forecasts, and its observations are an essential part of the forecast process as well as part of the long-term climate record. As the primary provider of weather data in the United States, it is crucial that NWS operations stay at the forefront of available technologies for observing, forecasting, and understanding the weather.

The 20th century saw an exponential growth in the technological capabilities of weather observations and forecasting. Because of the rapid rate of change, it was difficult for the NWS to keep pace and in the 1980s it became clear that to take advantage of new technologies in the most cost effective manner, and to provide better weather services to the nation, the NWS needed to change dramatically. The concept of a modernized and restructured weather service emerged.

Between 1989 and 2000, the nation invested approximately $4.5 billion to implement the Modernization and Associated Restructuring (MAR) of the NWS. New observational and computational systems were planned and deployed, and the NWS field office structure was redefined around new concepts for observing, forecasting, and service delivery to capitalize on the investments in these new systems. The NWS workforce was restructured around these concepts and substantial investments in training and recruitment developed a more professional workforce with the skills necessary for the modernized NWS.

To modernize its operations, the NWS developed and implemented five major technologies:

- **Automated Surface Observing System (ASOS):** an automated electronic sensor instrument system to replace manual weather observations at all NWS (and many other) surface observing locations;
- **Next Generation Weather Radar (NEXRAD):** a network of advanced Doppler radars to measure motions of the atmosphere responsible for severe weather such as tornadoes, detect heavy rainfall and hail, and increase lead times for prediction of severe weather events and flash floods;
- **Satellite Upgrades:** a new series of geostationary meteorological satellites to provide higher spatial and temporal resolution imagery and data to aid shorter-range forecasts and warnings, and a new series of polar orbiting meteorological satellites to provide improved, all-weather, atmospheric data to assist in longer term forecasting;
- **National Centers Advanced Computer Systems:** a tenfold increase in computing power to support the National Centers. Along with numerical weather prediction model improvements, this improved national guidance for forecasts and warnings; and
- **Advanced Weather Interactive Processing System (AWIPS):** a workstation-centric, advanced com-

puter and communications system to help forecasters integrate, visualize, and analyze all sources of weather data. The system allowed communication between each weather forecast office and distribution of centrally collected data and centrally produced analysis and guidance products, as well as satellite data and imagery.

To take advantage of these modern technologies, the NWS restructured their field office organization. Prior to the MAR, the NWS had a two-tiered office structure: 52 Weather Service Forecast Offices (WSFOs) had a core component of professional meteorologists and 204 Weather Service Offices (WSOs) were staffed with observers and meteorological technicians. This structure was replaced with a single-tiered system of 122 Weather Forecast Offices (WFOs). The intent was for WFO locations to be more evenly distributed across the nation, to provide more uniform provision of weather services and greater interaction with communities, specifically local media and emergency management. The combination of modernized technology and a reorganized operational structure contributed to improvements in forecasts on time scales of minutes to weeks, time scales that were the focus of the MAR. For example, the probabilities of detection and forecast lead times for both tornadoes and flash floods improved after the MAR. However, the false alarm ratios for tornadoes and flash floods have remained high. Hurricane track forecasts improved after the MAR, whereas hurricane intensity forecasts still need improvement.

No comprehensive assessment of the MAR plan and its execution, or comparison of the promised benefits of the MAR to its actual impact, has been conducted. Therefore, Congress asked the National Academy of Sciences to conduct an end-to-end assessment that addresses the past modernization as well as lessons learned to support future improvements to NWS capabilities. This report contains Phase I of the committee's work, a retrospective assessment of the MAR with a focus on lessons learned from the effort to plan, deploy, and oversee the MAR. Phase II will apply the lessons learned from the MAR to develop actionable recommendations for the NWS on how best to plan, deploy, and oversee future improvements, and will be presented in a later report.

Overall, the MAR led to a greater integration of science into weather service activities and improved outreach and coordination with state and local government, emergency management, and communities. The technological improvements provided forecasters with a wealth of new data and observations, allowing them to provide more accurate and timely forecast and warning services to the nation. The stated objective of the MAR in the Strategic Plan prepared by the NWS was

> to modernize the NWS through the deployment of proven observational, information processing and communications technologies, and to establish an associated cost effective operational structure. The modernization and associated restructuring of NWS shall assure that the major advances which have been made in our ability to observe and understand the atmosphere are applied to the practical problems of providing weather and hydrologic services to the Nation.

It is clear that the NWS succeeded in the deployment of observational, information processing, and communications technologies that have improved weather and hydrologic services. The MAR significantly increased the amount of data and information available to field forecasters, the private sector, and the general public. The forecast and warning products produced by the post-MAR NWS are greater in both quantity and quality. However, the cost-effectiveness of the operational structure is difficult to assess quantitatively, because of the challenges involved in assessing the value of decreased loss of life and property as a result of improved forecasts and warnings.

This summary presents the committee's findings and lessons about the MAR as a whole, as well as more detailed findings and lessons about six specific elements of the MAR: (1) management and planning; (2) modernization of technology; (3) restructuring of forecast offices and staff; (4) national centers; (5) partnerships; and (6) oversight and advisory groups. The evidence and analysis supporting these findings and lessons are contained in the main report.

## FINDINGS AND LESSONS LEARNED

The committee has two findings and one lesson about the MAR as a whole:

- The National Weather Service (NWS) had been unable to keep up with the pace of technological advances and had nearly become obsolete by the 1980s.

Therefore the NWS was not utilizing the full potential available to provide the best possible meteorological services to the nation. The $4.5 billion national investment in the Modernization and Associated Restructuring (MAR) was both needed and generally well spent. Overall, the MAR was successful in achieving major improvements for the weather enterprise.

• A framework was created and left in place following the Modernization and Associated Restructuring that allows and encourages the technology and to some extent the workforce composition and culture of the National Weather Service to continue to evolve.

**Lesson 1:** If a science-based agency like the National Weather Service, which provides critical services to the nation, waits until it is close to becoming obsolete, it will require a complex and very expensive program to modernize.

## MANAGEMENT AND PLANNING

• During the Modernization and Associated Restructuring (MAR) period from 1989 to 2000, the major components of the MAR were well planned and completed largely in accordance to that plan. Established processes were extensive and generally followed. However, notable budget overruns and substantial schedule delays occurred for nearly all of the project elements. This was due in large part to the MAR aggregating four major technology programs that had been separately initiated during the 1980s. Many of the MAR's cost and schedule issues were set in place by decisions that occurred during this pre-MAR period.

• Many of the institutional changes (management structure, culture, processes, partner relationships) introduced to implement the Modernization and Associated Restructuring (MAR) have been retained by the National Weather Service (NWS). Most of these "institutional byproducts" have been as valuable as the MAR improvements themselves and will help the NWS to continue to modernize. However, from viewing more recent projects, implementation of a rigorous systems engineering process to facilitate more effective management of the procurement and development of large, complex systems appears not to have been institutionalized within the National Oceanic and Atmospheric Administration. The systems engineering process needs to start at the beginning of the program, in the agency's program office.

**Lesson 2:** The budget, schedule, and technological issues encountered during execution of the Modernization and Associated Restructuring of the National Weather Service (NWS) reflected traditional challenges of large projects: inexperience of the government project-level leadership, shifting budget constraints, ambitious technology leaps, multiparty stakeholder pressures, cultural inertia, contractor shortcomings, and oversight burdens. Each represents important lessons for the NWS with regard to future projects of a similar nature:

- Expertise in system design, procurement, and deployment is essential to successful implementation of any complex technical upgrade.
- Dedicated leaders are crucial for resolving roadblocks and ensuring ultimate project success.
- Clearly defined system-level requirements, and competent management of those requirements, are essential to any contractual acquisition of a major system.
- Statistical indicators of forecast and warning performance are a major element for gaining and maintaining support for implementing new technologies.
- It is necessary to establish comprehensive performance metrics at the beginning of a process, evaluate them throughout the process, and reevaluate them after the process is complete.

## MODERNIZATION OF TECHNOLOGY

• The various technological problems that were encountered included lack of preliminary analysis and ensuing design problems, inadequate program management, and poor contractor performance. These problems were generally overcome and the major technology system upgrades were successfully executed.

• The Modernization and Associated Restructuring (MAR) provided for more uniform radar coverage and surface observations across the United States. The Next Generation Weather Radar network and Geostationary Operational Environmental Satellites dramatically improved the quantity and quality of data available to forecasters and enhanced the numerical weather prediction capabilities of the National Weather Service (NWS). Replacing human observers with the

Automated Surface Observing System introduced significant gains, despite possible adverse affects on the climate record and the loss of some important visual elements of the observation. The Advanced Weather Interactive Processing System (AWIPS) has been a critical technological advancement that integrates the data and information provided by other MAR elements and makes them easily accessible by forecasters.

• The Probability of Detection for both tornadoes and flash floods improved over the course of the MAR and after the MAR. Likewise the Lead Times of the warnings increased. However, the False Alarm Ratios (FARs) were not reduced and remain high.

**Lesson 3:** The time scale for implementing major change in government systems is very long compared to the time scale for major technological change. The pace of technological progress complicates the planning, procurement, and deployment of large, complex systems. While technology is changing so rapidly, in every aspect of the project where it is feasible, it is crucial to

- establish clear metrics for evaluating improvement in forecasts and warnings at the beginning of a major technological upgrade;
- use rapid prototyping and system demonstrations. An example includes the Program for Regional Observing and Forecasting Service (PROFS) and their Denver AWIPS Risk Reduction and Requirements Evaluation (DAR$^3$E) effort, which proved critical to the success of the Modernization and Associated Restructuring;
- evaluate such prototype systems under a variety of actual operational situations with multiple classes of users and stakeholders in order to refine the system design;
- establish the capacity for continual upgrades of complex systems, particularly those involving digital technology (e.g., high performance computing, and communications); and
- continually assess and apply the lessons of past systems, whether successful or unsuccessful.

## RESTRUCTURING OF FORECAST OFFICES AND STAFF

• The restructuring of offices and upgrading of staff brought more evenly-distributed and uniform weather services to the nation.

• During the early stages of the Modernization and Associated Restructuring, there was insufficient communication between National Weather Service management at the national level and the field office managers and their staff, as well as the employee union.

• National Weather Service staff was reduced, but technical capabilities and career paths were substantially upgraded, leading to little or no cost savings from the workforce reorganization.

• The staffing level that resulted from the Modernization and Associated Restructuring allows for at least two people on duty for all shifts, but timely planning and coordination by field office managers and supervisors are required to be able to increase the staffing level for times when severe weather threatens life and property.

• The Science Operations Officer (SOO) position created as part of the Modernization and Associated Restructuring, in principle, allows advancements in the science community to be more rapidly integrated into operations. Communication and dissemination of weather information at the local level has been much improved by the restructuring of the forecast offices and the creation of the Warning Coordination Meteorologist position.

**Lesson 4:** The Modernization and Associated Restructuring (MAR) of the National Weather Service (NWS) faced initial resistance from NWS employees and, to some extent, the general public. This resistance could have been lessened by, very early in the planning stages,

- engaging those whose career and livelihood were to be affected in planning the changes; and
- better engaging a diffuse public, and to some extent Congress, regarding the benefits of improved weather forecasts and warnings as opposed to the perceived cost of losing a forecast office in their community.

The restructuring dictated a degree of standardization between forecast offices, however it has become apparent that this needs to be effectively balanced with the flexibility needed to allow for customization at individual offices to respond to local requirements.

The MAR increased the overall education level of the workforce and set in place the need for routine training to keep the staff on pace with technological and meteorological advancements in the community. Staff development through in-person, hands-on training in a centralized classroom or laboratory of the type that occurred during the MAR has great value. Where relevant, online courses or self-directed study can be a useful supplement, but can sacrifice quality of learning and the connections made with colleagues that are essential to the overall operations of the NWS.

## NATIONAL CENTERS

- The overarching Modernization and Associated Restructuring goal to integrate science-based approaches to weather, climate, and hydrologic prediction, and to rapidly assimilate evolving facets of information technology, led to the formation of the National Centers for Environmental Prediction (NCEP), which have become a key part of the National Weather Service.
- Numerical weather forecasts produced by the NCEP and the associated guidance information and products, improved steadily over the course of the Modernization and Associated Restructuring. However, the performance of some NCEP models, particularly the Global Forecast System (GFS), continues to lag behind some other national centers, including the European Centre for Medium-range Weather Forecasts (ECMWF).

## PARTNERSHIPS

- Partnerships between the National Weather Service and other National Oceanic and Atmospheric Administration line offices, other Federal Agencies, state and local governments, academia, the research community, and to some extent the private sector through contractor relationships, while not perfect, especially in the early years, were essential to successful execution of the Modernization and Associated Restructuring.
- Improved relationships with other agencies and external partners have proven to be one of the more important outcomes of the Modernization and Associated Restructuring (MAR). These relationships increase the National Weather Service's societal impact and leverage its limited budget. Success of the MAR depended in part on leadership, initiative, and funding by National Oceanic and Atmospheric Administration and National Weather Service units operating outside the MAR. Though issues remain, partnerships with academia and government research institutions have increased research-to-operation capabilities, and the MAR elevated the media and emergency management community from a customer to a partner. The relationship between the NWS and the private sector took longer to improve, but it has generally evolved into a more constructive and productive one.

**Lesson 5:** The execution of the Modernization and Associated Restructuring required working with many partners, which provided cost-sharing and improved understanding of user needs. However, the relationships with the partners were not always as well conceived or managed as would have been desirable. This could have been avoided by involving all known stakeholders (e.g., other agencies, academia and the research community, the private sector, media, and emergency management) from the outset. The National Weather Service (NWS) operational staff is also a stakeholder, and need to be involved early in the design and procurement process to ensure system functionality and practicality. Engagement with stakeholders from both inside and outside the NWS would help the NWS better understand user needs and secure 'buy-in' to new initiatives.

## OVERSIGHT AND ADVICE

- Independent oversight and technical guidance helped draw attention to important issues and impediments that otherwise may have inhibited the success of the Modernization and Associated Restructuring (MAR). This external oversight provided accountability of the technical, scheduling, and budget metrics during the MAR process.
- Expert advice and oversight from outside the National Weather Service (NWS), and the receptiveness of NWS management to such advice, contributed to the success of the Modernization and Associated Restructuring.

**Lesson 6:** The Modernization and Associated Restructuring of the National Weather Service (NWS) showed that candid yet non-adversarial advice from outside experts and other interested parties was useful in the design and deployment of a large complex system. Because NWS management was receptive to such oversight and advice, the outside input was effective.

## ADDITIONAL IMPACTS

- The Modernization and Associated Restructuring (MAR) improved collaboration among hydrologic and meteorological operations within the National Weather Service, and allowed significant expansion of hydrologic forecast products and services. However, the challenges facing the River Forecast Centers were magnified because the MAR did not adequately take into account the unique requirements of hydrologic data management, modeling, and partner collaborations.
- The Automated Surface Observing System (ASOS) was not implemented in such a way that the climate record was preserved. Discontinuities that degrade computation of long-period statistics, created by changes in instrumentation and observing locations, are still a concern. However, the Modernization and Associated Restructuring continues to offer prospects for improvement of the overall national climate record over the long term.

The MAR was a large, complex process that lasted a decade, and cost approximately $4.5 billion. Despite issues, some more significant than others, in the end the MAR was an unqualified success. New technologies deployed during the MAR now provide forecasters with more observations of higher quality. NWS forecast and warning products were dramatically improved, in both quality and quantity. NWS now has stronger relationships with many of its partners in the weather enterprise. Changes in the distribution of field offices have allowed stronger connections with local communities. Weather services have great value to the nation, and the MAR was well worth the investment.

# 1

# Introduction

The mission of the National Weather Service (NWS) is to "provide weather, water, and climate forecasts and warnings for the United States, its territories, adjacent waters and ocean areas, for the protection of life and property and the enhancement of the national economy. NWS data and products form a national information database and infrastructure which can be used by other governmental agencies, the private sector, the public, and the global community" (NWS, 2011b). Public, marine, and aviation forecasts are provided routinely by the NWS, as well as unscheduled short- and long-fused advisories and life-saving warnings when conditions warrant. Seasonal and longer-term climate forecasts and warnings are also provided by NWS, and its observations are a critical part of the long-term climate record.[1]

In the 1980s, it became clear that to take advantage of new technologies in the most cost effective manner, and to provide better weather services to the nation, the NWS needed to change. The concept of a modernized and restructured weather service with a single tiered office structure, as contrasted with the existing two-tiered structure, emerged. A central part of this plan would be to replace the network of Weather Service Forecast Offices and Weather Service Offices with Weather Forecast Offices (WFOs), with principal staffing by professional meteorologists supported by meteorological technicians. Each office would have roughly the same size staff and area of responsibility—an area sized to allow for effective outreach and coordination with the user community, including the media and emergency management agencies. It was determined that about 120 WFOs evenly distributed across the country would be adequate to provide the services required.

In addition to the forecast office changes, important technological changes were planned and implemented. Surface meteorological observations would be automated and improved, allowing for the redeployment of staff positions to result in a workforce focusing on severe weather forecasts and warnings, and user community outreach. A Doppler radar network would be designed to give as complete national coverage as possible. The National Environmental Satellite, Data, and Information Service (NESDIS) would develop and deploy a new series of satellites in both geostationary and polar orbits. Computer upgrades would allow the National Meteorological Center (NMC) to continue to improve numerical weather prediction products used by the forecaster as guidance in forecast and warning development. Finally, an advanced data processing and communications system would be the heart of the redesigned NWS forecast office, providing an interactive display and work platform with access to all data and information from radars, surface and upper-air observations, satellite imagery, and output from the NMC. Data from local networks would also be accommodated

[1] Climate describes the variable aspects of the air-water-land surface system that operate at time scales longer than weather, typically beyond two weeks to a month. Thus a climate record is a long term (multiple years) record of observation data for temperature, precipitation, and other variables. Routine NWS climate forecasts include 6- to 10-day climate forecasts, 8- to 14-day forecasts, monthly forecasts, and seasonal outlooks with lead times of 12.5 months. Climate warnings include hazard assessments, drought outlooks, and warnings of emerging large-scale climate patterns such as El Niño and La Niña.

(NWS, 1989, 1990). The comprehensive strategy for reorganizing the field office structure and upgrading observing and forecasting technologies would be called the National Weather Service Modernization and Associated Restructuring (MAR).

Between 1989 and 2000, the nation invested an estimated $4.5 billion to implement the MAR (GAO, 1997a, 1998a). New observational and computational systems were planned and deployed, and the NWS field office structure was redefined around new concepts for observing, forecasting, and service delivery to capitalize on the investments in these new systems. The NWS workforce was restructured around these concepts and substantial investments in training and recruitment developed a more professional workforce with the skills necessary for the modernized NWS. Overall, the MAR led to a greater integration of science into weather service activities and improved outreach and coordination with state and local government, emergency management, local media, and communities. The technological improvements provided forecasters with a wealth of new data and observations, allowing them to provide more accurate and timely forecast and warning services for time scales of minutes to weeks, time scales that were the focus of the MAR.

## STUDY CONTEXT AND CHARGE TO THE COMMITTEE

The MAR was officially completed in 2000. No comprehensive assessment of the execution of the MAR plan, or comparison of the promised benefits of the MAR to its actual impact, has been conducted. Therefore, Congress asked the National Academy of Sciences to conduct an end-to-end assessment that addresses the past modernization as well as lessons learned to support future improvements to NWS capabilities (U.S. Congress, 2009; Box 1.1).

This report contains Phase I of the committee's work, a retrospective assessment of the entire NWS modernization program with a focus on lessons learned from the effort to plan, deploy, and oversee the modernization. Phase II of the committee's work will be presented in a later report. Phase II will apply the lessons learned in Phase I to provide NWS with recommendations on how best to plan, deploy, and oversee future improvements.

### BOX 1.1 Committee on the Assessment of the National Weather Service's Modernization Program Statement of Task

During the 1980s and 1990s, NOAA launched a major program to modernize the National Weather Service (NWS), investing $4.5 billion to modernize NWS technologies to advance weather forecasting. No complete assessment of the entire end-to-end NWS modernization enterprise has been done, thus Congress has asked the National Academy of Sciences to conduct an assessment of the now-completed National Weather Service modernization. The project should not only address the past modernization, but also focus on lessons learned to support future improvements to NWS capabilities. It should address high-impact weather and new science and technologies that allow for even better forecasts; the integration of new technologies and better models into NWS operations; workforce composition and structure; and improving current partnerships with private industry, academia, and other governmental agencies. Finally, the project should provide advice on how NWS can best plan, deploy, and oversee these future improvements based on lessons learned from the NWS modernization.

## STUDY APPROACH AND METHODOLOGY

The committee was formed in the fall of 2010 and will complete their charge over the course of approximately two years. To carry out the first part of its charge, the committee held three in-person meetings during which they heard input from a range of stakeholders and participants in the MAR. The committee reviewed the literature, oversight reports, NWS documents, and other relevant information, and met by phone. A critical aspect of the committee's information gathering process was visiting several WFOs. Each committee member visited their local WFO, spoke with staff about their perspectives on the MAR, and saw the MAR technologies in action. In addition, the committee sent a questionnaire to WFOs colocated with university or other research facilities to assess the effects of the MAR on weather research and the transition of research-to-operations, as well as the partnership between NWS and academia. This report is an assessment of the MAR and, as such, only considers technologies and other aspects of weather services that were officially part of the MAR planning and execution, as described in the Strategic Plan (NWS, 1989). With the passage of time some records of events relevant to the MAR have gone missing, and many of the people involved are no longer with us. That makes it difficult for the committee to reconstruct a comprehensive history, and some gaps in this assessment are therefore inevitable.

## ORGANIZATION OF THE REPORT

This report is organized chronologically. Chapter 2, Pre-Modernization Environment and Planning, summarizes the state of weather observation and forecasting technologies, as well as NWS operations and organizational structure in the 1980s. Finally, the chapter describes both the Execution Objectives and the Promised Benefits of the MAR. Chapter 3 describes the Execution of the Modernization and Associated Restructuring, comparing it to the Execution Objectives discussed in Chapter 2, and covering the period from 1989 to 2000. The discussion is structured around six major elements of the MAR: (1) management and planning; (2) modernization of technology; (3) restructuring of forecasts offices and staff; (4) national centers; (5) partnerships; and (6) oversight and advisory groups. Chapter 4 describes the Impact of the Modernization and Associated Restructuring, comparing the results of the MAR with the Promised Benefits discussed in Chapter 2, and covering the period after 2000. The discussion is structured around the same six components as Chapter 3, as well as a discussion of some additional impacts. Both Chapters 3 and 4 present specific Findings about the major aspects of the MAR. Finally, Chapter 5 presents the committee's Key Findings about the MAR as a whole and an assessment of the lessons learned from the committee's analysis of the execution and impact of the MAR.

# 2

# Pre-Modernization Environment and Planning

This chapter focuses on the state of the National Weather Service (NWS) in the 1980s, prior to the official start of the Modernization and Associated Restructuring (MAR) in 1989. During the period preceding the MAR, improved radar and other observation systems were already under development, the numerical weather prediction operations at the National Meteorological Center (NMC) were improving steadily, and the operational application of data and information from both polar orbiting and geostationary satellites had become a critical component of atmospheric observation and improved forecasting capability. However, the NWS could not fully realize the benefits of these rapidly evolving technological improvements within their existing organizational structure, staffing, and physical infrastructure. The MAR execution objectives were to address this problem, yielding several promised benefits.

## PRE-MODERNIZATION WEATHER SERVICE

In the 1980s, surface observations were being made manually, and were often inconsistent between observers and locations. Forecaster workstations, themselves a fairly recent innovation, operated across multiple computing systems, all with limited computational capability. The NWS radar network was composed of three different types of radars that could determine echo structure and intensity, important for tornado detection and forecasts, but had no capability to measure wind speeds; there were significant gaps in coverage, particularly in the West. The field office structure with approximately only one WSFO per state limited relationships between forecasters and local communities, especially in states with large populations and multiple media markets.

### Technology

#### *Surface Observations*

Prior to the MAR, NWS, Federal Aviation Administration (FAA), and Department of Defense (DOD) staff manually made surface observations. Methods of weather observation had changed very little in the 100 years preceding the MAR (McNulty et al., 1990), and studies had found large variations in manual observations from individual to individual, and from site to site (Chisholm and Kruse, 1974; Woodall, 1966). In addition, the growing aviation industry increased the demand for surface observations. The desire to better address mesoscale weather events (e.g., severe thunderstorms, hail, and tornadoes) required a denser network of observing stations taking frequent and continuous observations.

The NWS and FAA teamed with the DOD (i.e., Air Force and Navy) to begin the process of replacing manual surface observations at approximately 250 airports, which were not always recorded around the clock, with the Automated Surface Observing System (ASOS). The three agencies designed ASOS to improve upon the manual surface observation practices and standards, operate 24 hours a day, seven days a week, and increase the spatial resolution of surface observations by expanding from 250 to almost 1,000 airports around the country. The network was intended to automate the observation and dissemination of temperature, dew point, visibility, wind direction, wind speed, barometric pressure, cloud height and amount, and the type and amount of precipitation. The goal was acquisition of spatially and temporally uniform measurements, continuous observation and reporting, and more observing sites nationwide.

### *Radar*

The NWS weather radar system in the 1980s comprised some fifty-odd WSR-57 and WSR-74S (Weather Surveillance Radar) S-band "network" radars and nearly seventy WSR-74C C-band "local warning" radars. These radars displayed the storm echo patterns and measured radar reflectivity, related to storm intensity, in a semi-quantitative manner. Coverage at mid-levels for the atmosphere was fairly broad east of the Rockies, but only spotty farther west. The WSR-57s in particular were aging and becoming difficult and expensive to maintain. Thus the need for a replacement system in the not too distant future was becoming pronounced.

Fortunately, the development of the Next Generation Weather Radar (NEXRAD) was well under way long before the nominal beginning of the MAR. Early work using 3.2 cm (X-band) wavelength short-range continuous-wave (CW) Doppler radar technology had demonstrated capability to detect tornadic wind speeds (Smith and Holmes, 1961) in addition to measuring reflectivity. However, that system was limited by inability to determine range to the target and by problems with loss of signal intensity in conditions involving precipitation. For routine operational applications, the development of pulse-Doppler technology for long-range weather radar (at longer wavelengths less subject to attenuation) was needed to furnish both range and velocity information (Whiton et al., 1998). Improvements in data processing and display technology were also needed to present the information in usable formats.

Work on the pulse-Doppler technology also began around the late-1950s (Rogers, 1990), first under U.S. Air Force (USAF) auspices and later at the National Severe Storms Laboratory (NSSL). By the late 1960s it was evident that the technology could reveal storm signatures of potential value in forecast and warning applications (Donaldson et al., 1969); a tornado vortex signature was identified in the echoes from a 1973 Oklahoma storm (Burgess et al., 1975). However, it took the introduction of real-time computing and the development of color display technology in the early 1970s to provide a means for bringing the data from a single Doppler radar to meteorologists in a conveniently usable fashion.

In the mid-1970s the NWS jointly teamed with the DOD and the Department of Transportation (DOT) in anticipation of the need to replace the WSR-57, WSR-74, and FPS-77 radars deployed over the preceding 20 years, to form the Joint Doppler Operational Project (JDOP; Whiton et al., 1998). The experiments and tests performed at NSSL and by the NWS and USAF Air Weather Service in 1976 and 1977 showed that Doppler radar provided much earlier detection of severe and tornadic storms, and could also detect gust fronts that might present a hazard to flight operations at airports.

On the basis of the successful JDOP demonstration of the potential value of Doppler radar to the missions of the NWS, the USAF, and the FAA, development of the NEXRAD system got under way in earnest in 1979: the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM) approved a NEXRAD concept document and established a tri-agency NEXRAD Program Council (NPC); the NPC approved formation of a Radar Test and Development Branch (later to become the Interim Operational Test Facility, then the Operational Support Facility, and eventually the Radar Operations Center); and the Office of Management and Budget (OMB) directed the OFCM to conduct a tri-agency cross-cut study for NEXRAD. Finally, NOAA approved establishment of a NEXRAD Joint System Program Office (JSPO) to move forward with the development, contract award, and deployment of a NEXRAD network. An NRC report (NRC, 1980) added momentum to the effort to implement an operational Doppler weather radar capability. The NPC formed a NEXRAD Technical Advisory Committee in 1980 to provide recommendations on newly-developed capabilities that are ready for implementation as well as engineering and scientific developments needed to improve the NEXRAD capabilities. Thus the NEXRAD development process was under way well before the nominal beginning of the MAR. In fact, the NEXRAD system was eventually designated officially as the WSR-88D, the "88" signifying the year when the basic design was finalized, the year before the MAR officially began.

Congress appropriated the first funding for NEXRAD in the fall of 1980. The JSPO issued Joint Operational Requirements and NEXRAD Technical Requirements (NTR) documents in 1981 to initiate the process of system development and procurement (Whiton et al., 1998). Work by the three System Definition Phase contractors indicated that modifications to the NTR would be needed to define an affordable system. With those revisions accomplished two Validation Phase contractors began work in 1983; this phase, including Initial Operational Test and Evaluation (Part 1), was completed in 1987 and led to the selection of the Unisys design for the Limited and Full-Scale Production phases. During that period a different vendor promoted the idea of using C-band radars as a less expensive alternative to the S-band design, but a 1985 "Blue Ribbon Panel" headed by Raymond Kammer reviewed the revised NEXRAD requirements and found them to be "on target" and directly related to weather and public safety needs (ROC, 2011; U.S. Congress, 1985). The Unisys prototype arrived at the Operational Support Facility (OSF) in late 1988 for further operational test and evaluation, with production readiness established at the end of 1989—by which time the official MAR was under way.

Meanwhile, the site-survey contractor had begun work in 1983 to identify prospective sites for the NEXRAD network. A NEXRAD Siting Handbook issued in 1983 (JSPO, 1983) outlined the planned approach for deploying the radars. Insofar as possible, existing radar sites or other user facilities were to be used, simplifying problems of land acquisition, site access, and utilities. Guidance in the Siting Handbook indicated that radar coverage was to be the primary requirement. After preliminary surveys, in-depth surveys were conducted of promising candidate sites. A detailed report was prepared for each survey, focusing on coverage and cost issues (including particularly the cost of wideband communication between the radar site and the location of the principal users of the data). With the costs of wideband communication links at the time, the principal users had to be located not far from the radar site proper. In some cases the radar site was to be moved from city locations (which suffered from extensive ground clutter, a "cone of silence" or coverage gap, and radio frequency interference [RFI] problems) to more rural locations. While new or modified operational offices or centers were specifically not part of the NEXRAD system at this stage (though the costs for such things were later included in the estimated cost of the NEXRAD system; GAO, 1991a), under the restructuring some of those locations also became preferred locations for the new WFOs.

### *Satellites*

The National Environmental Satellite, Data, and Information Service (NESDIS) is the National Oceanic and Atmospheric Administration (NOAA) line office responsible for satellites and in this capacity was a major contributor to the MAR. Only a combination of geostationary and polar-orbiting satellites can provide the spatial and temporal coverage and resolution required to measure the atmosphere and Earth system for weather and climate information. As early as the late 1980s and early 1990s there was an understanding that modernization of the observing satellite systems was expected to lead to improvements in Numerical Weather Prediction (NWP). NWP models use input data describing temperature, moisture, and wind parameters in the atmosphere. These data are obtained via various observation technologies; however, none are as globally complete and areally consistent as those from satellite data. Upgrades to the sounders, including microwave sounders, were of particular interest to NWP.

Geostationary satellites, consistently stationed above the same point on Earth, are important for near-continuous monitoring of the tropics and mid-latitudes within a hemispheric view, but do not capture the polar regions as well. A set of polar orbiting satellites, each crossing above the equator at a different local time, work together to provide coverage of the entire Earth, including the poles. Each polar satellite observes a given point on Earth's surface and the atmosphere above it only twice a day. Although the polar system observations have lower temporal resolution in comparison to those from the geostationary system, they have the advantage of being at a higher spatial resolution due to the much lower orbital altitude. In addition, the temperature and vapor soundings derived from polar orbiters have better vertical resolution. The complete global coverage that the sounder data provides is used for initiation of global NWP models. In addition, the polar-orbiting satellites provide better all-weather performance.

The launch of the Television Infrared Observation Satellite (TIROS-1) in 1960 began significant strides forward in synoptic scale weather interpretation with routine global cloud observations from the system of polar orbiting satellites (NRC, 1999b). The images proved valuable in data-sparse areas, particularly in detecting and tracking tropical storms over the oceans (NRC, 1997b).

Beginning with the launch of the Applications Technology Satellite (ATS-1) in geostationary orbit in 1966, meteorologists obtained full disk images of Earth and its cloud cover every 20 minutes. The spin scan cloud camera implemented on the ATS-1 geostationary platform enabled observations of weather systems in motion during daytime (Purdom, 1996). Since then, each new series of geostationary satellites has incorporated improvements in both instruments and data provision. Improvements in the instruments included addition of infrared and microwave channels to the visible channels on the imager, allowing nighttime observations, and addition of a sounder capability to observe the vertical structure of the atmosphere. Since its first launch in 1975, the Geostationary Operational Environmental Satellite (GOES) data has been a critical part of NWS operations by providing cloud and water vapor imagery to the National Centers through direct receipt. The GOES series of satellites also began to assist in provision and transmission of additional data. For example, starting in the mid-1970s the GOES Data Collection System (DCS) was implemented, allowing for the relay of data from remote, ground-based data collection platforms through the satellite to a central processing facility.

### *National Centers Computing Capacity*

The need to modernize computational capacity at NWS national centers was well recognized at the time of the MAR and was one of the major components of the modernization. Kalnay et al. (1998) document the evolution of numerical weather prediction techniques within the NWS against the backdrop of evolving computing capacity from the 1950s through the mid-1990s. Computing capacity increased approximately six orders of magnitude (in terms of "flops" or "floating point operations per second") since the NWS undertook NWP activities in the late 1950s. Two emerging capabilities helped define and drive the MAR objectives for more uniform and scientifically-based forecast products: the power to generate timely and accurate information content and the uniformity of nationally distributable forecast products afforded by the growing computational capacity. Managing, disseminating, and interpreting this expanding volume of information content required changes in many areas. The downscaling of numerical prediction results to specific guidance information that forecasters could utilize for their specific location was another important development.

### *Forecaster Workstations*

Before the deployment in the late 1970s and early 1980s of the Automation of Field Operations and Services (AFOS), a computer-based forecaster workstation technology, the communication infrastructure of the NWS consisted of teletypewriter and facsimile circuits. AFOS consisted of a set of mini-computers and telephone communication systems organized as "regional loops" supported by hub-and-spoke networks that interconnected each Weather Service Forecast Office and its Weather Service Offices. The communications system was vulnerable to failure, especially in severe weather conditions (high winds, ice storms, etc.). In the late-1980s, the AFOS system became increasingly technologically obsolete and not worth modification or upgrading (NBS, 1988). Major advances in meteorological instrumentation and measurement techniques were providing new data and information, contributing to improved weather forecasting and warning. The Advanced Weather Interactive Processing System (AWIPS) project addressed the AFOS problem and was intended to harness the rapidly advancing technologies. AWIPS later served as the backbone of the MAR, providing forecasters with a system to use all available NWS sources of data. The first release of AWIPS was not a true "modern architecture" but a lengthy set of codes operating on updated, higher throughput, hardware. The software was later rewritten to become the modern, modular, open architecture it is today that can accommodate upgrades and improvements such as AWIPS-II, presently being staged for operational deployment.

### Operations

The NWS had a two-tiered office structure prior to the MAR. The first tier of 52 Weather Service Forecast Offices (WSFOs), about one per state, had a core component of professional meteorologists. The WSFOs prepared general forecasts for their assigned region of responsibility and provided severe weather warnings for their immediate local area covered by the station radar. They also recorded local observations and often had upper-air radiosonde observing responsibility. The second tier of 204 Weather Service Offices (WSOs) was staffed with observers and meteorological technicians. Some WSOs had local weather radars and had local responsibility for issuing severe weather warnings. All WSOs had surface observing responsibility and some performed upper-air observations. Some WSOs were open only part time.

It is difficult to obtain comprehensive data regarding the skill level, or performance metrics, of the NWS general weather forecasting prior to and during the MAR. Forecast verification data is collected centrally, and is made available to NOAA employees, and to other government employees and researchers on a case-by-case basis. However, some data are available for tornado and flash flood warnings (see Figure 4.3). For example, in the late 1980s, about 40 percent of tornado occurrences were detected, with an average warning lead time of five minutes and a false alarm rate of about 80 percent. There was a similar detection rate of about 40 percent for flash floods, with a warning lead time of near 10 minutes, and a false alarm ratio of about 60 percent.

## EXECUTION OBJECTIVES

In November 1988, via Public Law 100-685, Congress instructed the Secretary of Commerce to prepare a 10-year strategic plan for the comprehensive modernization of the NWS (U.S. Congress, 1988).[1] The strategic plan would set forth the basic service improvement objectives of the modernization. It would describe the critical new technology components as well as the associated staff and operational changes necessary to fulfill the objectives of weather and flood forecasting and warning service improvements.

In response to the Congressional request, the NWS prepared, in March 1989, the *Strategic Plan for the Modernization and Associated Restructuring of the National Weather Service*. The *Strategic Plan* stated the objective of the MAR as follows:

> [t]o modernize the NWS through the deployment of proven observational, information processing and communications technologies, and to establish an associated cost effective operational structure. The modernization and associated restructuring of NWS shall assure that the major advances which have been made in our ability to observe and understand the atmosphere are applied to the practical problems of providing weather and hydrologic services to the Nation (NWS, 1989).

The *Strategic Plan* emphasized that the MAR would be dependent on the development and implementation of several major technologies including

- **Automated Surface Observing System (ASOS):** an automated electronic sensor instrument system to replace manual weather observations at all NWS (and many other) surface observing locations, and increase the number of observing locations;
- **Next Generation Weather Radar (NEXRAD):** a network of advanced Doppler radars to measure the motions of the atmosphere responsible for severe weather such as tornadoes, to detect heavy rainfall and hail, and to increase lead times for prediction and warning of severe weather events and flash floods;
- **Satellite Upgrades:** a new series of geostationary meteorological satellites to provide higher spatial and temporal resolution imagery and data to aid shorter-range forecasts and warnings, and a new series of polar orbiting meteorological satellites to provide improved,

[1] Public Law 100-685 was later replaced by Public Law 102-567, which included the same requirements for a *Strategic Plan* and *National Implementation Plan* as well as more detailed guidance for the execution of the MAR.

all-weather, atmospheric data to assist in longer term forecasting;

- **National Centers Advanced Computer Systems:** a ten-fold increase in computing power to support the National Centers. Along with numerical weather prediction model improvements, this improved national guidance for forecasts and warnings; and
- **Advanced Weather Interactive Processing System (AWIPS):** an advanced computer and communications system to help forecasters integrate all sources of weather data. The system allowed communication between each weather forecast office and distribution of centrally collected data and centrally produced analysis and guidance products, as well as satellite data and imagery (NWS, 1989).

In Public Law 100-685, Congress also requested that one year after submission of the *Strategic Plan*, the NWS prepare and submit an initial implementation plan with annual revisions. The NWS published in March 1990 *The National Implementation Plan for the Modernization and Associated Restructuring of the National Weather Service (NIP)*. The NIP planned a transition to the modernized NWS that would be driven by service requirements and accomplished in two distinct stages. This staging was associated with the period of time between the deployment of new observational systems such as ASOS and NEXRAD, and that of the new information processing system, AWIPS. The staging would provide a stabilization period to allow field offices to adjust to, and gain familiarity with, the new Doppler radar system and data, and high resolution surface observation data (NWS, 1990).

Stage 1 would be characterized by an improvement in severe weather detection capability. This would result from meteorological interpretation of the new and enhanced observational data made available by the deployment of ASOS and NEXRAD (NWS, 1990). Stage 2 would be characterized by operation of a reliable predictive warning program. Forecasters using AWIPS would have the necessary tools to integrate, analyze, and interpret all the various data and information, and rapidly disseminate products (NWS, 1990).

Congress required that no WSFO or WSO be closed, consolidated, automated, or relocated unless the Secretary of Commerce certified to the appropriate Congressional committees that "such action would not result in any degradation of weather services provided to the affected area" (U.S. Congress, 1992). An independent advisory committee, the Modernization Transition Committee (MTC), was established to provide a review of each certification and advise the Secretary (U.S. Congress, 1992).

## PROMISED BENEFITS

The overall objective of the MAR was to improve weather services while simultaneously establishing a more cost efficient organization. The specific benefits the NWS hoped to achieve with the MAR included

- more uniform weather services across the Nation;
- improved forecasts;
- more reliable detection and prediction of severe weather and flooding;
- more cost effective NWS; and
- higher productivity for NWS employees (NWS, 1989).

The NIP, while still stating the overall objectives of the MAR as stated in the *Strategic Plan*, expanded and clarified the list of specific goals to include

- operational realization of a predictive warning program focusing on mesoscale meteorology and hydrology;
- advancement of the science of meteorology and hydrology;
- development of NWS human resources to achieve maximum benefit from recent scientific and technical advances;
- user acceptance and support of NWS modernization and associated restructuring service improvement objectives;
- strengthening cooperation with the mass media, universities, the research community, and the private hydrometeorological sector to collectively fulfill the Nation's weather information needs from provision of severe weather warnings and general forecasts for the public as a whole, which is a Government responsibility; to provision of detailed and customer specific weather information, which is a private sector responsibility;
- achievement of productivity gains through automation and replacement of obsolete technological systems; and

- operation of the optimum NWS warning and forecast system consistent with service requirements, user acceptability, and affordability (NWS, 1990).

By the end of Stage 2 of the implementation of the MAR, the NWS would have obtained the capability to forecast and warn of severe weather events with lead times of tens of minutes and with increased geographic specificity.

# 3

# Execution of the Modernization and Associated Restructuring

This chapter focuses on the implementation of the Modernization and Associated Restructuring (MAR) of the National Weather Service (NWS) during the period of 1989 to 2000. The chapter provides an overview of the management and planning issues, technology upgrades, and the reorganization of field offices and the work force. The actual implementation is compared to the MAR execution objectives presented in the preceding chapter, and summarized in specific findings about the major aspects of the MAR.

## MANAGEMENT AND PLANNING

The MAR was "the most complex project ever carried out in the Department of Commerce" at the time (Hayes, 2011). Implementation occurred during a period of rapid technological change (including the emergence of the Internet), and involved a number of major systems deployed across a geographically diverse nation, as well as several federal agencies and the direct participation of three National Oceanic and Atmospheric Administration (NOAA) line offices (NWS, the National Environmental Satellite, Data, and Information Service [NESDIS], and the Office of Oceanic and Atmospheric Research [OAR]). Any such undertaking requires rigorous management. A NOAA Deputy Assistant Administrator for Modernization was appointed to oversee the NEXRAD Joint System Program Office, the Office of Systems Development (which included the ASOS and AWIPS projects), the Office of Systems Operation, the Office of Hydrology, and the Transition Program Office. NWS established the Transition Program Office to support coordination activities between all the NWS offices involved in the MAR. Contracting, personnel management, external relations, and facilities construction was overseen by NOAA headquarters and the Department of Commerce (DOC; NRC, 1991).

### Management Context and Constraints

To understand the MAR management, it is helpful to first identify key context and contemporary issues within which the MAR was implemented (NRC, 1980, 1991; NWS, 1989):

- *Perception*. The perspective was that NWS was in need of substantial improvement (Kraus, 2011; NRC, 1980); there were high expectations that the MAR would improve the agency.[1]
- *Mission*. The MAR did not seek to change the primary NWS role to be the nation's authoritative source of weather information. However, the MAR did change the manner NWS interacted with other weather information sectors.
- *Operating Model.* The NWS operating model of free weather-related services to the nation was not questioned and did not change during the MAR.[2]

[1] This was true both formally and informally; the MAR was expected to provide a substantially better cost-benefit ratio than "business as usual" with payback of investment in 1.6 years (NIST, 1992).

[2] It had been questioned during the 1980s, with substantial discussion regarding privatization of some or all elements of NWS (Booz Allen & Hamilton Inc., 1983). Many national weather services in other countries use operating models that differ from NWS.

- *International Obligations*. NWS needed to maintain its international obligations, most notably through the World Meteorological Organization (WMO), and none were altered by the MAR.
- *Budget*. NWS and NESDIS are parts of NOAA and the DOC, and thus subject to NOAA and DOC considerations as well as their own.[3] Furthermore, NWS worked with the Federal Aviation Administration (FAA) on the Automated Surface Observing System (ASOS), and FAA and the Department of Defense (DOD) for the Next Generation Weather Radar (NEXRAD).
- *Downsizing Government*. The NWS expected the MAR to increase the efficiency of its operations and downsize its organization with no degradation of weather services. The agency planned to reduce the number of field offices from 256 to about 120, and to reduce its staffing levels from a pre-MAR level of 5,100 to about 4,000 through restructuring and automation (GAO, 1995d; NWS, 1989).[4] The long term net savings in staffing costs was used as part of the justification for the MAR (NWS, 1989).
- *Performance Guarantee*. Congressional Language (Public Laws 100-685 and 102-567) required certification that services did not degrade. This was an important factor in deciding how the MAR would be executed, with several key processes tied directly to this issue.
- *Congressional Politics*. In addition to agency-level political issues, NWS was highly sensitive to state, district, and local politics because of the national distribution of field offices and the plan to close or move many of them. There was high potential for politically-influenced congressional and Administration involvement, and resulting risks to the overall plan and delay, that played out in numerous Congressionally-requested reviews of individual office relocation plans (OAR, 2010) and even specific legislative direction for the location of particular offices (U.S. Congress, 1992).
- *Labor Relationships*. NWS had strong union participation at the field office staff level (National Weather Service Employees Organization; NWSEO). The MAR did not include plans to change the role of NWSEO, but the proposed change in workforce structure meant NWSEO and its members were strongly affected. Prior to the MAR, NWS had generally maintained limited interaction with NWSEO (NRC, 1994a).
- *Partnerships*. NWS depended on many partnerships with government, academia, media, and private sector entities. At the time of the MAR, some of these were generally strong (e.g., government, academia, research institutions, technology firms), others such as the media and private sector meteorology firms were informal to a fault, or simply absent.
- *Shared Responsibilities*. The MAR elements of ASOS and NEXRAD required shared responsibility with FAA and DOD. This inevitably introduced challenges from authority and coordinated budgeting. Within NOAA, the shared responsibility with NESDIS for satellites was important, but mostly handled in a cooperative and constructive way.
- *Public-Private Interaction*. A growing private sector marketing weather products was increasingly performing functions of data acquisition, modeling, and delivery of customized products. At the time, there was considerable friction between NWS and the private sector regarding perceived conflict of roles (NRC, 2003a).
- *Completeness*. The MAR did not focus primarily on some elements of the enterprise, such as the River Forecast Centers (RFCs). These, while proceeding along in development, did not receive the same priority in planning, implementation, and oversight as the other elements of the MAR.

**Budget and Schedule**

Information sources available to the committee are surprisingly poor for assessing budget and schedule performance of the MAR. The generally accepted authoritative source is GAO reports published throughout the MAR, which are rather sparse in their supporting details. The annual *National Implementation Plans* of the MAR documented budget requests; while not always identical to the funds expended, they provide some ability to interpret the GAO numbers.

[3] One anecdotal comment was that "[i]t is sometimes easier to get funding for new programs than for sustaining existing ones" (Kraus, 2011).

[4] Staff was ultimately reduced from 5,200 to 4,700 while changing the mix from one third meteorologists and two thirds technicians to the opposite (NRC, 1994a; Sokich, 2011). There were proposals for more dramatic staff reductions early in the planning stages (Booz Allen & Hamilton Inc., 1983).

**TABLE 3.1** Cost and schedule performance of the MAR as documented in GAO reports.

| MAR Element | Planned Cost ($M) | Final Cost ($M) | Planned Completion | Actual Completion |
|---|---|---|---|---|
| ASOS | 72[*,a] | 150[**,b] | 1990[a] | 1998[c] |
| NEXRAD | 340[a] | 800[†,b] | 1989[a] | 1996[b] |
| Satellite Upgrades[††] | 640[a,d] | 2,000[d] | 1989[a] | 1994[d] |
| Advanced Computer Systems | 47.5[e] | 106[b] | 1994[e] | 1999[b] |
| AWIPS | 350[a] | 539[b] | 1995[a] | 2000[b] |
| Other Costs (facilities, staff, R&D) | ~500 | ~1,000[‡] | n/a | n/a |
| TOTAL | 2,000[a] | 4,500[f,g] | 1994[a,h] | 2000 |

[a]GAO (1991a); [b]GAO (2000); [c]Nadolski (2011); [d]GAO (1997c); [e]GAO (1994); [f]GAO (1997a); [g]GAO (1998a); [h]GAO (1995b). Detailed information about each of these information sources can be found in the Reference list at the end of the report.

The planned cost for ASOS is in 1986 constant dollars; for NEXRAD is in 1980 constant dollars; for satellite upgrades is in 1991 constant dollars; and for AWIPS is in 1985 constant dollars.

[*]This cost was for 250 NWS locations initially planned.
[**]This cost was for the 314 NWS locations. The total cost of the 314 NWS, and 678 FAA and DOD locations was approximately $350 million (GAO, 2000).
[†]This cost was for the 125 NWS radars. The total cost of the 125 NWS, 12 FAA, and 29 USAF radars was approximately $1.2 billion (GAO, 2000).
[††]These budget figures are for the total GOES-Next system, including the government part of the effort, as well as the SS/L prime contract, the ITT subcontract, and various other subcontracts under SS/L (GAO, 1997c). The completion dates are for the launch of the first satellite in the series.
[‡]The actual amount of the Other Costs is hard to determine, but appears to be in the range of $900 to $1,200 million, as discussed in the text.

According to GAO initial MAR planning anticipated completion within 5 years of the formal MAR start[5] within a budget of $2 billion (GAO, 1991a). From this and other GAO reports, it is possible to construct the overall view of cost and schedule performance shown in Table 3.1. Each element is described in more detail later in this chapter.

Executing on budget and schedule was among the biggest challenges of the MAR. From the start, cost overruns and schedule delays received considerable visibility in the GAO and at the Congressional level. Problems persisted throughout the duration of the MAR; it even achieved the GAO designation of a high-risk Federal program for 1995 and 1997. The many GAO reports addressing these issues are discussed later in this chapter and listed in Appendix B.

Unlike the GAO, this committee had the luxury of reviewing cost and schedule issues in hindsight. Given this freedom, the committee identified a framework of four questions within which the review was accomplished:

1. Do the budget and schedule numbers reported in GAO reports and summarized in Table 3.1 accurately reflect the cost and schedule performance?
2. Were the cost and schedule issues encountered during the MAR out of the ordinary for projects of comparable magnitude?
3. What were the root causes of the cost and schedule issues?
4. What lessons can be learned for the future?

*Question 1: Do the budget and schedule numbers reported in GAO reports and summarized in Table 3.1 accurately reflect the cost and schedule performance?* While GAO cost and schedule numbers appear correct as cited, assessment of MAR cost and schedule performance is highly dependent on the GAO's definitions of when program elements started and what they included. The committee believes that the chosen definitions lead to a distorted picture of MAR schedule and budget performance.

First, GAO chose to compare actual costs in real year (inflated) dollars to planned costs in fixed year dollars for all program elements. The NEXRAD system, for example, was proposed in 1980 to not exceed $340 million in 1980 dollars (JSPO, 1980). By the 1988 planned completion, inflation had contributed

[5] While several GAO reports state that initial planning estimated that the MAR would be completed in 1994, the anticipated date of completion was in flux during the early stages of the MAR. The first *National Implementation Plan*, for example, estimated that the MAR would be completed in 1996 (NWS, 1990).

approximately a factor of 1.75 (the actual value depends on details of the year-by-year spend), suggesting the proposed cost should be adjusted to at least $600 million (even if it assumed that the original schedule had been maintained). Overall, inflation likely accounted for $800 million of the cited $2.5 billion cost overrun; planned costs should have been adjusted for this inflation by GAO for proper comparison.

Second, GAO chose a cost and schedule baseline (project start) going back as far as a decade before formal MAR initiation (e.g., 1980 for NEXRAD); although these projects were executed by NOAA, they preceded MAR management. An alternate approach might have been to use the date of MAR initiation and compare final cost and schedule to those estimated at MAR initiation. The cited figure of $2 billion for planned cost was updated to $4.6 billion as early as 1991; an updated baseline might substantially change the assessment of actual performance. Indeed, by the end of the MAR the GAO calculated the completion cost of the four major systems (ASOS, NEXRAD, Next Generation Geostationary Environmental Satellite [GOES-Next], and AWIPS) at $3.5 billion (GAO, 2000), well under the $4.2 billion expected by GAO in 1991 (GAO, 1991a).[6]

Third, some costs appear to have been improperly accounted for by GAO, such as inclusion of facilities in the NEXRAD cost prior to FY1992 (the original NEXRAD cost estimate explicitly excludes such costs). This cost was as much as $63 million per year in subsequent years; it is unclear how much from prior years is improperly included in the NEXRAD completion cost.

Fourth, it is not clear that all costs, such as the transient staff increase needed to execute the MAR, were properly included in the GAO reports. The difference between summing the program element costs shown in the table and the cited MAR total cost appears to correspond to MAR-related cost elements not included by the GAO but referenced in the NIP budgets. These internal R&D, construction, and temporary personnel costs were originally expected to be about $500 million. The actual cost is difficult to determine, but it appears to have been between $900 million and $1,200 million (NWS, 1990, 1991a, 1992b, 1993, 1994b, 1995, 1996c, 1997, 1998, 1999). If so, that would imply the total MAR cost was approximately $4.5 to 4.7 billion, comparable to the $4.5 billion cited by GAO. Other internal NWS costs essential to the MAR, such as the 1980s R&D work done on PROFS ultimately needed to implement AWIPS, are also not included. These would grow the cost further, though it is readily argued that such R&D should fall under normal operating budgets rather than the MAR.

In conclusion, the GAO cost numbers and schedules appear to be largely accurate based on a strict reading of GAO's assumptions, but the ability to draw conclusions about MAR cost and schedule performance is limited by these assumptions. The strict GAO accounting implies a total MAR cost growth of 150 percent. The considerations described here suggest the actual value is considerably less under assumptions deemed more appropriate by the committee, but any particular number depends subjectively on the assumptions used.

*Question 2: Were the cost and schedule issues encountered during the MAR out of the ordinary for projects of comparable magnitude?* The answer to this question depends to some extent on the interpretation of Question 1 as to what cost and schedule issues should be attributed to the MAR. For comparison, recent studies of NASA programs having roughly comparable complexity show an average cost growth ranging from 33 percent (Emmons et al., 2007) to 45 percent (CBO, 2004), while transportation infrastructure projects have had average cost overruns of about 28 percent (Flyvbjerg et al., 2002). These account for the cost of inflation, whereas the GAO numbers for the MAR do not. When the inflation difference is included, and the external factors (such as the Challenger failure) are accounted for, MAR cost and schedule issues appear to be high but not substantially out of line with experience on similar projects. There is no question that issues with virtually all MAR elements persisted through MAR completion as documented in GAO reports. But one argument might be that while these were all the responsibility of NOAA, many of the issues were inherited by the MAR and should not be attributed to it. As much as $1 billion had been spent prior to the formal MAR initiation, and many of the issues that subsequently plagued these program elements were already committed by that time.

*Question 3: What were the root causes of the cost and schedule issues?* GAO reported extensively on the prob-

[6] GAO included the cost for the entire NEXRAD system in the 1991 estimate but only the NOAA portion in the 2000 summary.

lems with MAR elements in a contemporary context, but the root causes are not well described and are still difficult to identify from other sources. More than half of the total overrun occurred within the satellite upgrade program element alone. This overrun has been widely attributed to poor government oversight and technical problems encountered by the contractor (GAO, 1989, 1991b). While correct, a deeper analysis reveals two major external contributing factors that are poorly referenced in GAO summaries.

The first is inadequate initial costing of the launch component, a result of the lack of full cost-accounting associated with Shuttle launches that was used to help justify the Shuttle program at the time. Following the Challenger accident in 1987, GOES-Next switched to expendable launch vehicles and had to adjust launch costs to reflect market values.

The second is the cost-constrained government environment within which GOES-Next was conceived, leading to an ill-advised procurement plan, which eliminated a critical development phase while at the same time requesting substantial technology advances.[7] While each of the MAR elements had distinct issues, the common internal contributing factor appears to have been weakness of the procurement process. In all cases, it is difficult to separate the relative roles of an inadequate government contracting process and poor contractor performance within the procurements. Examples of both can be identified. What can be said is that these issues were largely set in place prior to MAR initiation. MAR management appears to have taken repeated steps to recover; the fact that the accepted MAR expenditure of $4.5 billion (GAO, 2000) is actually lower than the 1991 estimate of $4.6 billion (GAO, 1991a) is a testament.

*Question 4: What lessons can be learned for the future?* Practical lessons unique to the MAR are difficult to identify beyond those that apply to the challenges of executing all large projects, of which there were many. These lessons could fill their own report. Certainly, contemporary issues, such as the 1980s debate about limited government and the planned use of non-market-cost shuttle launches, played a role. But no singular issue stands out as a clear MAR-specific lesson for the future readily identified in the history. The following should thus be viewed as informed opinions of the committee rather than a definitive analysis of MAR performance.

The MAR clearly suffered from poor 'project initiation' when its roots in the early 1980s are considered. It was pulled together from previously initiated program elements with different management teams, varying procurement experience, and only partially aligned objectives. There was no integrating architecture until well into the MAR. At some level, the problems with each program element were independent of the others. But a common theme was an attempt to do complex development with procurement processes not up to the task; ASOS: (GAO, 1995h); NEXRAD: (GAO, 1995f); GOES-Next: (GAO, 1991b); AWIPS: (DOC, 1992). Weak procurement processes lead to poorly-defined objectives, incomplete understanding of technical and programmatic risks, inadequate mitigation processes, overly rigid processes, and selection of contractors without sufficient experience or with design flaws in their proposals. Once these problems are set in place, program execution becomes a series of recovery actions. With the MAR, these issues had almost a decade to develop before coming under the MAR auspices. After MAR initiation, individual initiative seems to have been a critical element in completing the planned technological changes without further cost growth, although additional schedule delays occurred. The parallel development of a PROFS-based approach to replace the AWIPS contracted solution is one example—an excellent case of flexibility built into the process to recover from unanticipated problems. Decisions during the MAR undoubtedly contributed to further cost and schedule issues, but the most important lesson appears to be the need to establish a procurement process with sufficient definition yet adequate flexibility to accommodate the challenges of complex system development.

## Organization and Staff

The MAR implemented significant changes in both organization and staffing. Prior to the MAR, the NWS culture was resistant to change. This was

[7] Specifically, the Phase B development phase was eliminated, something usually done only for systems that have little or no new technology development. The planned improvements included a switch from a spinning spacecraft to one that is three-axis stabilized and the corresponding switch from instruments that scan based on spacecraft motion to those that stare and perform scanning internally.

understandable, based on the experience with Automation of Field Operations and Services (AFOS), the only other significant technological upgrade that was implemented NWS-wide. Therefore, as the MAR plan was introduced the staff generally accepted that change was inevitable. They were motivated to evolve the culture (Glackin, 2011), though they were anxious about the uncertainties of change. Planners anticipated these issues, but it is not clear that the human dimensions of the change were fully appreciated. Staffing levels underwent a temporary increase: 5,100 prior to the MAR, about 5,400 during the MAR, and evolving to 4,700 today (Friday, 2011; GAO, 1995d; Sokich, 2011).[8] Such a temporary increase was to be expected during the changeover from pre-MAR to post-MAR operations (GAO, 1995d), while at the same time ensuring the Congressional mandate for no degradation of service (U.S. Congress, 1988). NWS promised employees and NWSEO that any staff reduction would occur by attrition only (Friday, 2011).[9] The stated commitment to retain and formally retrain staff was essential to maintaining morale as well as enlisting cooperation of NWSEO, with the shared story being that staff would be better off as a result. Many NWS field office staff members recall that the change they encountered was hard at the time, but with years of hindsight they now see the change as worthwhile (committee member WFO site visits, see Appendix C for list of WFOs visited). Staff at RFCs was also affected by changes in office locations and staffing profiles, as well as new technologies and procedures for working with the WFOs. Other staff, such as those at the National Centers, was also affected through the consolidation of the centers.

[8] It is noteworthy that this staffing level is small compared to weather agencies in some other industrialized countries, such as Japan and China and certainly for Europe as a whole where each country has its own meteorological service and several countries operate an equivalent of the NWS National Center for Environmental Prediction (e.g., United Kingdom, France, Germany, a joint Scandinavian Center) as well as the European Centre for Medium-range Weather Forecasts. For example, Japan cites staffing of 5,555 during FY2008 and countries such as Germany, United Kingdom, and France typically fall in the range 2,000 to 4,000.

[9] Primarily retirement, though some staff left because they did not like the required relocation or personal changes (such as retraining from being a meteorological technician to being a professional meteorologist).

It is appropriate to ask what ongoing cost savings were achieved by this staffing reduction. The staffing mix was about one-third meteorologists and two-thirds technicians prior to the MAR and the reverse afterward, with an overall reduction from 5,100 to 4,700 (GAO, 1995d; NRC, 1994a; Sokich, 2011). Meteorologists are grade GS-12 to GS-14 employees while technicians are GS-9 to GS-11. With typical GS pay rates, this implies an increase in overall staff cost of about 7 percent, though a more thorough analysis with actual personnel data could reach a slightly different conclusion. Had the originally planned reduction to a staff level of 4,038 (GAO, 1995d) been achieved, a savings of 8 percent would have been obtained instead. Whether this originally planned staffing reduction was a target or a commitment is unclear. The MAR Strategic Plan (NWS, 1989) stated ambiguously ". . . lower costs associated with more accurate and timely warning and forecast services are accomplished while concurrently increasing the benefits. . ." Furthermore, cost savings are measured against a baseline, and NWS argued in part that the deployment of new technology would otherwise have required additional staff. "If the new technological network were constrained by the current field office structure, required staffing levels and overall costs would increase unnecessarily" (NWS, 1989).

**Processes**

The MAR was executed using a wide variety of processes. These included the following:

- *Planning and Documentation*. Several NWS and National Research Council reports (e.g., NRC, 1980) preceded the MAR and set the stage for what was expected from it. Execution plans were documented in a strategic plan (NWS, 1989), a sequence of annual implementation plans (e.g., NWS, 1990) that tracked progress, and a well-defined set of site-specific and transition plans. External reviews (e.g., General Accounting Office [GAO], Modernization Transition Committee [MTC], NRC) also contributed.
- *Plan Execution*. Analysis of these reports shows that execution largely followed the original plan. Real-time issues forced some key changes. One good example is the transition of the majority of the devel-

opment of the Advanced Weather Interactive Processing System (AWIPS) from a contracted provider to a NOAA entity. All of the major system procurements required frequent adjustments to respond to technical and programmatic issues.

- *Organizational Dynamics*. The NWS placement within NOAA and DOC determined which processes were employed and how. In contrast to a major technological procuring agency like DOD, DOC, possibly with the exception of NESDIS, rarely undertakes an effort the size and scope of the MAR, and therefore must create essentially a one-time process and assemble staff to undertake the unique systems acquisitions. It follows that DOC has essentially no room for extended evaluation or internal budget and program adjustment. Each decision becomes a budget decision.
- *Process Flexibility and Individual Initiative*. A critical contribution to MAR success was the individual initiative to deviate from process where it made good sense. Persistence and individual initiative from senior staff and the general workforce was in many cases critical to success when process alone could not overcome impediments.
- *Oversight*. Many oversight bodies examined and influenced the MAR process. This topic is addressed more completely later in this chapter.
- *Communication*. The original MAR plan encouraged active communication channels with Congress, the private sector, NWSEO, oversight entities, and other stakeholders. The continuing communication and outreach to partners through these channels was critical to MAR success.
- *Validation*. The AFOS program of data collection established a performance baseline that enabled performance improvement validation. By the final MAR annual report (NWS, 1999), several statistics for improvements in tornado warning accuracy and lead time, flash flood warnings, hurricane landfall prediction, and other metrics were available. However, publically available, systematic, long-term validation of surface weather forecasts over the United States is not widely available outside the NWS.
- *Commissioning*. The commissioning process evolved from an initial ad hoc effort to a regular and repeatable process as the MAR progressed. This process satisfied the Congressional language mandating no degradation of services.

**Finding 3-1**
**During the Modernization and Associated Restructuring (MAR) period from 1989 to 2000, the major components of the MAR were well planned and completed largely in accordance to that plan. Established processes were extensive and generally followed. However, notable budget overruns and substantial schedule delays occurred for nearly all of the project elements. This was due in large part to the MAR aggregating four major technology programs that had been separately initiated during the 1980s. Many of the MAR's cost and schedule issues were set in place by decisions that occurred during this pre-MAR period.**

## MODERNIZATION OF TECHNOLOGY

As described in Chapter 2, the MAR included the development, procurement, and deployment of technologies in five major areas: surface observations, the radar network, satellites, computing upgrades, and a forecaster interface to integrate the data and information made available by the other elements of the modernization. The systems procured as part of the MAR all involved major technology upgrades, which require long lead times, on the order of many years, and in the case of satellite systems, on the order of a decade. One of the strengths of the MAR was the development, prototyping, and demonstration of operating concepts through a number of risk reduction activities. The MAR planning included the Modernization and Associated Restructuring Demonstration (MARD), which was intended to showcase the new capabilities of the modernized NWS (NWS, 1989, 1990). The Program for Regional Observing and Forecasting Services (PROFS) created a laboratory that used prototypes of NEXRAD and AWIPS to develop operating concepts for the post-MAR weather offices. These included the Denver AWIPS Risk Reduction and Requirements Evaluation (DAR$^3$E) and the Norman AWIPS Risk Reduction and Requirements Evaluation (NAR$^3$E), which assisted in transitioning PROFS prototypes into operation.

### Automated Surface Observing System

As part of the MAR, the NWS cooperated with the FAA and the DOD to change the paradigm for surface weather observing in the United States. The new observation strategy deployed automated sensors to perform much of the work previously done by human weather observers. The instrumentation suite was labeled the Automated Surface Observing System (ASOS). At the time of the MAR, staff at about 250 airports across the nation manually gathered surface airway observations (SAO). Staffing limitations prevented some SAO sites from operating 24 hours per day. The ASOS deployment plan increased the number of surface observation sites to about 1,000. In addition, ASOS allowed for the possibility of 24-hour operations, and more frequent observations than its SAO counterparts.

ASOS automatically collects surface weather data and electronically provides observations to weather observers, weather forecasters, airport personnel, pilots, air traffic control specialists, and other users. The system automatically collects, processes, and error checks data; and formats, displays, archives, and reports the weather elements included in the basic Aviation Routine Weather Report (METAR) and Aviation Selected Special Weather Report (SPECI). These data typically include temperature, pressure, wind, type and intensity of precipitation, runway visibility, sky condition, and ceiling height. To date, there are 1,009 ASOS stations deployed. These include 315 operated by NWS, 571 operated by the FAA, and 123 operated by the DOD (Nadolski, 2011). NWS electronics technicians (52 Full Time Equivalent [FTE]) conduct the operations and maintenance for NWS and FAA ASOS sites through an interagency memorandum of agreement (Nadolski, 2011).

The ASOS Preproduction Development contract ($34M) was awarded to competing industrial sources in April 1988. Program reviews were completed in October 1988 (Preliminary Design Review), in March 1989 (Hardware Critical Design Review), and in May 1989 (Software Design Review). The release of the Request for Proposals for the Deployment Phase of the ASOS contract occurred in June 1989. In 1990, a "limited production" run of 55 ASOS units for the three participating agencies were created (NWS, 1990). These limited production units supported other modernization prototype activities, primarily in the central and southern plains. AAI, Inc. won the production contract in February 1991 and provided for the balance of all required ASOS systems (Nadolski, 2011).

When AAI, Inc. was let the contract for full production of ASOS in the early 1990s, there were already 55 "limited production"-run ASOS sites located in the southern/central plains. McNulty et al. (1990) studied the Kansas ASOS sites and tried to determine whether ASOS resulted in improved forecasts. Although the results were inconclusive, it was clear that it was left to the scientific community to determine what metrics would be used to evaluate the success of ASOS. Over the next decade, numerous publications appeared that redefined the metrics, as well as gauged ASOS against those metrics. Some examples follow.

In 1993, an NRC report found problems with the reliability of ASOS (NRC, 1993), and in November 1994, commissioning of ASOS sites was halted (GAO, 1995h). Also in 1994, then NWS Director Joe Friday stated, "[o]perational use of ASOS has allowed the NWS to review ASOS performance in a real-world environment. This experience has confirmed that ASOS can provide timely and accurate observations for the aviation and meteorological communities" (Friday, 1994). On behalf of itself and its partner agencies, NWS had bought 617 units as of December 1994, and 491 of those had been accepted. Forty seven of the 491 accepted units had been commissioned (GAO, 1995h). No human observers had yet ceased recording surface observations.

In 1995, a General Accounting Office (GAO) report was commissioned that was the most critical of ASOS to date, stating that "ASOS' overall reliability during 1994 winter testing, measured in terms of mean hours between critical system failures and errors, was only about one-half and one-third of specified levels, respectively" (GAO, 1995h). The report stated that reliability testing was not performed before deployment, so this problem surfaced after ASOS was deployed. The report documented that six of the eight ASOS system sensors did not meet contract specifications for accuracy or performance.

The 1995 GAO report led the NWS to develop a proposal to conduct limited tests comparing ASOS with manual observations for a period of six months at 22 commissioned and four noncommissioned ASOS sites. This ASOS Aviation Demonstration was designed to assess the "operational representativeness and system performance" of ASOS in different weather regimes (NWS, 1996a). At the time, "operational representativeness" was defined as "the ability to provide accurate and timely weather observations in support of aviation operations," and "system performance" was defined as "the ability of ASOS to generate and transmit complete observations through the communications network" (NWS, 1996a). The Demonstration occurred in 1995, and the results were reported in an internal NWS document in February 1996 (NWS, 1996a). The Demonstration found that while there were some differences between automated and manual observations, "the operational representativeness and availability of the ASOS system was, in general, very good." The Demonstration also highlighted a higher number of short duration failures than expected. Modifications to the sensor suite were developed to address this problem, and while they were not deployed during the Demonstration, commissioning of ASOS sites resumed based on expected improvements in the sensor suite (NWS, 1996a).

The main impetus behind the deployment of ASOS was achieving the cost and staff reduction goals of the MAR. This contributed significantly to gaining Congressional approval for the MAR. The deployment of ASOS enabled a reduction in the number of NWS field offices and reduced the staffing levels needed to make surface observations. The deployment of ASOS also shifted the NWS workforce toward one with fewer technicians and more professional meteorologists.

### Next Generation Weather Radar

As noted in Chapter 2, the tri-agency NEXRAD program was well under way prior to the official beginning of the MAR. The NEXRAD program initially did not provide for adequate prototype demonstrations under operational conditions. An Initial Operational Test and Evaluation (Part 2) carried out by the USAF (1989) using the Unisys NEXRAD prototype provided an independent test that highlighted a number of problems requiring attention (NRC, 1991). These ranged from reliability concerns, software algorithms and documentation issues, to training programs. According to the GAO (1991a), since 1980 the schedule for completion of the NEXRAD system had slipped by seven years and the estimated cost escalated by a factor of more than four (though the latter was based on current-year dollars on both ends). Factors in addition to inflation contributing to the cost increase included an increase in the number and change in the types of units to be procured; inclusion of costs such as WFO construction, training, and logistics not incorporated in the original estimates; and technical and contractual problems.

Efforts to deal with these problems continued through the spring of 1991, when the tri-agencies and contractor reached a comprehensive settlement of contract claims and deficiencies. Meanwhile, in 1990 the option to start Full-Scale Production had been exercised and the first Limited Production Phase unit had been delivered. Further Operational Assessment took place with that unit in the spring of 1991. However, the reliability problems continued into the mid-1990s (GAO, 1995f).

The prototype and the first half-dozen fielded systems operated with circular polarization, mainly to facilitate the suppression of ground-clutter echoes (earlier operational weather radars operated with linear polarization). However, research on microwave propagation through rain had revealed a difference in the propagation velocity (and hence in the phase shift) of horizontally versus vertically polarized waves (e.g., Oguchi and Hosova, 1974; Seliga and Bringi, 1976), a property of the medium that would gradually degrade the circularly-polarized signal as it passes through. A circularly-polarized research weather radar had been operating in Alberta for some 15 years (McCormick, 1968) and this behavior of the circularly-polarized waves was known (e.g., Humphries, 1974). This unacceptable feature necessitated a redesign of the system and conversion of the already-fielded systems to linear polarization. The failure to account for the results of prior research in this case was a shortcoming of the JSPO operation.

The NEXRAD program was supported from the beginning in both engineering and scientific matters, first with an Interim Operational Test Facility (established about the time the NTR was issued) to assist in the development of hardware, software, and operational concepts. This organization transitioned to an Operational Support Facility (OSF; later renamed Radar Operations Center) to support deployment, maintenance, operation, application, and upgrade of the WSR-88Ds. As NWS field sites began making use of the Limited Production Phase radars in late 1991, the OSF began operating a Hotline (eventually 24/7) to provide consultation with the field staff as questions and problems with the new system arose. The OSF supported deployment of the NEXRAD systems with a vigorous training program to help ensure effective operation and use of the new systems in the field. At the same time maintenance training was conducted at the NWS Technical Training Center. The NEXRAD Technical Advisory Committee monitored the evolving program and provided engineering and scientific advice and recommendations. OSF began issuing a series of software builds in 1995 to introduce solutions to identified problems and upgraded capabilities. Moreover, a NEXRAD Product Improvement Program was established to capitalize on continuing advances in technology and science underlying the processing and use of the radar data.

These aspects are pursuant to a trio of recommendations in the second report of the NRC's National Weather Service Modernization Committee (NRC, 1992b):

> Modernization must continue beyond the implementation of systems now being procured. Provision should be made to . . . take advantage of scientific developments as well as improved computational and information systems as they become available.
>
> Steps should be taken to ensure the continued development and improvement of Next Generation Weather Radar processing algorithms as new developments and operational experience accumulate. . . .
>
> The National Weather Service and the National Oceanic and Atmospheric Administration should create technical advisory panels for each of the major systems that contribute to the technical modernization. . . .

The first Full Scale Production NEXRAD was delivered in mid-1992, and the last of the initially planned NWS radars was installed in 1997. An NRC panel reviewed the nationwide coverage of the network in the mid-1990s and noted a few locations for which coverage was less satisfactory than that provided by the earlier systems (NRC, 1995b). Under the Congressional "no degradation of service" mandate, action was taken to provide better coverage to those locations. Three NEXRAD systems were added to the network in 1997-1998; another radar was installed in 2000, and yet another is to be added in 2012.

### *NEXRAD Information Dissemination Service*

In the pre-MAR era, the NWS did not collect radar data at a central location and had limited capacity for redistribution of data from remote radar sites. In addition, users (researchers, universities, commercial companies, broadcasters, etc.) interested in collecting radar data, analyzing and studying it, and/or potentially redistributing it, had to provide their own communication equipment and the appropriate transmission lines (Baer, 1991). During the development of NEXRAD, a more robust capability to disseminate WSR-88D data to users was part of the design. The NWS outsourced this capability, through a competitive procurement, to four companies (Alden Electronics Inc., Kavouras Inc., Unisys, and WSI Corporation) and called the contractual agreement the NEXRAD Information Dissemination Service (NIDS). Through the NIDS agreement a suite of select WSR-88D base and derived radar reflectivity and velocity products (NIDS products) were made available to subscribers such as television stations, private weather forecasting companies, energy companies (gas and electric utilities), airlines, and other industries (Baer, 1991; Klazura and Imy, 1993; Morris et al., 2001; Pirone, 2011). Special subscriber status was provided via the NIDS contract to universities, and federal, state, and local government agencies. NIDS providers were allowed to charge such special subscribers for only the cost of delivery of the NIDS products, with restrictions on data redistribution. Alden, Kavouras, Unisys, and WSI each paid a one-time access fee of $780 per radar site and a recurring maintenance fee of $1,395 per site via a NIDS Access Agreement (Baer, 1991). The four NIDS providers were given exclusive rights to redistribute the radar data to recover their costs of collecting the data from all sites and providing it on a display terminal for quality control purposes at NWS headquarters.

During the transition from the WSR-57/74 radars to the WSR-88D radars, NEXRAD data was merged into the value-added radar products, including radar data mosaics, winter storm mosaics, and other innovative reflectivity-based radar products that have become commonplace and easily accessible through a multitude of media. It is clear that this acquisition strategy for radar data via NIDS allowed competitive market forces to provide benefits not only to the government, but also to the weather industry, and ultimately the public. Despite these benefits, such dedicated vendor arrangements were problematic from a user perspective. Such arrangements have the unintended side effect of impeding hydrometeorological research and innovations in calibration and correction methodologies because they can make data difficult or costly to obtain. These arrangements are antithetical to the free flow of scientific data and information upon which the scientific enterprise is founded, as well as the operating model of the NWS. The NIDS contract expired on December 31, 2000, and with the intervening advances in communication technologies the NWS became the sole provider for NEXRAD data (NRC, 2003a).

**Satellite Upgrades**

The life cycle of a multi-satellite system procurement can be long relative to the upgrade or development of some of the other assets of NOAA. A full system procurement, including planning, design, build, integration, pre-launch test, launch, and on-orbit operational test activities, can easily extend over 10 years for a five-satellite system. Factors affecting the schedule include launch requirement date for each satellite, the number of satellites and instruments involved, changes in product requirements, and the design complexity of spacecraft and instruments. The upgrade goals for the geostationary system stated in the MAR *Strategic Plan* (NWS, 1989), as well as the plans for the NEXRAD network, had been under development well before the MAR, and may have been implemented in any case. However, it is likely that the MAR made the realization of the NEXRAD and satellite upgrade goals possible by gaining the necessary public support and financial support from Congress. The satellite system that was part of the MAR planning, referred to as GOES-Next, will be addressed here.

The desired polar system upgrades foreseen in the MAR *Strategic Plan* included all-weather atmospheric data (by implementing microwave imagers and sounders, for example). However, in May 1994 President Clinton signed a directive requiring DOD and DOC to integrate their separate satellite systems. The Defense Meteorological Satellite Program (DMSP) and the Polar Operational Environmental Satellite (POES) converged into a single, national system, the joint National Polar-orbiting Operational Environmental Satellite System (NPOESS; GAO, 1995c). This system and the associated program effort reflected the complexity involved when a single system is to meet the needs of multiple, diverse communities with differing requirements. NOAA did not manage NPOESS. Instead an Integrated Program Office had that responsibility. Thus it was not a part of the MAR and will not be addressed here.

The MAR included development and launch of the GOES-Next satellite system. NESDIS is the line office within NOAA responsible for satellite systems. Acting on behalf of NESDIS, the National Aeronautics and Space Administration (NASA) awarded a cost-plus-award-fee contract in 1985 to Space Systems/Loral, Inc. (SS/L, formerly the Ford Aerospace Corporation), with an instrument subcontract to ITT Corporation (GAO, 1991b). Five new satellites were to be developed and built, each with an imager and a sounder. GOES-Next system improvements ultimately resulted in the collection of substantially more weather data of higher quality. However, the program experienced several technical issues, and substantial cost and schedule overruns. The official estimate of the overall development cost increased over 200 percent, from $640M in 1986 to $2.0B in 1996 (GAO, 1997c). The costs include the government effort as well as the contractor effort. The launch of the first satellite was delayed from July 1989 to April 1994, leading to a potential gap in geostationary satellite coverage. Fortunately, NESDIS obtained use of a European METEOSAT, and avoided the threatened outage (NRC, 1997b). The second satellite (GOES-9) exhibited signs of imminent momentum wheel failure three years after launch and was taken out of operation (GAO, 2000). All five satellites were ultimately launched, becoming GOES-8 (launched April 1994), GOES-9 (May 1995), GOES-10 (April 1997), GOES-11 (May 2000), and GOES-12 (July 2001).

The development, execution, and technical problems that occurred during the program effort can be summarized as follows:

- *Lack of preliminary analyses and ensuing design complexity*. The typical engineering analyses usually required for a technical program were not authorized by NESDIS or required by NASA prior to GOES-Next development work. They concluded there was sufficient proof-of-concept in "body-stabilized" spacecraft and instrument design heritage, and NOAA was facing

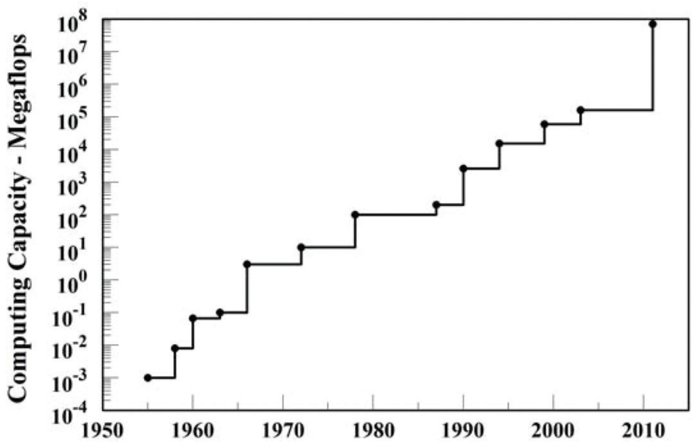


**FIGURE 3.1** Growth trajectory of National Weather Service computational capacity since the beginning of the numerical weather prediction era in the mid-1950s. The y-axis units are floating point operations per second ('flops'), which are a measure of computing power. SOURCE: Based on data from Kalnay et al. (1998) and VandenBerghe (2010).

budget and scheduling issues. Challenging stability/pointing requirements led to complex spacecraft and instrument designs. At the start of the program, NESDIS, NASA, and contractors did not fully recognize this challenge and complexity. Prior systems benefited from the Operational Satellite Improvement Program (OSIP), a NOAA-NASA agreement in effect from 1973 to 1981. With OSIP, NASA funded all development satellites that would later become NOAA operational systems. The elimination of OSIP by NASA resulted in NOAA having no engineering support to design, develop, and test new spacecraft and instrument technologies before incorporating them into the satellite systems (GAO, 1997b).

• *Inadequate program management*. ITT instrument work was subcontracted directly to SS/L. This led to inadequate NASA direction and a restriction of the necessary collaboration between NASA and ITT. Prior to this, NASA directly managed the instrument subcontracts.

• *Poor contractor performance*. Instrument problems resulted from lack of proper direction of the instrument subcontract by SS/L and poor staffing plans and quality of workmanship at ITT. Component problems caused a reduction in the expected operational life from five years to three years for the first two satellites (GAO, 1997c).

In spite of the technical, cost, and schedule issues associated with the program, it is important to stress the substantial improvements in the frequency, spatial resolution, and quality of the new GOES data. For the first time, the system provided simultaneous, independent, imaging and sounding on a continuous basis. These improvements were large steps in technical development that enabled the provision of data that enhanced the ability to study the atmosphere and improve forecasts. Additional detail is provided in the Satellites section of Chapter 4.

### National Centers Advanced Computer Systems

Although National Centers[10] computational facilities had undergone continuous upgrades prior to the MAR and have been upgraded frequently since the MAR (Figure 3.1), the time-period surrounding the MAR was coincident with the emergence of numerical weather prediction (NWP) skill and the advent of computing systems that could produce forecasts, for public dissemination, and use in a timely manner. At that time, it was foreseen that numerical forecast products, developed at NWS National Centers (then the National Meteorological Center [NMC]), would increasingly provide an informational backbone from which standardized analyses and forecasts would flow (NWS, 1989). The timely and consistent flow of forecast information from central computing facilities to forecast offices

[10] The National Centers are the NWS office responsible for providing worldwide forecast guidance products.

required state-of-the-art computational systems as well as upgraded telecommunication and digital display and analysis systems. Specifically, high performance computing required to support data ingest and data assimilation systems as well as numerical prediction models required a full order of magnitude greater capacity than was being used at the NMC at the beginning of the MAR. Additionally, the shift in the computational paradigm from shared memory supercomputers to massively parallel systems occurred during the MAR. Thus, the MAR specifically identified the procurement of the next generation of high performance computer as a key element in the modernization process. The final cost of the computer upgrades was $106 million (GAO, 2000). This procurement, along with the related realignment of the NMC into the National Centers for Environmental Prediction (NCEP) appears to have been an important element of the MAR and has played a significant role in the continued scientific and technological evolution of NWS prediction capabilities. In fact, it is thought that the continued upgrade of supercomputing facilities was and has continued to be "instrumental for improved models to support forecasts made by NWS meteorologists and by commercial forecasters and the private sector industry . . . [and has] ultimately led to [NWS's] on time delivery of products" (Uccellini, 2011).

### Advanced Weather Interactive Processing System

The Advanced Weather Interactive Processing System (AWIPS) was the cornerstone of the MAR. It was designed to receive, process, and integrate data from ASOS, NEXRAD, GOES, and other observing systems, as well as output and guidance from the National Centers and products originating at other international processing centers under the WMO World Weather Watch. AWIPS plays a critical role in the analysis of data and in the preparation and dissemination of weather-related products and services. It consists of a workstation-based system at WFOs and other NWS sites, and a satellite broadcast network (NOAAPORT) that connects to the AWIPS sites and supports data and product distribution. The WFOs use an IP network (OPSNET or NOAAnet) to communicate among themselves.

As discussed in Chapter 2, AWIPS was developed to address the problem of the obsolete Automation of Field Operations and Services (AFOS) system. In 1984 NWS formed an AWIPS Requirements Task Team (ARTT) composed of representatives of NWS administrative, development, and field offices, as well as what became the Forecast Systems Laboratory (FSL) in Boulder, Colorado. This task team worked closely with NWS meteorologists and hydrologists to obtain feedback on forecasting needs, and with competing contractors to obtain feedback on requirements costs and achievability. The work of the ARTT was used to refine and validate the AWIPS requirements; these requirements formed the basis of the functional requirements included in the AWIPS Request for Proposals (RFP) and the Development Phase contract.

As part of the process to refine and validate requirements, NOAA engaged in extensive prototyping of system functions and interfaces, involving forecasters in the effort. Early prototyping, begun in 1984, included development of a pre-AWIPS unit based on research code developed by the Program for Regional Observing and Forecasting Service (PROFS) at the FSL. This was essentially a workstation environment in the FSL laboratory. The PROFS/FSL process involved NWS forecasters in the development and test activities (GAO, 1993). FSL began placing the workstation in the Denver forecast office for forecasters to experiment with. The effort included personnel who worked at both FSL and the Denver forecast office, communicating workstation knowledge to forecasters and forecaster comments on utility back to FSL. Ultimately the effort led to the Denver AWIPS Risk Reduction and Requirements Evaluation ($DAR^3E$) effort, which included a complete suite of hardware for workstations and servers. Once tested in the operational environment and stabilized in Denver, a similar system was placed at the Norman, Oklahoma forecast office for additional testing ($NAR^3E$; NRC, 1992b).

The National Bureau of Standards (NBS) reviewed the AWIPS procurement plan for the 1990s and concluded the approach to the development of the requirements for AWIPS was sound (NBS, 1988). Based on a quantitative assessment of the anticipated data volume, the AWIPS requirements were considered to be a reasonable set of assumptions using modern proven technologies and techniques. In November 1988, after the four year long Requirements Phase, Definition Phase contracts were awarded to two competing contractor teams, Computer Sciences Corporation and Planning Research Corporation (PRC; U.S. Congress, 1996). During this phase the contractor teams worked with NWS to further define and validate requirements and to develop competing designs for AWIPS. In December 1992, after an award date slip of over one year, PRC was selected as the Development Phase prime contractor to provide the AWIPS hardware, system software, and some portion of the hydrometeorological technique software (GAO, 1993). Various NOAA offices were to provide the remainder of the technique software for integration into AWIPS by PRC. In addition, PRC would provide the AWIPS Communications Network (ACN). The total deployment was projected to take four years (NRC, 1992b). The DAR$^3$E activities continued as a parallel risk reduction and demonstration effort as PRC began work on the AWIPS contract.

After early successes in demonstrating the feasibility of system functions, design problems and disagreements between NOAA and PRC in 1993 and 1994 stymied progress (GAO, 1997e). These delays created concern that the deployment of AWIPS into the forecast offices would be substantially delayed and affect the capability of the NWS to utilize the data from the new observing components of the MAR. Accordingly, an AWIPS Independent Review Team (IRT) was formed. In its Final Report of June 1994 the IRT concluded that,

> [a]lthough real progress has been made, the AWIPS program is currently at a standstill due to a combination of factors: complex requirements, contractor performance problems, lack of an accepted system design, contract and communication problems, and distributed leadership (AWIPS IRT, 1994).

The IRT analyzed the overall management responsibility and concluded that the major problems were distribution of authority and responsibility, and lack of an overall AWIPS system design. They concluded that elements of a successful AWIPS deployment would include

- NOAA assuming responsibility for system design, applications code development, and overall system performance;
- PRC retaining responsibility for the design and development of the AWIPS system components other than the applications code, integrating all the components, and working with NOAA to deploy AWIPS; and
- designing the development builds to evolve capability in smaller steps allowing more frequent integration and evaluation of the components, assuring early identification of problems, and easing the integration of AWIPS into the operations by testing the builds in increasingly realistic environments (AWIPS IRT, 1994).

Acting on the IRT recommendations, the NWS restructured the AWIPS program in 1994. With these changes, significantly more design and development responsibility was transferred to the government, in particular to the FSL. In August 1996 the NWS decided that FSL's pre-AWIPS code was to form the core of the AWIPS WFO and RFC environment. The FSL system focused solely on WFO needs and RFC requirements were to be addressed by government development by the Office of Hydrology (OH) and local RFC applications. PRC retained design and development responsibilities for the National Control Facility. During the critical 1997 to 2002 development period, PRC and the government developers worked extremely closely on integration and test efforts. After development at PRC offices, development versions were released to government test facilities and field sites for testing before full scale deployment. This close working relationship was a major contributor to the success of the last five year push. During this period, all software releases occurred according to schedule, with no slips.

One concern expressed at the time was that research lab (e.g., FSL) software lacked quality assurance and configuration management processes for production-level software (GAO, 1997e), although this appears not to have been a major problem over the long term. Review reports also indicated that a very large, complex AWIPS requirements set may have contributed to the program problems. AWIPS consisted of about 22,000 requirements, grouped into about 450 higher-level capabilities. The AWIPS System/Segment Specification related about 75 percent of the capabilities to five broad functional areas. The early prototyping efforts and this functional breakdown of requirements were valuable in ensuring that proposed AWIPS capabilities were anchored in user needs. However, this did not ascertain whether the requirements were based on mission-based goals. The requirements review process did not attempt to validate requirements back to mission improvements. These issues in the requirements development and validation process may have contributed to the contractor's failure to develop a viable AWIPS design (GAO, 1996c).

A 1997 assessment of fiscal requirements noted that the first three AWIPS systems deployed in laboratory or forecast office settings (Boulder, Denver, and Norman) resulted in improvements in warning times and accuracy of some forecasts (Kelly, 1997). The assessment also concluded that like many large information technology programs, AWIPS had "experienced technical difficulties, cost growth and schedule delays" that appeared to have caused considerable oversight from external agencies and eventually resulted in a Congressional mandate to complete development and deployment activities within a $550 million cap.

Ultimately, AWIPS deployment in the field was completed in 2000, within the $550 million mandated spending cap, by a final build cycle. Software additions and enhancements continued beyond the MAR period, into 2002 and through the present. NOAA officials recognized that designing AWIPS was not an easy task. They also concluded it was probably unrealistic to expect a contractor to have the corporate knowledge—the understanding of operational weather forecasting and complex meteorological processes—necessary for successfully designing such a system (GAO, 1997b). The successes and failures of the AWIPS development process provide important lessons about how to satisfy multiple user needs; develop, validate, and manage requirements; instill operational software development standards; and determine a most effective work share between government and contractor based on the specific program goals.

The AWIPS program experienced delays and cost overruns but in the end it was considered a major success. The capabilities of AWIPS have improved the capability of WFOs to efficiently ingest, manipulate, and analyze tremendous amounts of data, thus helping to improve accuracy and timeliness of forecasts and warnings (Jackson, 2011).

### Changes in the Technological Environment

As detailed plans for the MAR were formulated in the late 1980s, the telecommunications and computing environments were very different than what prevailed at the end of the MAR. AT&T (The Bell System) was broken up in 1984, and competitors were beginning to appear. This occurred first in voice lines followed in the late 1980s by data services. In the planned NEXRAD radar installations, the highest data rates were between the Radar Data Acquisition (RDA) unit at the radar site and the Radar Product Generator (RPG) in the WFO. The data rate needed to support this link was on the order of 1.5 Mb/s (megabits per second), a so-called "T1" link (Vogt, 2011).

In the late 1980s, commercial suppliers of T1 links charged thousands of dollars per month including a distance dependent charge (Wallace, 1988). The resulting costs were viewed as prohibitive and among the major factors leading to the colocation of radars and WFOs. Coaxial cable connection could be used over short distances without incurring any telecommunications charges.

During the 10-year rollout of the MAR, the costs for telecommunications and computing dropped precipitously. Moreover, the modern Internet burst on the scene during the 1990s. The first high-speed Internet backbone was NSFNET, which operated at T1, and then, in 1989, at T3 (45 Mb/s) speeds (Living Internet, 2011). The first web browser, Mosaic, appeared in 1993. Traffic on the Internet backbone grew at 15 to 20 percent per month during the mid-1990s, as thousands of networks made the technical changes enabling them to join the Internet. Data communications were revolutionized, both from a cost and a capability perspective. All this drastically changed the technical environment while the MAR was proceeding.

In addition to the impact on communication costs, the costs and capabilities associated with AWIPS also changed in real time. The FSL dealt with this change by creating a series of prototype AWIPS-style systems that were tested by selected forecast offices. The resulting feedback was used to improve, upgrade, and 'harden' the software (GAO, 1996c). Among other great advantages, this prototyping process incorporated the improvements in computing and telecommunications technologies that were occurring independently of the MAR.

In hindsight, telecommunications costs need not have been a major factor motivating the colocation of radars and WFOs. The time scale for major government technical initiatives is quite different than the time scale over which change occurs in digital technologies. Hence, federal programs with a large digital technology component need to be aware that prevailing costs and capabilities during the planning period are not appropriate for their forecasts of eventual costs and capabilities. This dilemma is not easily overcome and is a factor that needs to be taken into account. An agency capability for rapid prototyping and user-feedback during a major acquisition is one way of dealing with the reality of rapid technological change. Another can be leasing of computation capabilities as opposed to purchase, because provision can be made for constant upgrading of agency capability.

**Finding 3-2**

**The various technological problems that were encountered included lack of preliminary analysis and ensuing design problems, inadequate program management, and poor contractor performance. These problems were generally overcome and the major technology system upgrades were successfully executed.**

## RESTRUCTURING OF FORECAST OFFICES AND STAFF

Restructuring of the NWS involved substantial reduction in the number of field offices, relocation and/or realignment of the functions performed at many of those offices, and staff changes including reduction in total numbers along with upgrading of the overall professional levels.

### Consolidation of Offices

The 52 Weather Service Forecast Offices (WSFOs) and 204 Weather Service Offices (WSOs) were replaced by 122 Weather Forecast Offices (WFOs). The distribution of WFOs was based on attaining an even distribution of offices across the nation for equal service provision, and it generally followed the distribution of NEXRAD radars. Each WFO was assigned responsibility for forecasts and warnings for a county warning area (CWA) covered by its NEXRAD.

The transition to the new organizational structure required closing more than half the existing offices, a politically sensitive issue. The "no degradation of service" requirement of Public Law 100-685 called for a certification of no degradation before any office could be closed. An elaborate certification procedure was established to meet this requirement (U.S. Congress, 1988). It included commissioning of the newly-installed technologies (ASOS, NEXRAD, and AWIPS) and demonstration that forecasting and warning services could be provided to the CWA before the WSO or WSFO previously serving that area could be closed. The certification process was overseen by the Modernization Transition Committee (MTC), a Federal Advisory Committee.

### Workforce

The field staffing was changed from a mix of about one-third professional meteorologists and two-thirds meteorological technicians before the MAR to the reverse after the MAR (Sokich, 2011). Meteorological technicians, while required to become certified in several important meteorological tasks, are not required to have a professional atmospheric sciences degree. Before the MAR, they were mainly responsible for observations, including radar, aviation surface weather, and upper air (via radiosonde) observations. In the WSOs, they were also responsible for issuing severe weather warnings (e.g., tornado, severe thunderstorm, flash flood) based on radar observations. Other duties included answering phones and attending to the NOAA Weather Radio. Meteorologists have professional atmospheric sciences degrees. Before the MAR, meteorologists were mostly found only at WSFOs. Generally at WSOs, the Meteorologist in Charge (MIC) was the staff person with a meteorology degree. At WSFOs, journeyman and lead forecasters held degrees in atmospheric sciences and were responsible for severe weather warnings within their area of responsibility, in addition to statewide aviation, marine, and public forecasts, discussions, and summaries. The lead forecasters at WSFOs also served as shift supervisors at their office while also overseeing the work of all WSOs under their jurisdiction.

With the revised makeup of WFO staff planned under the MAR, the question of bringing staff meteorological technicians up to the required levels of training arose. A program was established at San Jose State University to provide training equivalent to a B.S. degree in meteorology; support was offered to any of the meteorological technicians who wished to qualify for meteorologist positions. The program was free of cost to the technicians who participated. While not many went into the program (Sokich, 2011), it did allow some to upgrade their skills and thus bring the benefit of their experience into the modernization era. NOAA also initiated a Cooperative Agreement with the University Corporation for Atmospheric Research (UCAR) to implement the Cooperative Program for Operational Meteorology, Education, and Training (COMET). COMET, which still exists, provided professional development courses for operational forecasters (NWS, 1991a). Most of the training was intended to be taken through "distance learning" facilities. This was initially a challenge, but the advent of the Internet created a truly flexible capability for distance learning. NEXRAD training was provided in Norman, Oklahoma (NWS, 1991a), and was viewed favorably by the workforce (NRC, 1994a). Training on the new technologies was also provided for the electronics personnel. The initial plan was for maintenance, at least for ASOS, to be contracted out. However, it was determined that retraining existing electronics technicians would be more cost effective (Sokich, 2011).

In addition to training, the change in field office distribution required relocation of many staff, which caused some dissatisfaction within the workforce (NRC, 1994a). However, the upgrading of staff was accomplished without forced termination of any of the in-place personnel. The reduction in total staffing level was achieved primarily through retirements.

The National Weather Service Employees Organization (NWSEO) played a crucial role in the process, becoming more engaged than ever before in defending and helping define the future role of its constituent members. One proposal (Booz Allen & Hamilton Inc., 1983) was to reduce staff to less than 3,000 employees, down from the pre-MAR figure of 5,200. However, the final number of employees after the MAR was far greater (4,700) due in part to the efforts of NWSEO and NWS management (Friday, 2011; Hirn, 2011). Communication about the MAR between NWS management and field level staff was perceived as inadequate (NRC, 1994a). A 1994 NRC survey of employee attitudes about the MAR found that while 66 percent of respondents felt they received enough information about the new technologies, 61 percent felt they received too little information about the implementation process and timing of the MAR (NRC, 1994a). This lack of communication with field office employees likely contributed to some of the initial resistance to the MAR. The 1994 NRC survey found that within job categories, meteorological technicians were the least optimistic about the MAR (NRC, 1994a).

Before the MAR, each WSFO was led by a Meteorologist in Charge (MIC) and a Deputy MIC (DMIC). The DMIC had a diverse set of responsibilities, from personnel management of the WSFO staff and staff scheduling, to attending to media requests and educational outreach. The Deputy could well have been the most multidimensional person on staff. The MAR's groundbreaking division of deputy duties into the Science Operations Officer (SOO) and the Warning Coordination Meteorologist (WCM) allowed for a more focused approach to two critically important tasks at the WFOs. These new positions were responsible for incorporation of ongoing scientific advances into WFO operations, and communication with the external user community, respectively. The SOO in essence was the office's lead scientist, typically holding a Ph.D. or M.S. and a strong scientific background. This enhanced WFO staffing provides for improved forecast and warning performance by enabling increased situational awareness and recognition of evolving severe weather, speed and accuracy of issued warnings, and frequency and quality of "follow up" severe weather communications that augment the initial warning messages.

### Changes in Customer Linkages

Customer service advanced significantly with the creation of the WCM position at WFOs. Before the MAR, outreach from NWS to the user community was spotty at best. As noted, this was one of many functions of the DMIC at most WSFOs. WSO sites were staffed by technicians focused on data acquisition and the issuance of storm-based warnings. In the few U.S. cities with a WSFO, ad hoc staff efforts to reach out to the general population often superseded infrequent efforts from the MIC or DMIC (Santos, 2011).

Before the MAR, communication links were mostly one-directional. For example, media requests were typically handled on a case by case basis. Professional meteorologists were located at WSFOs in less than a quarter of the country's main media markets. The creation of the WCM increased and strengthened the linkages between the NWS and media outlets. A strong partnership between the NWS and the media and emergency management community is crucial to facilitate timely and accurate delivery of lifesaving messages.

The field of emergency management was undergoing its own modernization during the decade of the MAR. The end of the Cold War provided the final incentive to transition away from the civil defense posture of earlier decades. The 1990s saw a significant shift to preparing for all hazards that face communities. There was a greater emphasis on preparedness by individuals and communities and on mitigation against future disasters.

The services of the NWS continued to be of great value to emergency managers (EMs) during the MAR. While at some field offices special telephone hot lines or radio communication devices provided a direct link between the NWS and EMs, there was no uniformity of linkages or services to the EM community. In some offices, state and local EMs were customers in the same manner and priority as an individual citizen. Those charged with first response to disasters received the NWS warnings at the same time and in the same manner as the general public. The local authorities then issued their own instructions about evacuation, sheltering, and other emergency measures.

The improvement in NWS warning times for tornadoes, flash floods, and other fast breaking events contributed to the overall time needed for action by local governments and individuals, but the process remained linear, with information passing from NWS to local governments, to individuals and households.

**Finding 3-3a**
**The restructuring of offices and upgrading of staff brought more evenly-distributed and uniform weather services to the nation.**

**Finding 3-3b**
**During the early stages of the Modernization and Associated Restructuring, there was insufficient communication between National Weather Service management at the national level and the field office managers and their staff, as well as the employee union.**

## NATIONAL CENTERS

Concomitant with the goals of the MAR was the need to implement and sustain more science-based approaches to weather, climate, and hydrological prediction, and to rapidly assimilate evolving facets of information technology. To do so required restructuring of the relationship between WFOs, RFCs, and the various National Centers. At the time of the MAR, the National Meteorological Center (NMC) had six components: Automation, Development, and Meteorological Operations Divisions; the Climate Analysis Center; the National Hurricane Center; and the National Severe Storms Forecast Center (McPherson, 1994). The National Centers, as they exist today, serve to support many core activities of the NWS through the collection, ingest, analysis, and archival of weather, climate, oceanographic, space environment, and hydrology data; the development of data assimilation and numerical modeling systems; and the generation of many forecast products.

Although most of the Centers were affected by the MAR in some manner, the most significant changes were experienced through the development of the National Centers for Environmental Prediction (NCEP). The overarching mission of NCEP has been to deliver science-based environmental predictions to the nation and the global community. As the principal developer of prediction models and forecast products, the specialized centers within NCEP played, and continue to play, critical roles in the evolution of the science-based prediction methodologies upon which most forecast products are based. Timely and efficient access to products being generated by NCEP was one of the motivating factors in the development of the AWIPS system. The education and perpetual training of NWS staff is also driven by the rapidly evolving technology being incorporated by NCEP as well as other National Centers.

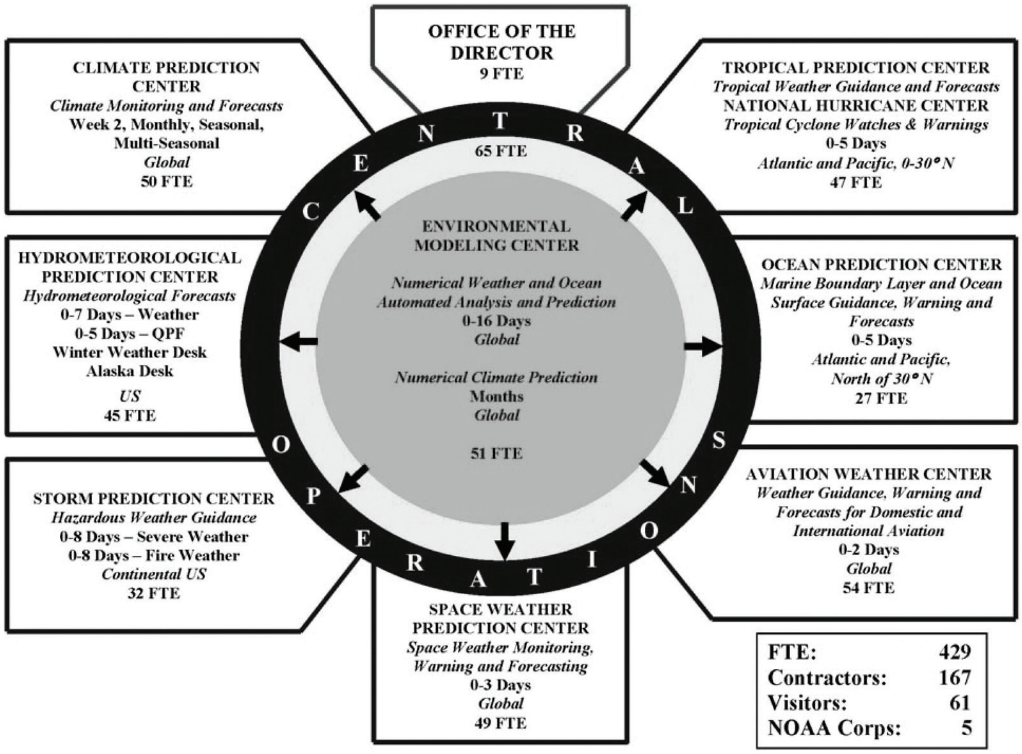


**FIGURE 3.2** Organizational structure of the National Centers for Environmental Prediction (NCEP) that resulted from the 1994 reorganization. The reorganization was not officially part of the MAR, but the concept for reorganization was based largely on the principles of the MAR. Data provided by the NWS indicate that the number of FTEs was largely unchanged by the reorganization. The Space Weather Prediction Center did not become part of NCEP until 2005 when it moved from the Office of Oceanic and Atmospheric Research. SOURCE: National Weather Service.

In 1995, NCEP was formed out of existing NOAA components (McPherson, 1994; UCAR, 2010). The individual components, many of which were previously housed at the NMC, now include (see also Figure 3.2):

- *Office of the Director (OD)*: provides overarching management to the nine centers;
- *Aviation Weather Center (AWC)*: provides aviation warnings and forecasts of hazardous flight conditions at all altitudes within domestic and international air space;
- *Climate Prediction Center (CPC)*: monitors and forecasts short-term climate fluctuations and provides information on the effects climate patterns can have on the nation;
- *Environmental Modeling Center (EMC)*: develops and improves numerical weather, climate, hydrological, and ocean prediction through a broad program in partnership with the research community;
- *Hydrometeorological Prediction Center (HPC)*: provides nationwide analysis and forecast guidance products out through seven days;
- *NCEP Central Operations (NCO)*: sustains and executes the operational suite of numerical analyses and forecast models and prepares NCEP products for dissemination;
- *National Hurricane Center (NHC)*: provides forecasts of the movement and strength of tropical weather systems and issues watches and warnings for the United States and surrounding areas;
- *Ocean Prediction Center (OPC)*: issues weather warnings and forecasts out to five days for the Atlantic and Pacific Ocean north of 30ºN;
- *Space Weather Prediction Center (SWPC)*: provides space weather alerts and warnings for disturbances that can affect people and equipment working in space and on Earth; and
- *Storm Prediction Center (SPC)*: provides tornado and severe weather watches for the contiguous United States (CONUS) along with a suite of hazardous weather forecasts (NWS, 2011a).

As stated by McPherson (1994), "the operations concept for the [MAR] includes a vertically-integrated forecast process in which the national centers will provide a suite of products consisting of output from numerical models (EMC), statistical adjustments to the model fields (HPC, CPC), and value added products (essentially all units) . . ." These products would then be digitally transmitted to forecast offices via the AWIPS system and used as the basis for issuance of local forecasts, watches, and warnings. Therefore, following restructuring, NCEP served as the principal data ingest point for all available domestic and international meteorological data.

Prior to the MAR and the formation of NCEP, many of the centers such as the CPC, EMC, and OPC focused more on model development and evaluation than forecast product generation. The pre-NCEP modus operandi of the centers was necessitated by the fact that many numerical prediction techniques were still in the early stages of development and possessed very modest levels of skill and reliability. However, scientific advances in NWP, coupled with the enormous revolution in observational capability and computational capacity occurring in the late 1980s and 1990s, was accelerating prediction science. Thus, the restructuring of the NWS national centers into the present structure, particularly the creation of NCEP, was motivated by the need to make new observations and forecast products instantly available to NWS forecasters.

**Finding 3-4**
**The overarching Modernization and Associated Restructuring goal to integrate science-based approaches to weather, climate, and hydrologic prediction, and to rapidly assimilate evolving facets of information technology, led to the formation of the National Centers for Environmental Prediction, which have become a key part of the National Weather Service.**

## PARTNERSHIPS

Execution of the MAR by the NWS depended on the involvement of many partners. Development and deployment of all the observational systems of the MAR involved other NOAA line offices as well as other federal agencies. The NWS worked with the private sector through contracted work, and the research community played a large role in the development of MAR technologies, particularly AWIPS.

As a complex program, the MAR required a major, coordinated effort across the NOAA line offices. A key partnership of the MAR consistsed of NWS and the other NOAA line offices involved in carrying out the MAR: NESDIS and OAR/ERL. The leadership (Directors) of NWS, NESDIS, and ERL formed an ad hoc group that was referred to as the "Troika." The principal function of the group was to pull together the programmatic, budget, and technological aspects of the MAR to address, coordinate, and direct the various offices working on the MAR activities within each line office, and to present a unified program, budget request, and technological picture to NOAA and DOC management. The work of the Troika required very intense support, especially from the NWS staff overseeing the MAR. After the last AWIPS was commissioned and critical staff left the NWS, the Troika activity diminished. While the end of the MAR removed the motivation for an arrangement as formal as the Troika, coordination across line offices was a strength of the MAR, and the NWS could benefit from similar coordination today.

### Other Federal Agencies

The FAA, DOD, and NASA all participated with the NWS in the financing and implementation of the MAR. The FAA, DOD, and NWS cooperated in the development and deployment of ASOS and NEXRAD. NASA managed the development and procurement of GOES-Next, and that relationship was discussed earlier (Bjerkaas, 2011; Misciasci, 2011).

The FAA, DOD, and NWS formed a tri-agency program to manage and fund the development and deployment of ASOS. These agencies planned to install 868 ASOS units by FY1997 at a cost of $351 million (GAO, 1995h). The FAA and NWS anticipated that the ASOS installations would allow the NWS to eliminate human weather observers at many airports. However, many aviation users perceived that this would have the effect of reducing the overall quality of surface observations. To some extent this is the case; the ASOS data are essentially point observations, while human observers were able to incorporate some information about the surrounding area.

Of the 163 planned NEXRAD radars, 144 were to be located at sites within the CONUS operated by both the NWS and the DOD, while 19 were to be placed at locations in Hawaii, Alaska, the Caribbean, the Atlantic, the Pacific, and Korea (GAO, 1995f). The CONUS sites were selected to provide coverage to support the respective missions of the three agencies. The non-CONUS sites were selected to support FAA and USAF aviation safety and resource protection tasks. Several of the non-CONUS sites also provided needed information to the NWS about approaching off-shore weather. Data from the radars are shared among the three agencies.

The three agencies originally planned to purchase and deploy 175 NEXRAD radars (including 115 for NWS, 44 for the Air Force, and 16 for the FAA). That number was eventually decreased to 163 due to changes in requirements and funding limitations (GAO, 1995f). The radars were to be purchased, operated, and maintained by the respective agencies, but data from the radars were to be shared among the agencies. The NEXRAD JSPO, organizationally residing within NOAA, but staffed and funded by the FAA, DOD, and NWS, was established with responsibility for managing the acquisition of the radars.

A 1995 GAO report noted that the USAF NEXRAD radars, while essential to the NWS to issue quality forecasts and warnings, were not available as much as the three agencies had agreed was necessary (GAO, 1995f). The requirement specified that each NEXRAD radar be operationally available 96 percent of the time. In 1994 and 1995, only 38 to 90 percent of USAF radars met this requirement on a month-to-month basis (GAO, 1995f). The report specifically identified the inefficiency of the USAF's supply and logistics process for spare NEXRAD parts as compared with the NWS. This problem was resolved after the USAF identified NEXRAD as a unique support responsibility in their supply system and converted from contracted to government employee maintenance.

Aviation weather services in the United States are provided to nonmilitary aircraft by the FAA, the NWS, and the private sector. The DOD provides its own tailored weather services for its military operations and shares its weather data with other elements of the weather enterprise. The NRC report *Aviation Weather Services: A Call for Federal Leadership and Action* summarized the situation in 1995. The report noted that aviation weather is a specialized area that falls outside the mainstream of general-purpose weather services and makes the point that aviation meteorologists need to be sure to spend enough time with weather users to develop a detailed understanding of the operational situation and information needs of those users. The report found that in 1995 there was insufficient time spent in this area, and noted that the MAR had the potential to exacerbate the problem by moving many weather service offices away from local airports (NRC, 1995a).

### Private Sector

The private sector plays two critical roles within the weather enterprise: (1) contracted development of NWS and NESDIS systems and contracted provision of supercomputer capability, and (2) provision of weather services to end users. The first of these is a relatively normal aspect of government projects, and is addressed elsewhere in this report within the relevant technology system descriptions. The second, provision of useful products based on NWS data, is more unusual, particularly with regard to the relationship between public and private roles and deserves focused treatment.

The private sector has been an important element of the weather enterprise for many decades, with at least 50 companies operating in 1980 (NRC, 1980). At the start of the MAR, the private sector was growing rapidly as an important element of the weather enterprise for provision of services. Weather services companies, such as AccuWeather (founded 1962) and The Weather Channel (founded 1982), had been around for some time. They served both the media market for communicating weather to the public and the enterprise market that uses weather information for operational and decision-making needs (including financial instruments such as insurance). In part, this helped fill a role the NWS did not want to serve, such as providing TV visualization and newspaper layouts. Other important private sector roles included providing software and other tools for meteorologists, building and operating private sensor systems such as for road weather, supplying communications infrastructure, and building major NWS systems (ASOS, satellites, etc.).

Nevertheless, within NWS many viewed the private sector as competition. This perception was exacerbated by private sector lobbying during the 1980s for substantial privatization of NWS services. Although this position was embraced by only a portion of the private sector, the environment polarized the two communities. At the time of the MAR, the convergence of growing market needs for advanced weather services (beyond what was available from NWS) and emerging information technologies (cable TV, computers, mobile telephony) greatly stimulated private sector growth. The tension initially worsened as the private sector was poorly integrated by NWS into MAR planning or execution.

The first substantive step toward improving the relationship between NWS and the private sector was publication of the 1991 Public-Private Partnership Policy (NWS, 1991b). It defined the relationship and respective roles of the NWS and private sector. The policy statement's primary purpose was to strengthen the foundation of a public-private partnership that had evolved over 50 years. The goal was a partnership that enhances total service to the American public, government, and industry. It resulted in more frequent interaction between NWS and the commercial weather providers (e.g., NWS director meeting with providers, interactions at the American Meteorological Society's annual meeting; Ritchie, 2011). However, to members of the private sector, these interactions were insufficient. The commercial weather sector was in a growth curve. There was pressure on both sides to find a way to properly capture opportunities. During the MAR, the private sector was not brought in on a foundational basis (Frederick, 2011). In the view of many, the NWS was trying to compete with (even undermine) the commercial weather sector (Myers, 2011). It wasn't until the NRC's *Fair Weather* report in 2003, which presented recommendations for strengthening the public-private partnership, that these issues began to be fully addressed (NRC, 2003a).

Despite these conflicts, by the end of the MAR the commercial weather sector had greatly benefited from the increase in NWS's foundational data elements and numerical weather forecasting improvements. Better accuracy, timeliness, and localization of weather warnings and information were also beneficial. However, the transitional MAR period was challenging, as cost overruns and schedule slips made it difficult to plan for availability of new NWS datasets to support innovative private sector products.

**Research Community**

Partnership with the research community was key to the success of the MAR. There was debate about whether the modernized NWS should include a research function, but in the end the primary long-term research role remained with OAR. However, the introduction of the SOO positions (many have doctoral degrees) at the WFOs allowed a substantial effort in applied research related to ongoing problems faced in carrying out the WFO missions. Of course the technical developments (e.g., ASOS and NEXRAD) evolved from many prior years of research. However, it was important to avoid the pitfalls that beset the earlier AFOS system; the developer of AFOS worked largely independently of the intended users and the result was a system that, at least initially, failed to meet the real needs of those users. To avoid that hazard, many features of the MAR underwent rapid prototype testing; PROFS, operated by FSL, was a major component of this effort. The PROFS staff had access to a Doppler radar and experience in merging radar, satellite, and other data in computer and display systems. The $DAR^3E$ effort in the 1980s and 1990s (e.g., Rasmussen et al., 1992; Wilson et al., 1988) subjected many of the modernization concepts to critical assessments by prospective users. Experienced forecasters were brought in to work with and evaluate the capabilities of the prototype systems, and suggest shortcomings and desired improvements. Data and products from PROFS were transmitted to the WSFO in Denver for evaluation of utility in their ongoing real-time forecast and warning mission.

Ultimately software developed by PROFS and tested in this manner was chosen to replace that developed by the AWIPS contractor; the latter had been developed pursuant to a lengthy set of requirements but without ongoing assessment of how well it could meet the actual needs of the eventual users, as discussed in the AWIPS section. The PROFS system was developed in parallel with the contractor software as a risk reduction effort (NRC, 1996c).

The effectiveness of the NWS in carrying out its mission depends upon integrating advances in science and technology into its processes for producing and disseminating weather information, forecasts, warnings, and other products and services. Many of those advances originate in the academic community, and that community is also the primary source of the professional staff of the NWS. Thus close linkages with the academic community can facilitate the education of NWS staff and the transfer of research-to-operations, as well as stimulate the researchers to investigate problems of concern to the NWS. The NOAA system of cooperative institutes on university campuses that existed prior to the MAR is one way of maintaining an effective relationship with the research community.[11]

The COMET Program, established in 1989 by an agreement between NOAA and UCAR, provides one mode of enhanced collaboration with the research community. Training is a major component of the COMET program; some on-site short courses are offered to meteorologists and hydrologists, and an extensive set of modules is accessible online. COMET also supports a number of small collaborative research efforts, related to problems of concern to the NWS, which involve NWS staff as well as university faculty and students (Auciello and Lavoie, 1993; Johnson and Spayd, 1996; Waldstreicher, 2005).

**Finding 3-5**

**Partnerships between the National Weather Service and other National Oceanic and Atmospheric Administration line offices, other federal agencies, state and local governments, academia, the research community, and to some extent the private sector through contractor relationships, while not perfect, especially in the early years, were essential to successful execution of the Modernization and Associated Restructuring.**

## OVERSIGHT AND ADVISORY GROUPS

The magnitude of the MAR was large, both in scale and cost. The reorganization of staff and relocation and closure of offices introduced political issues. The NWS received a large amount of oversight and technical advice both from within and outside the government, throughout the execution of the MAR.

### Modernization Transition Committee

The Modernization Transition Committee (MTC) was mandated by Congress in Public Law 102-567 and chartered pursuant to the Federal Advisory Committee Act in July 1993 (DOC, 1993). The committee consisted of 12 members appointed by the Secretary of Commerce, with five members from federal agencies that provide or use weather services, and seven members from the academic, research, private sector, emergency management communities, as well as representatives of the workforce (DOC, 1993). The primary role of the MTC was to ensure that no degradation of weather services would occur with the closure of any WFSO or WSO, by reviewing the certifications prepared by NWS. The MTC was also responsible for advising the Secretary and Congress on implementation of the *Strategic Plan* and the annual development of *National Implementation Plans*. The committee served as an advisory body for implementation of the modernization criteria mandated by Public Law 102-567, and matters of public safety in the provision of weather services (DOC, 1993).

### National Research Council

An NRC National Weather Service Modernization Committee, mandated by Congress in Public Law 102-567 (U.S. Congress, 1992), provided oversight and review of various aspects of the MAR from 1990 (NRC, 1991) until the MAR was declared completed (NRC, 1999b). Over that decade the committee produced 15 reports that provided findings and recommendations

[11] The cooperative institutes that were in existence at the time of the MAR and conduct some weather-related research include the Cooperative Institute for Research in Environmental Science at the University of Colorado (CIRES; est. 1967), the Cooperative Institute for Marine and Atmospheric Studies at the University of Miami (CIMAS; est 1977), the Joint Institute for Marine and Atmospheric Research at the University of Hawaii (JIMAR; est. 1977), the Joint Institute for the Study of the Atmosphere and Ocean at the University of Washington (JISAO; est. 1977), the Cooperative Institute for Mesoscale Meteorological Studies at the University of Oklahoma (CIMSS; est. 1978), the Cooperative Institute for Meteorological Satellite Studies at the University of Wisconsin (CIMSS; est. 1980), and the Cooperative Institute for Research in the Atmosphere at Colorado State University (CIRA; est. 1980).

to guide the NWS and NOAA in putting the new technologies and new organizational structure in place to improve weather services to the nation. Topics of the reports included staffing and services as well as the technologies being introduced (Appendix B). This committee provided external expert review that, while not always welcomed, was generally considered an asset to the MAR. The NEXRAD Product Improvement Program discussed previously is an example of implementation of a committee recommendation.

### NEXRAD Technical Advisory Committee

A NEXRAD Technical Advisory Committee (TAC) was established in 1981 to review technical aspects of the tri-agency program, provide recommendations for needed scientific and technical advances, review proposals to accomplish those advances, and review the readiness of new developments for full implementation. This committee continues to serve under a somewhat revised charter; the "modernization" of the NEXRAD system is an ongoing process that did not end in 2000. The TAC comprises primarily representatives from the three involved agencies (four from each); however, it is chaired by an outside engineer or scientist and includes two at-large representatives appointed by the chair to provide external input. The committee establishes technical needs that, if met, would enhance the NEXRAD capabilities, and evaluates proposed hardware or software improvements to the system for readiness for implementation. Though the NRC National Weather Service Modernization Committee recommended similar technical advisory committees for each of the major MAR systems, none were formed during (or subsequent to) the MAR.

### U.S. General Accounting Office and Department of Commerce Inspector General

Oversight by the U.S. General Accounting Office (GAO[12]) and Department of Commerce Inspector General (IG) was thorough and significant, with over 20 reports addressing various aspects of the MAR. Appendix B includes a list of the GAO reports produced during the decade-long period of oversight. The GAO provided oversight of four major MAR programs: ASOS, NEXRAD, GOES-Next, and AWIPS. The GAO reports often highlighted key design and implementation inadequacies of the MAR systems acquisitions and provided recommendations to address these problems. Also, the GAO addressed schedule delays and budgetary issues.

At least six GAO reports (GAO, 1989, 1991b, c, 1996a, 1997c, 2000) addressed problematic aspects of the GOES-Next program. The reports highlight that GOES-Next experienced technological problems, significant cost overruns, and schedule delays in the development of the five GOES satellites.

The AWIPS program provides another example of the extent of GAO oversight. AWIPS, which in many respects was the integrator of the modernization, encountered significant costs overruns and schedule delays. The original budget for AWIPS was $350 million and it was expected to be fully deployed by 1995 (GAO, 1991a). In 1995, the NWS estimated that the cost to develop AWIPS was $525 million, and that it would be fully deployed by 1999. The GAO investigated and found the estimate to be inaccurate (GAO, 1996b, d). Subsequently, the DOC committed to a $550 million budget for AWIPS, however the GAO noted that the costs were likely to exceed that amount due to the complex nature of the system (GAO, 1997e). AWIPS was initially deployed with less than full functionality and required additional upgrades to be added to future software builds, adding additional costs. The GAO reported that a systems architecture that described the overall blueprint for AWIPS was lacking (GAO, 1994), and the NWS embraced the GAO recommendation to develop such a systems architecture (GAO, 1999) near the end of the MAR.

A number of other GAO reports also highlighted design and implementation flaws, as well as schedule delays and budgetary issues for the ASOS (GAO, 1995h) and NEXRAD (GAO, 1995f, g) programs. Other reports addressed concerns regarding personnel issues and staffing (GAO, 1995d), or evaluated the MAR progress from a broader perspective (GAO, 1995a) including identifying future risks at the midway point (GAO, 1995i).

The DOC IG also provided oversight of the MAR.

[12] Effective July 7, 2004, the GAO's legal name was changed from the General Accounting Office to the Government Accountability Office.

For example, early in the program, concerns about NWS management of the MAR were raised by the IG (DOC, 1990). Other IG reports addressed concerns about fair competition for the modernization development program awards (DOC, 1999) and addressed the AWIPS system (DOC, 1992). These IG reports and inquiries added further oversight to the MAR, and provided federal guidance when needed.

### Congress

To the benefit of the NWS there were a number of members of Congress who supported the opportunities for improvement of weather services presented by the MAR. Having advocates in Congress helped reach the final decision for implementation and to see the needed appropriations survive the budget process. Clearly, there were champions of the MAR in Congress. These members understood the value of new technologies that could track weather events in real-time, and allow the NWS to issue warnings in time to save lives and property. These champions of the MAR were able to impress upon their colleagues the importance of improvements to NWS technologies.

NWS and DOC management and their representatives were able to adequately communicate with members of Congress to build the support necessary for appropriations of significant funding for the procurement and implementation of new technology, training and retraining of personnel, location and relocation of facilities, and to reorganize the NWS. Working with members who had the ability and interest to garner support from other members from critical geographic areas regardless of party affiliation was important.

Nevertheless, there were many aspects of the MAR that invited Congressional oversight. The closing and relocation of many local forecast offices was of particular interest, because members wanted to ensure that their constituents would have no degradation of services. Public comments identified 32 areas of concern about degradation of service related to NEXRAD coverage. An NRC assessment of NEXRAD coverage determined that degradation of radar coverage did not necessarily equate to degradation of services (NRC, 1995b). There were only a few instances where a Member succeeded in preventing the closing of a forecast office or other NWS facility, but on occasion a planned radar location was altered. Some frustration arose from the different interpretations of degradation of service: whether degradation could be determined from meteorological criteria, or whether it was related to a change in the number of jobs or money spent in a state or congressional district. It appears that while such political challenges could have derailed the overall project, this did not materialize, largely because of good communication between NWS and Congress.

The circumstances that came together in the 1980s and brought about major decisions to change the NWS were significant. NWS invited oversight by Congress, and Congress welcomed the information about growing technological capabilities and saw the benefit of improved forecasts and warnings. These positive working conditions made it possible to obtain the necessary appropriations to implement the vision of a modern NWS and make the difficult decisions about office closures and relocation.

**Finding 3-6**
**Independent oversight and technical guidance helped draw attention to important issues and impediments that otherwise may have inhibited the success of the Modernization and Associated Restructuring (MAR). This external oversight provided accountability of the technical, scheduling, and budget metrics during the MAR process.**

# 4

# Impact of the Modernization and Associated Restructuring

This chapter focuses on the effects of the Modernization and Associated Restructuring (MAR) of the National Weather Service (NWS) on the provision of weather services to the Nation after 2000. The actual impact of the MAR is compared to the promised benefits presented in Chapter 2, and summarized in specific findings about the major aspects of the MAR. The MAR brought such major changes in the capabilities and operation of the NWS that its effects took, in many cases, several years after 2000 to be realized. This is particularly true about the skill of atmospheric analysis and forecasting, which has improved steadily since the end of the MAR, as well as the relationship of the NWS with both the private sector and the emergency management communities. Therefore, this chapter contains several rather extensive discussions of MAR impacts extending up to the present day.

## MANAGEMENT AND PLANNING

In addition to the planned system improvements that were the objective of the MAR, execution of the project itself left a legacy of institutional and cultural changes at NWS, largely for the betterment of the organization. Critical to understanding this legacy is differentiating between the near-term impacts during the MAR (influenced by the challenges of dealing with change) and the longer-term impacts (after the changes had been institutionalized).

### Management Context and Constraints

The capability of NWS to function within the greater context of issues discussed in Chapter 3 was considerably improved as a result of the MAR. The staff perception now is that NWS is widely seen as more authoritative, it is doing its job better,[1] it manages relationships more effectively, and it is more focused on customers and understanding their needs (committee member WFO site visits, see Appendix C for list of WFOs visited). That is not to say that contextual issues have disappeared. Technology is still evolving more rapidly than the NWS can respond, particularly in the area of communications (e.g., social media) and applications. Infrastructure put in place during the MAR is now as much as two decades old, and could present a cost liability as it requires replacement. There is also an increasing need to leverage partnerships; these partnerships bring new challenges, such as quality and standards arising in the case of data partnerships (e.g., weather observing networks from a variety of sources; NRC, 2003b).

### Budget and Schedule

NOAA and NWS's experience with the budget and schedule challenges of the MAR could have resulted

[1] Employee comments from one WFO included "the reorganization allowed us to focus better, and the modernization allowed us to do a better job within that focus."

in an improved capability to manage large, complex procurements, but it is not clear whether that was achieved. Issues with upgrading the NEXRAD system to dual-polarization radars and the implementation of AWIPS-II, suggest that either many of the MAR lessons were not internalized within the agency or that they are not relevant in the current environment. There have also been issues with the National Polar-orbiting Operational Satellite System (NPOESS) program. Although it was managed under an Integrated Program Office and not according to the typical NOAA program approach, it appears to also not have benefited substantially from lessons learned from the MAR.

## Organization and Staff

One of the most important results of the MAR was the organizational transition of the meteorological staff. The ratio of technicians to professional meteorologists evolved from 2:1 to 1:2 and the number of staff was reduced by about 10 percent (Sokich, 2011). Based on committee member visits to WFOs (see Appendix C for list of WFOs visited), the transition is now viewed positively by employees, but a wide range of issues persist, presenting opportunity for further improvement. Employees appear to have learned and retained the value for ongoing innovation and change, recognizing that it is essential to ongoing organizational survival and improvement. The NWS focus on extensive staff training has been retained as well, but much of the training is now done online or on the job due to budget limitations (Spangler, 2011). A key issue that arose during the MAR, the balance between standardization of office size and structure and local flexibility, remains a central tension within the organization. Activities and process development to better achieve the correct balance are an ongoing focus. For example, there is some concern that requirements of some staff positions vary from office to office, and that these variations are not adequately reflected in job descriptions and staffing levels. Field office location continues to be a concern in some cases, particularly where the WFO is not sited close to the primary community within its area of responsibility. The MAR had clear and lasting impacts at the field level that are discussed in more detail later. It is less clear whether the MAR improved the overall organizational efficiency at the executive level. However, the realignment of the National Centers that restructured several of the core technological activities of the NWS presumably had a streamlining effect on the management of NWS activities.

## Processes

Many of the processes introduced to execute the MAR have been retained in one form or another. One key process, the research-to-operations transition, continues to be a major issue (MacDonald, 2011) and has been the subject of numerous NRC reports (e.g., NRC, 2000, 2003b, 2010). Partner relationships, (Congress, private sector, the National Weather Service Employee Organization, media, emergency managers) have been substantially improved in most cases (Friday, 2011; Hirn, 2011; Myers, 2011). Overall NWS processes are now more flexible and responsive to evolving context, though there is considerable room for further improvement.[2]

Among the more important legacies is the capability to assess performance,[3] instituted in the early 1980s and used during the MAR in part to satisfy the Congressional mandate for no degradation of service. However, it is often difficult to obtain performance statistics outside the NWS. The government procurement process, within which NOAA and NWS have limited flexibility to configure procurement to their particular needs, continues to be a major constraint. There is evidence of this in the upgrade of the NEXRAD system to dual-polarization radars and the implementation of AWIPS-II.

A notable issue with the processes involved in implementing the MAR was the lack of a systems architecture (GAO, 1994). Necessary elements include developing a system-of-systems architecture and concept of operations based on defining achievable, quantifiable mission goals and prioritizing user needs. Such an architecture would have tied the top-level goals and objectives for each individual system with the specific user needs for each individual system, and synthesized these into a set of system-of-systems goals that are

[2] An example is the ASOS system, which logs data every minute but only reports hourly summaries. To access minute-scale data, each WFO must connect with each ASOS site using dial-up access.

[3] Performance and performance degradation can involve subtle issues, as with changes in WFO performance when an office is moved, or changes are made in the storm reporting system (Smith, 1999).

functions of the separate systems all working together. In the case of the MAR, the individual systems were ASOS, NEXRAD, GOES-Next, the National Centers computer systems, and AWIPS. One possible goal of this system-of-systems could have been a specific, measurable improvement in Probability of Detection for various types of severe weather or even an overall scorecard that encompasses multiple metrics that are deemed important to the NWS and made available to the public. Exercise of this rigorous process would next have led to development of an optimal set of top-level requirements for the respective individual systems' contractors.

Tying the mission goals and key performance metrics to specific user needs via top-level requirements analysis and documentation is essential to enable the contractor to develop a design against a set of requirements that meets both the mission goals and the user needs. Providing a clear and concise set of documents to the contractor early in the process is crucial so that they can execute efficiently and be held accountable for meeting budget, schedule, and performance goals. Lack of such a systems architecture introduces considerable risk to a program the size and complexity of the MAR. The larger and more complex a program effort is, the more important it is to utilize effective systems engineering processes. Without this the program manager (whether government managing contractor or contractor managing subcontractor) loses a major management tool. Setting mission performance metrics also allows for a quantitative assessment of the success of a program upon completion. An illustration of the lack of adequate application of the system engineering process is the AWIPS program. AWIPS requirements were based on user needs, but they were apparently not tied to mission-based goals (GAO, 1996c). Also, the large, complex set of over 20,000 requirements indicates a lack of prioritization of user needs. The contractor failed to develop a design that met the needs of the primary users, but with a lack of prioritization and overwhelming number of requirements, this is understandable.

**Finding 4-1**

**Many of the institutional changes (management structure, culture, processes, partner relationships) introduced to implement the Modernization and Associated Restructuring (MAR) have been retained by the National Weather Service (NWS). Most of these "institutional byproducts" have been as valuable as the MAR improvements themselves and will help the NWS to continue to modernize. However, from viewing more recent projects, implementation of a rigorous systems engineering process to facilitate more effective management of the procurement and development of large, complex systems appears not to have been institutionalized within the National Oceanic and Atmospheric Administration. The systems engineering process needs to start at the beginning of the program, in the agency's program office.**

## MODERNIZATION OF TECHNOLOGY

Although the technologies improvements of the MAR fell behind schedule and had larger than anticipated costs, they contributed to the capability of the NWS to provide improved weather services to the nation. This improvement is particularly evident in the forecasting and detection of severe weather such as tornadoes and flash floods, and will be discussed at the end of this section.

### Automated Surface Observing System

The replacement of human observers with the Automated Surface Observing System (ASOS) was quite controversial at the time of the MAR, and continues to be controversial. Through the years, a number of conflicting reports from a variety of sources have both lauded and criticized ASOS and its implementation. From the outset, the ASOS implementation was designed to provide a more robust, hourly, and automated surface observation capability at over 1,000 airports (Figure 4.1). The manual observations being collected at the time of the modernization were at 250 airports, and the observations were only taken during the hours that each airport was open. Although automation was seen as both a cost cutting measure and an opportunity to collect more data, the numerous stakeholder groups that were destined to use the data questioned the quality of the data collected. In addition, each of the primary users of ASOS, the NWS, FAA, and DOD, had a different set of requirements for the data and clear, cohesive metrics to evaluate the success of ASOS were never determined. Each user group had a different set of metrics, and therefore judged the suc-

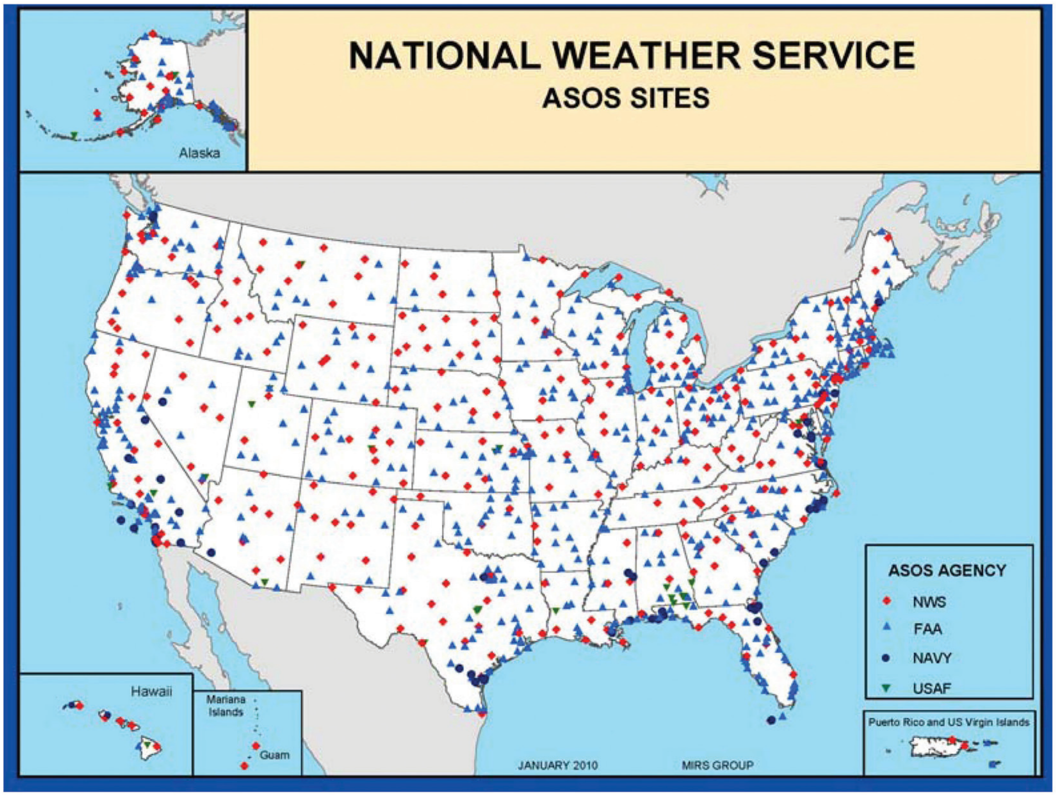


**FIGURE 4.1** Locations of Automated Surface Observing System (ASOS) sites in the United States. The 315 ASOS sites managed by the National Weather Service are indicated by red diamonds. Blue triangles, blue circles, and green triangles indicate the 571 Federal Aviation Administration, 75 Navy, and 48 Air Force ASOS sites, respectively. SOURCE: National Weather Service.

cess of ASOS through its own lens. Another key issue in the implementation of ASOS was the lack of field testing. This lack of preliminary reliability testing led to problems with the sensor suite remaining undiscovered until after ASOS was deployed (GAO, 1995h). Furthermore, ASOS algorithm development likely could have benefited from the type of prototyping that occurred for AWIPS through PROFS.

At the end of the MAR era, there were still internal reports being commissioned by both the FAA and NWS to examine ASOS. For example, a 1999 FAA document claims, ". . . after years of development, ASOS correlates quite closely with human observations most of the time" (AOPA, 1999). No references are listed, no studies are cited, and it is only an anecdotal statement.

NEXRAD resulted in the ability for NWS forecasters to observe weather phenomena at higher resolutions than its pre-MAR technological predecessors, but the advancement for weather and climate forecasting that was realized from the deployment of ASOS was not as dramatic. Because ASOS was designed primarily to support airport aviation needs, and because of well documented issues with sensor performance as they pertain to weather and climate studies, many scientists turned to developing their own networks for surface observing. These regional and state networks, called mesonets, were typically operated by state entities and agencies. Examples include the Oklahoma Mesonet (commissioned in 1994) and the Florida Automated Weather Network (FAWN; commissioned in 1997). Data from these mesonets have become important resources for the NWS severe weather warning operations as well as research. Because the mesonets are state initiatives the coverage is not even across the nation, or sometimes even across a region. Such uneven coverage needs to be addressed as the weather enterprise further develops. A 2009 NRC report provided recommendations for creating a "network of networks" with even coverage across the nation (NRC, 2009).

By 2003, the NRC *Fair Weather* report outlined nine major examples of ASOS failures where climate studies are concerned. The report states, "[i]n the ideal, the ASOS observations would be error-free and representative of actual conditions. Therefore the interim climate summary, daily climate summary, preliminary climate data, and final official climate record would all agree with each other and all reflect the best possible estimate of conditions. As the nine representative cases make clear, this ideal situation is not always met" (NRC, 2003a). In addition, Horel et al. (2002) state that the widespread use of ASOS will continue to impede efforts to monitor Earth's climate and study its variability. The impact of ASOS on the climate record is discussed later in this chapter and in Appendix E.

**Next Generation Weather Radar**

The 1-degree beamwidth and Doppler capability of the NEXRAD radars provided forecasters with enhanced ability to identify weather features of concern. The NEXRAD network is largely responsible for the improvement in the NWS capability to detect severe weather such as tornadoes, as discussed below. The broad national coverage of the NEXRAD radars was also a distinct improvement over that of the predecessor WSR-57, WSR-74, and Air Weather Service FPS-77 systems (Figure 4.2). Maddox et al. (2002) provide a more recent analysis of NEXRAD coverage.

The NEXRAD Product Improvement Program has continued to capitalize on continuing advances in technology and science underlying the processing and use of the radar data. An "R&D" NEXRAD at NSSL provides a testbed for evaluating proposed system improvements (Zahrai and Zmic, 1993).

Implementation of the recommendations from NRC (1991) in the NEXRAD program benefitted the nation through an organized research-to-operations program leading to a series of substantial upgrades to the basic NEXRAD system. Examples range from the conversion from the initial proprietary computational system to an open architecture to the forthcoming polarimetric upgrade.

Another recommendation related to the need for ongoing training programs for NWS personnel was as well not implemented:

> The National Weather Service should develop a continuing comprehensive training and education program so that the skills of the Next Generation Weather Radar maintenance and operational staffs, as well as the meteorologists and hydrologists, reflect the ever-changing state of the art (NRC, 1991).

The intensive on-site training provided at the outset of the MAR has been gradually reduced in scope; the Warning Decision Training Branch does provide a comprehensive program, but the number of people who can take advantage of it is limited. A series of COMET modules provides some online training, but these lack the hands-on element provided by the on-site experience and are not regarded as comparable. This is an item of special concern as the polarization upgrade to the NEXRAD system comes online.

Perhaps the main remaining radar coverage issue had to do with the difficult problems encountered in complex terrain. A mountaintop site provides a long-range view, but cannot see down into many of the valleys where most people would live (a problem exacerbated by the NEXRAD restriction to a minimum elevation angle of 0.5 degree). A valley site may address that problem for one or a few valleys but cannot provide broad area coverage. The NEXRAD site selection generally opted for the mountaintop; for some purposes such sites provide adequate support of forecasting and warning functions (e.g., NRC, 2005), but for others they are less satisfactory (e.g., Reynolds, 2011; Westrick et al., 1999).

NEXRAD radars are owned and operated by the USAF and the FAA, in addition to the NWS. Missions of those agencies differ from those of the NWS, and this occasionally led to some nonuniformity of operations. For example, availability of the USAF radars was an issue in the early days. Archiving of the data on a routine basis is of interest to the NWS, while the other two agencies are concerned mainly with data related to some event such as an aircraft incident; this has led to gaps in the archival record. In a similar vein, distribution of wideband data or products to neighboring installations is more important to the NWS functions than to the USAF or FAA operations; the latter tend to focus on specific airfields. Again, this has led to unevenness in the export of data from different NEXRAD sites. At the same time, it must be said that the FAA has pushed for development of capabilities (such as a

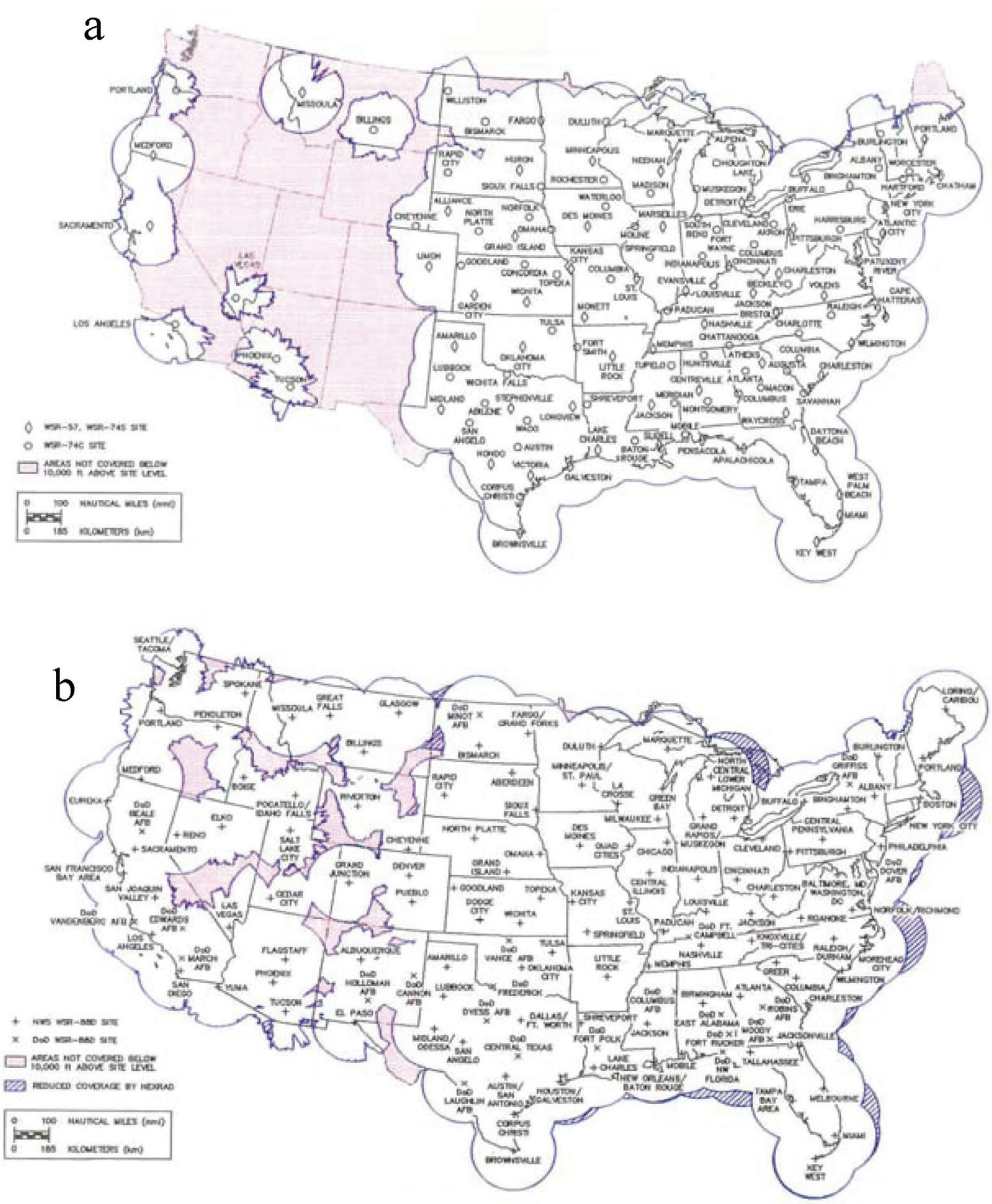


**FIGURE 4.2** (a) Composite pre-NEXRAD coverage at 10,000 feet above site level for CONUS is indicated by white circles. Radar locations are indicated by diamonds (WSR-57 and WSR-74S) and circles (WSR-74C). The pink shading indicates areas that have no radar coverage below 10,000 feet above site level. (b) Composite NEXRAD coverage at 10,000 feet above site level for CONUS is indicated by white circles. WSR-88D radar locations are indicated by + (National Weather Service radars) and × (Department of Defense radars). The pink shading indicates areas that have no radar coverage below 10,000 feet above site level. The striped blue shading indicates areas where coverage at the 10,000 feet level is reduced compared with the pre-NEXRAD network. SOURCE: U.S. Department of Commerce.

gust-front algorithm) that would aid the aviation mission but are of less interest to the NWS.

## Satellite Upgrades

NOAA's objectives for GOES-Next were continuous Earth-viewing with retention of the existing visible imaging, higher resolution infrared (IR) imagery, improved Earth location capabilities, and a separate sounder. Despite the difficulties in program design and execution, GOES-Next introduced substantial data and product improvements. On earlier geostationary satellites, the imager and sounder could not simultaneously collect data because they used the same telescopic viewing apparatus, and the spin-stabilized satellite rotated on its axis viewing Earth only six percent of the time on each 360-degree rotation (GAO, 1997c). Although the initial development of a three-axis, body-stabilized spacecraft design for GOES was problematic, it ultimately resulted in successful establishment of a valuable approach. These improvements together enabled continuous, simultaneous, independent imaging and sounding. Each instrument had flexible scan control, allowing for coverage of small areas, hemispheric, and full disk global scenes. Meteorologists were able to access close-up, continuous observations of dynamic, short-lived weather phenomena, such as local severe storms and tropical cyclones, as well as obtain data on the atmospheric temperature and water vapor structure.

The implementation of GOES-Next resulted in substantial improvements to the frequency, spatial resolution, data quality, and spectral resolution of NWS geostationary satellite data. Specific impact areas include

- *Imagery*. Due to the Earth-pointing capability of the GOES-Next satellite, the five-channel imager could produce imagery every 5 to 10 minutes for local-scale severe weather events and every 15 minutes for CONUS coverage, and scan the full disk northern hemisphere in less than 30 minutes (with images provided every 3 hours). The continuous viewing capability is critical for monitoring severe storms (GAO, 1991b). Improvements were made in the spectral resolution and signal-to-noise performance, as shown in Table 4.1. New uses of imager data were developed. For example, the data were combined with the NEXRAD radar data to enhance winter snowstorm forecasting, nighttime fog detection was enabled using two IR channels, and the higher resolution IR imagery was useful in predicting and monitoring severe thunderstorms. Additional results include

  - best 6.7 μm (IR water vapor channel) imagery ever; an order of magnitude improvement enables identification of mesoscale disturbances embedded within synoptic scale features;
  - better wind data inferred from cloud drift with 4 km image resolution for better edge detection and improved target selection;
  - improved wind data inferred from water vapor imagery in clear regions with 8 km spatial resolution and better signal-to-noise at 6.7 μm;

**TABLE 4.1** Comparison of Measured Imager Performance for GOES-7 (Pre-MAR Generation Satellite) and GOES-8 (GOES-Next Generation).

| Wavelength (μm) | IGFOV[a] at nadir (km [E/W × N/S]) | SSR[b] (km [E/W × N/S]) | Noise |
|---|---|---|---|
| | *GOES-7 Characteristics* | | |
| 0.55-0.75 | 0.75 × 0.86 | 0.75 × 0.86 | 6 bit data + 2 counts (3 sigma) |
| 3.84-4.06 | 13.8 × 13.8 | 3.0 × 13.8 | 6.0 K @ 230 K<br>0.25 K @ 300 K |
| 6.40-7.08 | 13.8 × 13.8 | 3.0 × 13.8 | 1.0 K @ 230 K |
| 10.4-11.3 | 6.9 × 6.9 | 3.0 × 6.9 | 0.2 K @ 230 K<br>0.10 K @ 300 K |
| 12.5-12.8 | 13.8 × 13.8 | 3.0 × 13.8 | 0.8 K @ 230 K<br>0.40 K @ 300 K |
| | *GOES-8 Characteristics* | | |
| 0.52-0.72 | 1.0 × 1.0 | 0.57 × 1.0 | 10 bit data + 8.1 counts (3 sigma) |
| 3.78-4.03 | 4.0 × 4.0 | 2.3 × 4.0 | 4.0 K @ 230 K<br>0.16 K @ 300 K |
| 6.47-7.02 | 8.0 × 8.0 | 2.3 × 8.0 | 0.27 K @ 230 K |
| 10.2-11.2 | 4.0 × 4.0 | 2.3 × 4.0 | 0.40 K @ 230 K<br>0.12 K @ 300 K |
| 11.5-12.5 | 4.0 × 4.0 | 2.3 × 4.0 | 0.40 K @ 230 K<br>0.20 K @ 300 K |

[a] Instantaneous Geometric Field of View: The detector IGFOV (or footprint) is the size of a pixel on Earth's surface that a single detector, in the array of detectors associated with a specific wavelength, is able to "view" when looking directly below the spacecraft (the sub-satellite point).
[b] Sampled Subpoint Resolution (SSR): Because the combination of the imager's scan rate and detector sample rate exceeds the pixel E/W IGFOV, the viewed scene is oversampled. An IGFOV of 4 km oversampled by a factor of 1.75 provides an effective resolution, or SSR, of 2.3 km.
SOURCE: Purdom (1996).

  - fog, water, and ice cloud detection both day and night using continuous 3.9 μm imagery with other channels;
  - identification of super-cooled cloud;
  - monitoring of snow and ice cover and the detection of cloud over snow;
  - improved detection of forest fires and biomass burning;
  - useful imagery well beyond the satellite's 60-degree zenith angle making possible the detection and tracking of sea ice and polar lows;
  - improved low light imaging capability with 10-Bit visible-channel data;

- enhanced land and sea surface temperature monitoring capability using 30-minute interval multispectral IR capability (Purdom, 1996).

• *Soundings*. With the launch of GOES-8 in 1994, continuous geostationary sounder data was available for the first time. The new, independent sounder produced 18 channels of IR data in addition to one in the visible, yielding improved vertical resolution. Soundings retrieved from the GOES-Next data proved to be useful aids in qualitative interpretation. They provided timely information about changes in atmospheric moisture and stability and gradients were better delineated. In 1997, measurements of precipitable water from the sounder were included for the first time in the input to numerical weather prediction (NWP) models (GAO, 1997c).

• *Systematic Impacts*. The Advanced Weather Interactive Processing System (AWIPS) included the capability to display GOES-Next satellite data on the Weather Forecast Office (WFO) workstations and to combine this imagery data with other data to aid the forecaster. The satellite improvements were critical to WFOs along the west coast, improving their capability to analyze approaching weather over the data-sparse Pacific Ocean as well as moisture surges and tropical disturbances from Mexico, the Gulf of Mexico, and the Caribbean. Many recommendations were made to NOAA by the GAO and others regarding the approach to satellite system procurement. NOAA and NASA apparently took these recommendations into consideration when planning the follow-on series of geostationary satellites, after GOES-Next. Approaches considered included procuring "clones" of prior satellites and/or instruments via sole source contracts. NOAA weighed the potential benefits of significant technological advances against the schedule and budget risks involved. NASA was positioned to once again act on behalf of NESDIS and manage the instrument contracts directly (GAO, 1996a).

## National Centers Advanced Computer Systems

The strategic and operational planning for the MAR emphasized the need for dramatic upgrades in the computing capabilities of the NWS. The cited rationale included the capability to run ever more complex general circulation models and data assimilation algorithms. New computational capacity was required to assimilate the new observations available as part of the MAR, particularly the satellite retrievals and later radiances, into the various global and mesoscale numerical weather prediction models.

Public Law 100-685 called for "detailed plans and funding for meteorological research to be accomplished under this title to assure that new techniques in forecasting will be developed to utilize the new technologies being implemented in the modernization" (U.S. Congress, 1988). The *Strategic Plan* stated that "[f]undamental model improvements are necessary to satisfy these requirements and provide guidance products of sufficient quality and frequency to support the warning and forecast operations at each office" (NWS, 1989). The Development Division within the National Meteorological Center (NMC), together with the research in numerical modeling being undertaken at the Geophysical Fluid Dynamics Laboratory (GFDL; Princeton, NJ) were both continually involved in model development. But, so far as the committee can ascertain, the MAR planning did not explicitly include benchmarks, or a timeline, for the very extensive software development effort involved in dramatic improvements in modeling and data assimilation. It seems that it was assumed these developments would occur, without specific planning as a component of the MAR. However, by the end of the MAR, there had been substantial improvements in atmospheric modeling and data assimilation, as well as the development of an evolutionary capacity of computing technology within NWS.

## Advanced Weather Interactive Processing System

Development of an advanced computer and communications system to help forecasters in field offices integrate all sources of weather data, to assist them in analyzing fast-breaking storms, and to aid in the timely preparation of warnings and forecasts was a major accomplishment of the MAR. The system provides a communications network that interconnects each WFO and includes the capability for distribution of centrally collected data and centrally produced analysis and guidance products, as well as satellite data and imagery. Together this system is termed the Advanced Weather Interactive Processing System (AWIPS) and NOAAPort (NWS, 1989).

By the end of the MAR, AWIPS was, and continues to be, used to

- provide computational and display functions at operational NWS sites;
- provide open access, via NOAAPort, to extensive NOAA datasets that are centrally collected and/or produced (e.g., NCEP NWP products, products from other centers such as NHC and SPC, and international centers producing global analyses and predictions);
- acquire and process data from an array of meteorological sensors including ASOS, NEXRAD, GOES instruments, local sources (e.g., mesoscale networks, river flow gauges, atmospheric sounders) and other sources (e.g., sensor data from commercial aircraft via the Aircraft Communications Addressing and Reporting System [ACARS]);
- provide an interactive communications system to interconnect NWS operations sites and to broadcast data to these sites; and
- assist forecasters in preparation and dissemination of warnings and forecasts in a rapid, highly reliable manner.

With the implementation of AWIPS, forecasters are now able to sit down at one workstation and view a large, complex set of weather data in as many as twelve windows. The total spectrum of weather information can be overlaid and integrated on a single map to get a unified picture of what's happening and aid in forecasting. According to one forecaster,

> AWIPS has greatly improved [forecasters'] ability to quickly ingest, manipulate, and analyze immense amounts of data. One of the most important capabilities introduced with AWIPS has been to combine graphical data (e.g., geopotential height analyses) with imagery (including satellite imagery), then view these data on a loop with easy zoom and pan capability. This has been an important function of WFO workstation technology given the rapid increase in available numerical model data (Jackson, 2011).

Although AWIPS met the meteorological forecaster needs, it did not adequately address hydrologic applications. This inadequacy reflects issues in both the requirements development and AWIPS build and test processes. The forecaster-user was very well integrated into the entire development and build cycle; the hydrologist-user needs were unable to be as well addressed due to time and budget constraints, among other issues. The lesson here is that, if all users are equal, all user-needs need to be equally addressed from program initiation throughout all processes, and this effort needs to be reflected in the planned schedule and budget. In addition, an important component, GFE (Graphical Forecast Editor), was not integrated into the AWIPS core software package. Short term warnings use AWIPS; long term forecasts and hydrology use GFE. However, because AWIPS uses the open source Linux operating system, additional software development and integration is facilitated. As a result of the MAR, forecaster workstations and some servers were also upgraded. Prior to the MAR, offices as part of AFOS had a few unlinked workstations connected via "store and forward" regional communications loops. WFOs now have half a dozen workstations linked by a high speed national data network.

## Performance of Post-Modernization Forecasts and Warnings

The performance of post-MAR forecast and warning operations of the NWS were dramatically improved by the MAR. The following review is limited to tornado and flash flood warnings; numerical weather prediction and its application to general weather forecasts; and hurricane and extratropical storm forecasts, as these are the types of weather of most interest to the public (winter weather forecast performance data from before the MAR are not available).

### *Tornado and Flash Flood Warnings*

As proposed in the *Strategic Plan*, one major goal of the MAR was to provide more reliable detection and prediction of severe weather and flooding. Perhaps the most striking result of the MAR has been the improvement in the probability of detecting and issuing warnings for severe weather events (e.g., Figure 4.3a,b). The probability of detection (POD)[4] and warning for

[4] From the AMS Glossary of Meteorology: "POD and FAR are useful evaluators for binary, yes/no kinds of forecasts, and detection techniques. For example, if A is the number of forecasts that rain would occur when it subsequently did occur (forecast = yes, observation = yes), B is the number of forecasts of no rain when rain occurred (no, yes), and C is the number of forecasts of rain

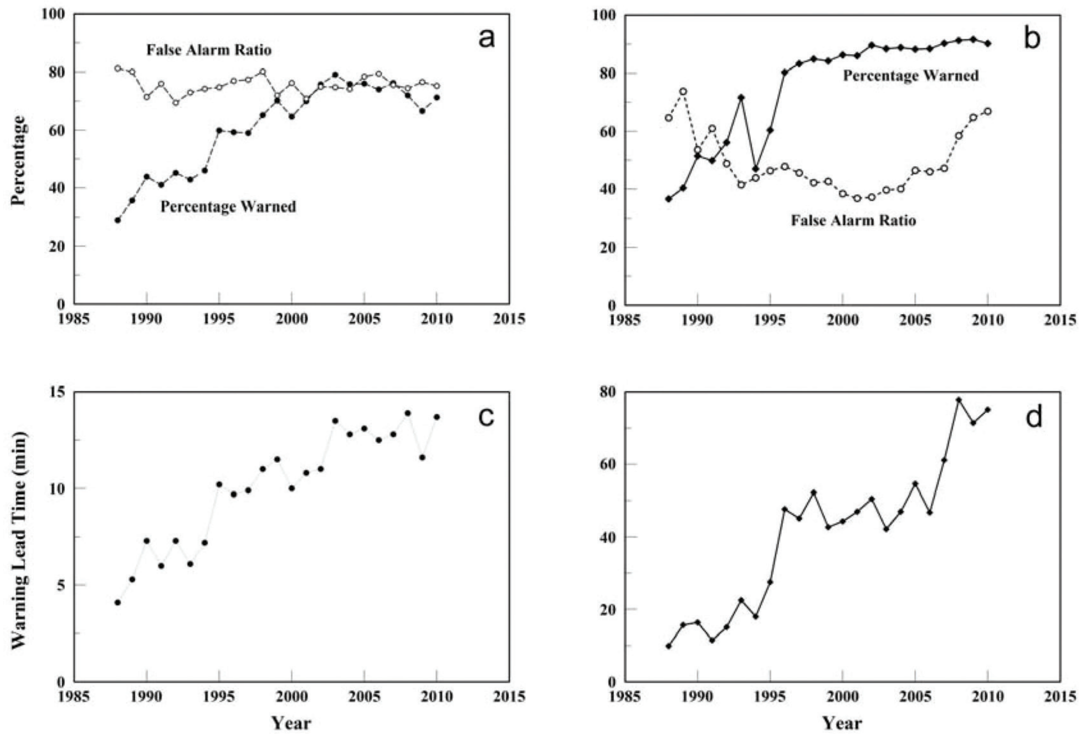


**FIGURE 4.3** Probability of detection (POD)[4] and False Alarm Ratio (FAR)[4] for (a) tornado warnings and (b) flash flood warnings. Lead times[5] for (c) tornado warnings and (d) flash flood warnings. The POD and warning lead times for both tornadoes and flash floods increased steadily over the course of the MAR, while the FAR for tornadoes and flash floods remained relatively constant. SOURCE: Based on data provided by the National Weather Service.

tornadoes and flash floods increased steadily from the beginning of the MAR until it was completed in 2000. At the same time, the average lead times[5] of tornado warnings issued on the basis of observations increased from under five minutes to over 12 minutes (Figure 4.3c) and flash flood lead times increased from about ten minutes to over 40 minutes (Figure 4.3d). The failure of the accompanying false alarm ratios (FAR)[4] to decrease at the same time as the POD has increased has been a disappointment. This problem could have several causes including the unreported occurrence/confirmation of predicted tornadoes or the occurrence of funnel clouds that did not reach the ground, or the common problems of atmospheric sampling caused by the limitations of the void under the radar beam caused by Earth's curvature. In any event, the warning system continues to issue many warnings that are not reported and/or realized. Increased scientific understanding of these severe weather processes and integration of such understanding into operations, as well as further improvements in technology—especially radar and radar coverage—could help improve the false alarm ratio.

The NWS severe weather warning system continues to be impacted by problems associated with the dissemination of the warnings to the population at risk. Again in the severe weather occurrences (tornado outbreaks) in 2011, timely warnings were issued but the loss of electrical power due to earlier severe weather left many households in the path of the storms without adequate means to hear the warnings and take necessary lifesaving actions.

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when rain did not occur (yes, no), then POD = A/(A+B) and FAR = C/(A+C). For perfect forecasting or detection, POD = 1.0 (or 100 percent) and FAR = 0.0 (or 0 percent)."

[5] Lead time is the time from when the warning is issued until the time the event is reported within the warned area.

### *Numerical Weather Prediction and its Application to General Weather Forecasts*

In addition to improved severe storm and flash flood detection resulting from the MAR technologies and service restructuring, one of the promised benefits of the MAR was to improve NWS forecasts and warnings, making them as accurate and timely as possible. Forecasts result from a complicated process that starts with obtaining all possible observations, such as direct measurements of surface and upper-air properties and remote measurements by satellites and radar. These observations are assimilated into the initialization process for numerical models, and the model output is post-processed using Model Output Statistics (MOS) procedures to develop guidance which is used, along with real-time observations and the model output itself, by field office forecasters to make forecasts.

The NWS has performed numerical prediction operations at NCEP[6] beginning in the mid-1950s and continuing to today. The four-times per day execution of the models produces a wide variety of analyses and products on regional, national, hemispheric, and global scales. An evaluation of the overall performance of the NCEP global numerical weather prediction operation over the period 1985 to 2009 is presented later in this chapter (Figure 4.11).

It is a major step to go from a numerical model prediction to information that can be used as guidance to forecasters producing general weather forecasts out to about 10 days. The NWS has developed Model Output Statistics (MOS) procedures that downscale NWP model output through a statistical interpretation of the model parameters in terms of surface weather variables appropriate for the forecast time in question. MOS relates observations of a weather element to be predicted (e.g., maximum or minimum temperature, or probability of precipitation) to appropriate variables (e.g., model outputs, initial observations, and geoclimatic data such as terrain, and normal conditions) using multiple regression techniques.

At the time of the MAR, the MOS were calculated each forecast cycle for specific forecast points and the model output was interpolated to observation locations. MOS were applied to most surface weather variables. Dallavalle and Dagostaro (2004) examined the application and value of MOS alone compared to the local forecasts produced by NWS field forecasters utilizing their professional judgment as well as the MOS guidance for the period 1966 to 2004. The study analyzed forecasts for 80 stations distributed across the CONUS. Recently updated results, with data through 2010, for 36- and 60-hour forecasts of minimum temperature are shown in Figure 4.4, and for 24- and 48-hour forecasts of probability of precipitation (PoP) are shown in Figure 4.5. The study reported by Dallavalle and Dagostaro (2004) included other parameters (e.g., maximum temperature) and other forecast lead times and for the cold season as well as the warm season, with similar results as shown in Figures 4.4 and 4.5. The results clearly show the improvement in the quality of both the local forecasts and the guidance—largely reflecting the model improvement. The skill between the MOS and the locally generated product converges later in the period, showing the increasing relative value of guidance in the forecast process.

### *Hurricane and Extratropical Storm Predictions*

The National Hurricane Center (NHC) uses a variety of models as guidance in the forecasting process. Figure 4.6 illustrates the performance of the various models showing annual average forecast track errors for the period 1994 to 2009. The solid black line is the annual average track errors for the resulting Official 48-h NMC Forecast that is issued to the public. Over the 16-year period the performance of the various models has converged, with less scatter later in the period, reflecting better data and improved model physics as well as improved computing power. The improvement in the Official Track Forecast is apparent, especially after 2001.

The long-term trend in the Official Hurricane Track errors for the period 1970 to 2009 is illustrated in Figure 4.7. The dramatic improvement in the forecast skill is apparent for all forecast lead-times although the record for the 96-h and 120-h lead times is short (since 2001) and does not extend back to the MAR period. Much of the progress in the Official Forecast can be attributed to the major advances made in numerical prediction models and the improved data resources as

[6] Prior to 1994, the principal national center was the National Meteorological Center (NMC).

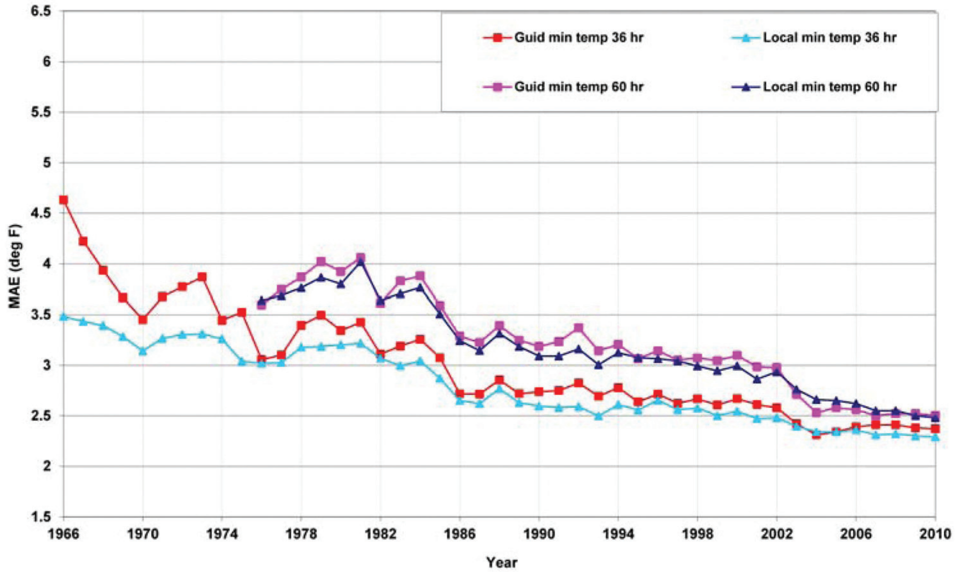


**FIGURE 4.4** Mean annual absolute error for warm season local forecasts and MOS guidance forecasts of tonight's (36-hr; light blue and red, respectively) and tomorrow night's (60-hr; dark blue and pink, respectively) minimum temperature generated during the 0000 UTC cycle. Mean is calculated for 80 stations distributed across CONUS. The improvement in both local forecasts and guidance is indicated by the decline in the mean absolute error. SOURCE: Meteorological Development Laboratory, National Weather Service.

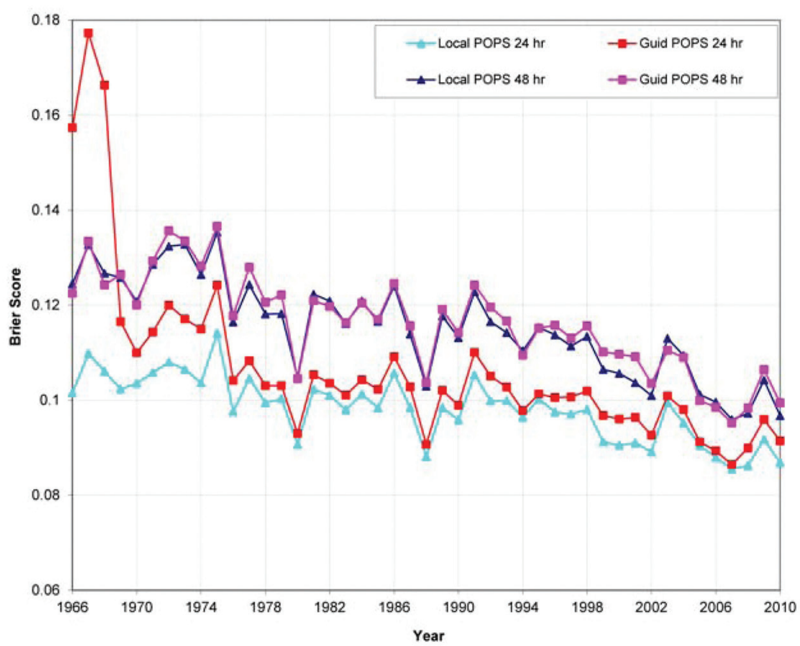


**FIGURE 4.5** Improvement in Brier score (Brier, 1950) of locally generated forecasts and MOS guidance probabilities of precipitation for the 12- to 24-hour (24-hr; light blue and red, respectively) and 36- to 48-hour (48-hr; dark blue and pink, respectively) forecasts during the warm season. In this analysis, results from both the 0000 and 1200 UTC cycles were combined. The improvement in both local forecasts and guidance is indicated by the decline in the Brier Score (a perfect Brier score is 0.0). SOURCE: Meteorological Development Laboratory, National Weather Service.

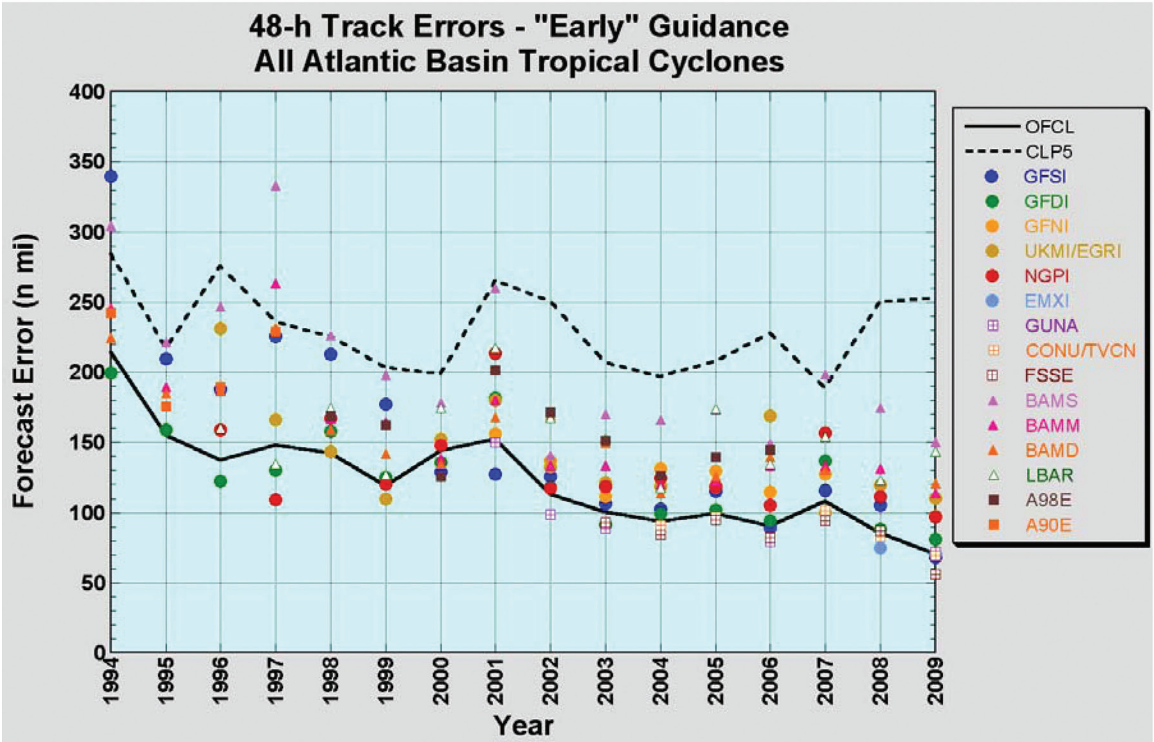


**FIGURE 4.6** Annual average guidance 48-hr track errors for the Atlantic basin tropical cyclones for the period 1994 to 2010 from all available models. The solid black line shows the annual average 48-hr errors for the National Hurricane Center official forecast and the dashed line is the error for the "CLIPPERS" Climatology and Persistence model, which provides a statistical baseline for comparison. The colored symbols identify the various individual models. More information about the individual models is available from the source. Availability of better data, improved model physics, and improved computing power led to less scatter in the performance of the various models. The annual average track error has declined. SOURCE: National Hurricane Center, National Weather Service.

well as the growth in computing power available to NCEP and to other centers both in the United States and around the world. The skilled application of the guidance to the operational analysis by the NHC forecasters contributes to the improvement as well.

Forecasts for extratropical storms have improved as well. Charles and Colle (2009) compared the quality of NWS storm forecasts over time from 1978 to 2007 on the basis of displacement errors in the forecast positions of the centers of extratropical cyclones, compiling results from previous literature. The results are shown in Figure 4.8, and show that there was a steady improvement over that period, which includes the MAR.

Forecasts of hurricane intensity, however, have not seen the marked improvements of hurricane track forecasts. The lack of progress in the prediction of hurricane intensity is illustrated in Figure 4.9. Considerable gains in observations, especially from within the eye of the storms, and a much more concentrated research effort are required before improvements can be expected.

**Finding 4-2a**

**The Modernization and Associated Restructuring (MAR) provided for more uniform radar coverage and surface observations across the United States. The Next Generation Weather Radar network and Geostationary Operational Environmental Satellites dramatically improved the quantity and quality of data available to forecasters and enhanced the numerical weather prediction capabilities of the National Weather Service (NWS). Replacing human observers with the Automated Surface Observing System introduced significant gains, despite possible adverse affects on the climate record and the loss of some important visual elements of the observation. The Advanced Weather Interactive Processing System has been a**

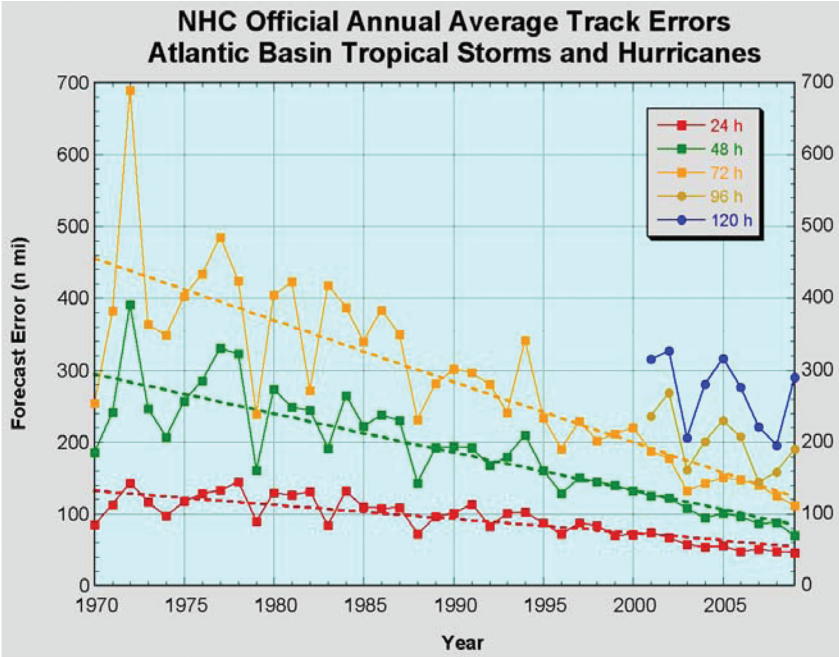


**FIGURE 4.7** Annual average official track errors for Atlantic basin tropical storms and hurricanes for the period 1970 to 2010 with least squares trend lines imposed. The different forecast times are indicated by red (24-hr), green (48-hr), yellow (72-hr), gold (96-hr), and blue (120-hr). Data for the 24-hr, 48-hr, and 72-hr forecast show a steady decline in the annual average track error. Data for 96-hr and 120-hr forecasts are only available after 2001, so the trend in the forecast error is more difficult to discern. SOURCE: National Hurricane Center, National Weather Service.

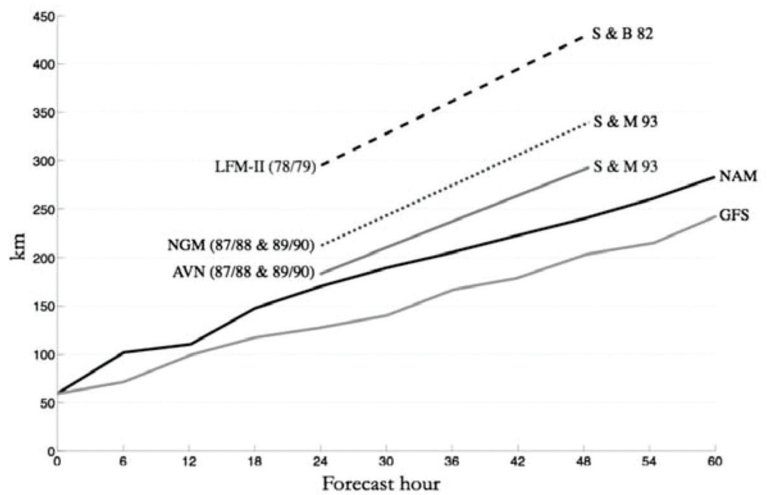


**FIGURE 4.8** Extratropical cyclone displacement errors (km) versus forecast hour for different National Weather Service forecasts for the period 1978 to 2007. The solid, black line represents the North American Mesoscale (NAM) model and the solid, light gray line represents Global Forecast System (GFS) model for the period 2002 to 2007. The black, long-dashed line represents the Limited Area Fine Mesh-II (LFM-II) model displacement errors for the 1978-1979 cool season. The data were originally published in 1982 by Silberberg and Bosart (labeled as S&B 82). The black, short-dashed line and the dark gray line represent the Nested Grid Model (NGM) and Aviation Model (AVN) displacement errors for the 1987-1988 and 1989-1990 cool seasons. These data were originally published in 1993 by Smith and Mullen (S&M 93). The results show a steady improvement in the performance of extratropical cyclone forecasts. SOURCE: Charles and Colle (2009).

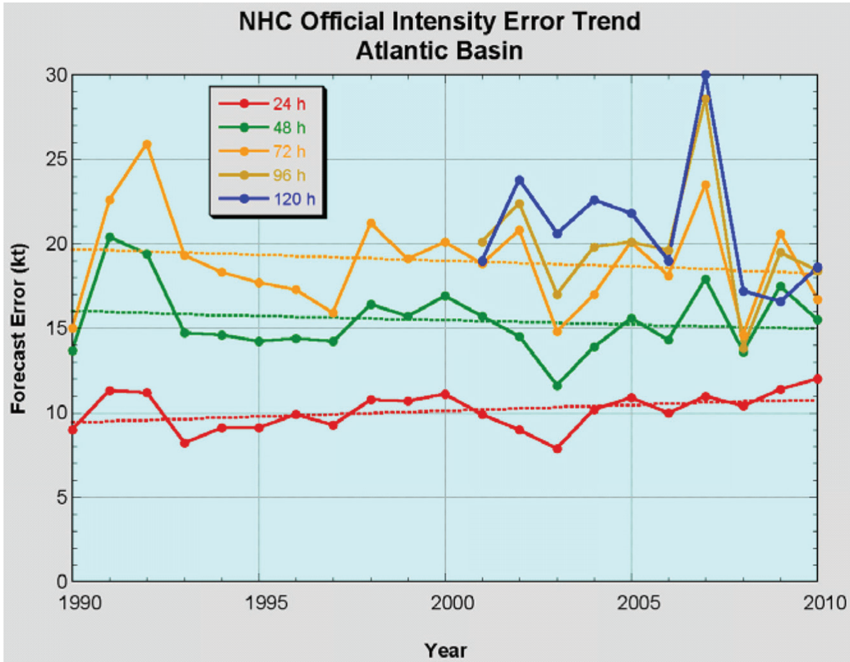


**FIGURE 4.9** Annual average official intensity errors for Atlantic basin tropical storms and hurricanes for the period 1970 to 2010 with least squares trend lines imposed. The different forecast times are indicated by red (24-hr), green (48-hr), yellow (72-hr), gold (96-hr), and blue (120-hr). Data for 96-hr and 120-hr forecasts are only available after 2001. Data for all forecast times show a lack of improvement in hurricane intensity forecast errors. SOURCE: National Hurricane Center, National Weather Service.

**critical technological advancement that integrates the data and information provided by other MAR elements and makes them easily accessible by forecasters.**

**Finding 4-2b**

**The Probability of Detection (POD) for both tornadoes and flash floods improved over the course of the MAR and after the MAR. Likewise the Lead Times of the warnings increased. However, the False Alarm Ratios (FAR) were not reduced and remain high.**

## RESTRUCTURING OF FORECAST OFFICES AND STAFF

Restructuring of the NWS involved substantial changes in both the office and workforce distributions. Many of these changes were viewed negatively by some NWS employees during the MAR period (NRC, 1994a), but hindsight has shown that they have greatly improved the capability of the NWS to provide weather services to the nation, and the changes are now viewed favorably by the staff (committee member WFO site visits; Hirn, 2011).

### Consolidation of Offices

With the completion of the MAR, weather forecast and warning services are provided to the nation by 122 WFOs, with distribution more or less uniform across the CONUS (Figure 4.10). Each WFO has an associated NEXRAD radar, and the WFOs provide more uniform distribution of forecasting and warning services. Though there are now fewer "local" offices, the forecast and warning services are provided by staff with higher skill levels and with more advanced technology at their disposition.

Provision for much better linkages to the user community are in place as a consequence of the MAR. However some forecast offices are not necessarily optimally located within their community. Since the MAR, the availability of inexpensive wideband communication has eliminated the need to site WFOs close to their

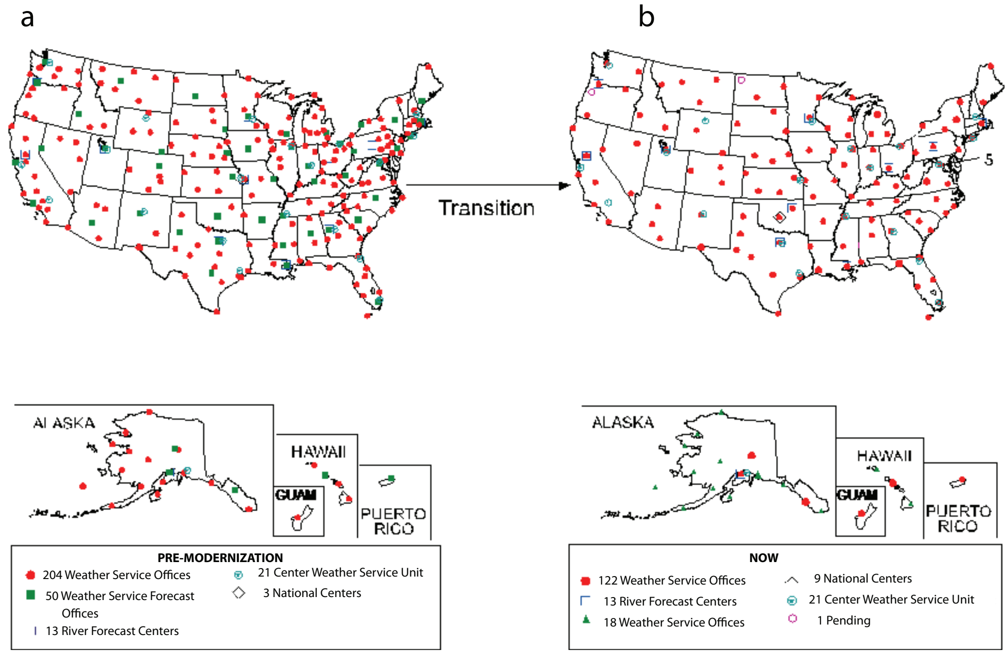


**FIGURE 4.10** (a) Locations of the 204 Weather Service Offices (red diamonds) and the 52 Weather Service Forecast Offices (green squares) before the MAR. (b) Locations of the 122 Weather Forecast Offices (red diamonds) after the MAR. SOURCE: National Weather Service.

radar. In some cases, relocating the WFO closer to the primary community in the area of responsibility would provide better service. Such primary communities vary by location, but include media markets, emergency management, and university or research facilities. Locations could be determined on the basis of predetermined service criteria. The full consequence of forecast office relocations on staffing is not entirely clear. There are examples of both the remoteness of some locations negatively affecting recruitment of meteorologists, and of journeyman meteorologists who view positions at remote WFOs as opportunities to gain important field experience and advance their careers.

## Workforce

While achieving the goal of an agency-wide staff reduction, the restructuring of the field office management and staff positions had a profound impact on the services provided. Placing professional meteorologists on staff throughout the country, instead of solely at a smaller number of centralized forecasting facilities, allows for increased use of numerical modeling and a more scientific approach to weather forecasts and warnings. The NWS can now maximize the utilization of new science and evolving technologies like NEXRAD and AWIPS. The proportion of professional meteorologists increased significantly and the GS pay grades were increased, making the work more professionally rewarding (Hirn, 2011). As discussed in Chapter 3, the increase in the average pay grade, and thus salary costs, likely balanced out any cost savings from a reduced workforce.

The creation of the Science Operations Officer (SOO) and the Warning Coordination Meteorologist (WCM) positions resulted in dedicated staff for two critically important tasks. The SOO serves as the focal point for the integration of new science and technologies into WFO operations. The SOO also leads research relevant to local weather issues, and coordinates the continuing professional development of the WFO staff through training. As the NWS has moved away from training at a centralized facility and toward remote educational efforts in each WFO, staff training has become one of the primary tasks of the SOO (Santos, 2011). Since the end of the MAR, an Information Technology Officer (ITO) has been added. The addition of the ITO led to the full utilization of AWIPS capabilities, and has helped maintain the still-evolving AWIPS technology.

The quality of the NWS's warning capability corresponds with its capability to muster an ample, fully trained local staff at its WFOs as severe weather unfolds. With current staff levels, there are always two people working each shift, 24 hours a day, 7 days a week. Though this works well in fair weather, it can become problematic during severe weather, particularly when events develop rapidly under seemingly benign conditions. While managers at individual WFOs generally plan ahead to add sufficient staff to cover forecasted dangerous weather situations, more innocuous weather scenarios that suddenly and unexpectedly "blow up" often lead to shortcomings that are directly attributable to having insufficient manpower. Several recent Service Assessments (e.g., NWS, 2003, 2009, 2010) illustrate the critical role that adequately enhanced staffing (or lack thereof) plays in the success (or weakness) of NWS warning performance during major events. Appropriate levels of staffing, beyond the normal fair weather staffing, during major weather events, are critical for fulfilling the NWS's "protection of life" mission.

**Changes in Customer Linkages**

By creating a liaison between NWS and the media and emergency management communities in the WCM position, the MAR significantly improved customer service. Innovations such as NWS-Chat,[7] although not officially part of the MAR, now allow for direct communication between NWS forecasters, broadcast meteorologists, and emergency managers.

This strengthened relationship between NWS and media came at a time when electronic media outlets invested millions of dollars in technology that allowed broadcast meteorologists to track dangerous weather in real-time and provide continuous on-air coverage of breaking weather situations. Increasingly, NWS Service Assessments (e.g., NWS, 2007, 2009) point to the importance of TV and radio broadcasts in providing awareness and a call to action to protect life and property. Each WFO is somewhat unique in its approach, but after the MAR, there are several examples of WFOs and local media outlets sharing resources, including Doppler radar imagery and mesonets.[8]

The WCM also brought the NWS much closer to the emergency management community. The core missions of emergency management and the NWS are very similar, and WCM efforts to provide continuing education and maintain strong relationships with local emergency managers have facilitated rapid sharing of crucial information during the severe weather threats. The MAR elevated the emergency management community from merely a user of weather services to a partner in the protection of life and property, therefore the post-MAR relationship between NWS and emergency management is discussed in greater detail in the later section on Partnerships.

**Finding 4-3a**
**National Weather Service staff was reduced, but technical capabilities and career paths were substantially upgraded, leading to little or no cost savings from the workforce reorganization.**

**Finding 4-3b**
**The staffing level that resulted from the Modernization and Associated Restructuring allows for at least two people on duty for all shifts, but timely planning and coordination by field office managers and supervisors are required to be able to increase the staffing level for times when severe weather threatens life and property.**

**Finding 4-3c**
**The Science Operations Officer position created as part of the Modernization and Associated Restructuring, in principle, allows advancements in the science community to be more rapidly integrated into operations. Communication and dissemination of weather information at the local level has been much improved by the restructuring of the forecast**

[7] NWS-Chat is an Instant Messaging program that enables communication between media and emergency management and NWS operational personnel, and is particularly useful during hazardous weather situations. It allows sharing, in both directions, of data, weather observations, and spotter reports.

[8] For example, the WFO in Miami uses and relies on the WeatherBug mesonet, not only via direct ingest into the AWIPS workstations, but through the Web sites of the stations in each market who have the local contract with WeatherBug (Channel 4 in Miami, Channel 12 in Palm Beach, and Channel 2 in Fort Myers). While there is excellent radar coverage on the southeast coast of Florida, NWS does occasionally use NBC2's weather radar imagery from the Fort Myers area in southwest Florida. Additionally, NWS-media collaboration is greatly enhanced by NWS-Chat.

**offices and the creation of the Warning Coordination Meteorologist position.**

## NATIONAL CENTERS

Each of the goals of the MAR directly affected and was affected by the research, technological development, and services conducted within all of the NWS national centers, particularly those within NCEP. As the science and technology of weather, climate, and hydrologic prediction evolved, the demand for more quantitative, accurate, and precise forecast products from local forecast offices and national operational forecast centers increased. To develop and deliver such products, work undertaken at the National Centers had to evolve, and the products needed to be better disseminated to local forecast offices. By most accounts the NWS national centers in general, and the reorganized NCEP in particular, have made significant progress in the development and delivery of such products.

The current scientifically and technologically advanced state of NWS could not have been achieved without the significant influence of the National Centers and an information infrastructure to provide data and forecast products to forecast offices. Furthermore, the reorganizing of NCEP appears to have enabled an environment that can evolve as computational capacity and scientific advancements evolve. Since the reorganization of NCEP, several major supercomputer acquisitions as well as the development of 'backup' computational facilities have occurred. Numerical modeling and data assimilation algorithms and the database and computational architectures on which they depend have, in turn, evolved significantly since the MAR. The continuing evolution of NCEP and its capabilities underscore the success of the MAR in enabling a more evolutionary paradigm to prediction operations as opposed to a move to a new narrow or singular operational paradigm. These successes can be measured in terms of the continually improving skill of weather, climate, and ocean models. There has been a great broadening of the user base and breadth of products being generated by the National Centers now, as opposed to the pre-MAR period.

Progress in NWP at NCEP has been significant and MAR-era improvements have placed the NWS as one of a handful of world leaders in weather and climate predictions, although other national centers still outperform NCEP by certain measures of numerical modeling skill. One objective way to evaluate the performance of NWS global medium-range forecasts is to compare their accuracy to that of model-based forecasts made by other operational weather centers of the state of the atmosphere at around 18,000 ft (500 hPa). Figure 4.11 compares the upper atmosphere forecast performance of several operational centers, including NWS, for 1985 to 2009, averaged over the Northern Hemisphere.

Clearly, most of the models, including the GFS, have exhibited steadily increasing skill over the post-MAR period, although the European Centre for Medium-range Weather Forecasts (ECMWF) consistently outperformed NCEP (and all other operational global medium-range forecast models) throughout this period.

Wedam et al. (2009) compared surface forecasts of sea level pressure along the East and West Coasts of the United States during the winters of 2005 through 2008. On average, the NCEP errors were 26 percent greater than those of the ECMWF.

Both NCEP and the ECMWF have been producing probabilistic ensemble forecasts operationally since December 1992. In order to compare performance, a verification exercise was carried out jointly by staff from both agencies and also from the Meteorological Service of Canada (MSC) using 2002 data (Buizza et al., 2005). The ECMWF ensemble outperformed the NCEP ensemble at all lead times.

Froude et al. (2007) and Froude (2010) compared the performance of the NCEP and ECMWF ensemble forecasts for forecasting extratropical cyclones in the Northern Hemisphere. The ECMWF consistently produced better forecasts than NCEP.

Recent reports have made steps toward assessing the reasons NCEP is still outperformed by other national centers, and point to important future directions for enhancing the GFS (e.g., NRC, 2010; UCAR, 2010).

**Finding 4-4**

**Numerical weather forecasts produced by the National Centers for Environmental Prediction (NCEP) and the associated guidance information and products, improved steadily over the course of the Modernization and Associated Restructuring. However, the**

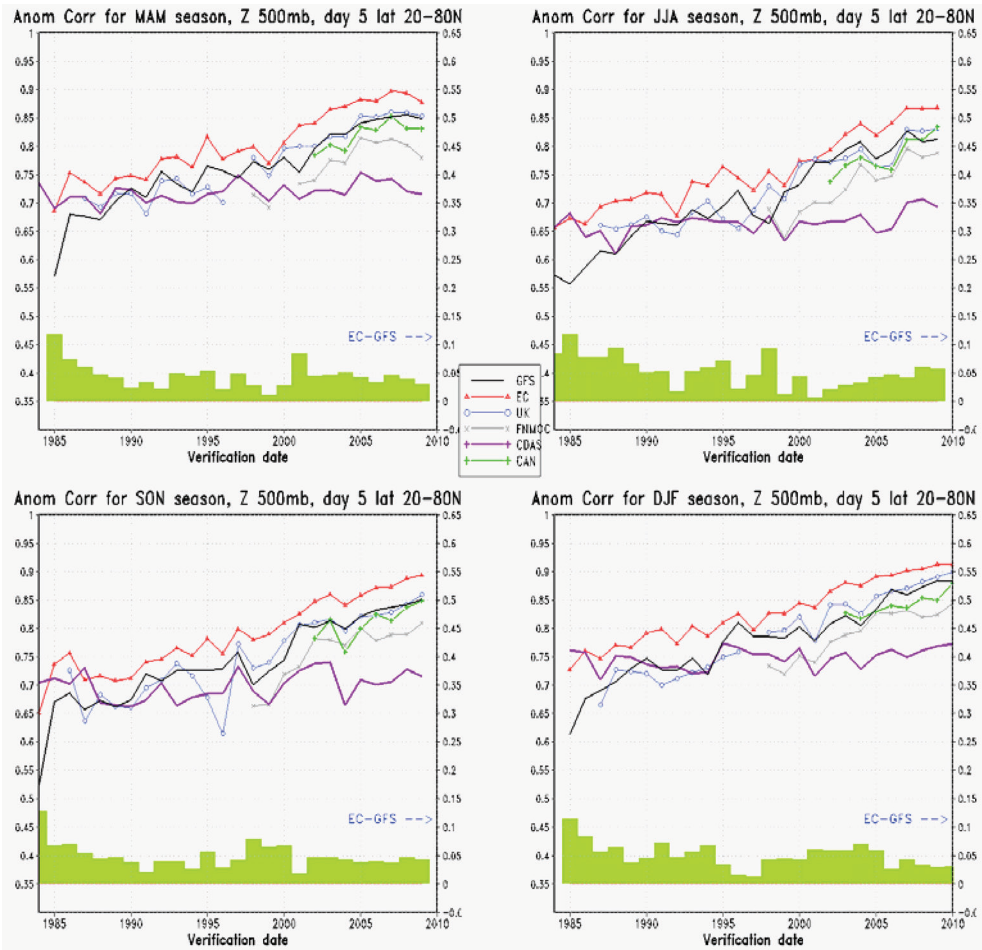


**FIGURE 4.11** Seasonal mean anomaly correlations of 5-day forecasts of the 500 hPa heights for different forecast models (NCEP's Global Forecast System [GFS], ECMWF [EC in figure legend], UK Meteorological Office [UKMO], Fleet Numerical Meteorology and Oceanography Center [FNMOC], the Coordinated Data Analysis System [CDAS], and Canadian Meteorological Centre [CMC]) from 1985 to 2009. A higher anomaly correlation indicates better model forecast performance. Seasons are three-month, non-overlapping averages. The green shaded areas at the bottom are the difference between the ECMWF and GFS performance. The data show that performance of all models increased steadily over the period, but GFS performance still lags that of the ECMWF. SOURCE: National Centers for Environmental Prediction.

**performance of some NCEP models, particularly the Global Forecast System, continues to lag behind some other national centers, including the European Centre for Medium-range Weather Forecasts.**

## PARTNERSHIPS

In general, the MAR strengthened the relationships between the NWS and other members of the weather enterprise. This was particularly true of the partnership between the NWS and the private sector, a relationship that historically had difficulties. For example, the availability of weather information from ASOS, NEXRAD, and GOES-Next to the private sector and public has been critical in expanding the weather enterprise, and likely contributed to the increase in both quantity and quality of meteorology research. Because of its open-source nature, AWIPS is used by other federal agencies, universities, and research institutions, which facilitates scientific collaboration.

### Other Federal Agencies

Among the many successes of the partnerships of NWS with FAA, DOD, and NASA in financing and implementing the MAR was the capability of the individual agencies to achieve a step-function increase in technological capability at a relatively smaller per-agency cost. Individuals close to the MAR generally believe that the joint acquisition also resulted in a closer working relationship between meteorologists associated with the four agencies (Bjerkaas, 2011; Misciasci, 2011), although there is still room for improvement in the relationship between the NWS and its federal agency partners.

According to the 1995 NRC report on aviation weather:

> the NWS now realizes that the FAA did not serve as an effective intermediary between the NWS and aviation weather users with regard to generating performance requirements for the Automated Surface Observing System (ASOS). Partly as a result of this situation, the NWS has had to augment some ASOS units with human observers and develop plans for increasing the capabilities of deployed ASOS units to meet aviation needs (NRC, 1995a).

A finding from that report was the need to develop a common understanding of aviation weather requirements between the FAA and NWS as a critical first step in planning improvements. Revisions to the 1977 FAA-NWS umbrella Memorandum of Understanding (MOU) in the late 1990s and in 2004 have helped to develop this understanding. As a result, maintenance and capability upgrades to the NEXRAD system are viewed as reflecting the needs of both agencies, although the ASOS system receives negative marks in this regard as discussed above (Heuwinkel, 2011).

The MAR observing systems were designed specifically to meet the mission requirements of NWS, FAA, and DOD. Other federal, state, and local government agencies meet their observational data needs to varying degrees with data from these systems. For example, a 2004 NRC report that focused on road weather notes that "[a]ltough the ASOS provides useful data, it was never intended to be used to characterize the roadway environment; therefore, additional networks that target the roadway environment are needed" (NRC, 2004). Other federal agencies that use and rely on weather data to help meet their operational responsibilities include the Federal Emergency Management Administration (FEMA), Environmental Protection Agency (EPA), Nuclear Regulatory Commission (NRC), Department of Energy (DOE), U.S. Geological Survey (USGS), U.S. Forest Service (USFS), Bureau of Land Management (BLM), NOAA, National Park Service (NPS), Federal Highway Administration (FHWA), and the U.S. Coast Guard (NRC, 2002).

Since the time period of the MAR, declining costs for instruments and widespread availability of affordable digital data communication has led to a proliferation of remote and in situ sensor networks. Such networks, owned by a variety of public and private sector entities, now exist alongside the national observing technologies established by the MAR. Research into ways of forming new partnerships that organize and share the large volume of information from this totality of observing infrastructure is currently ongoing (e.g., NRC, 2004, 2009, 2010).

### Private Sector

One MAR legacy is a greatly improved relationship between NWS and the private sector, based on the personal experience of various committee members and the limited testimony received from private sector participants (Friday, 2011; Myers, 2011). It took at least five years after the formal end of the MAR (and at least two years after the NRC's *Fair Weather* report) for any kind of noticeable improvement, but today both the NWS and the private sector view the relationship as more synergistic than competitive. Implementation of recommendations from the *Fair Weather* report has played a role in this improvement, along with significant efforts from professional weather associations such as the American Meteorological Society (AMS), the American Weather and Climate Industry Association (AWCIA), and the National Council of Industrial Meteorologists (NCIM). The long-term constructive institutional role of the American Meteorological Society, specifically the Commission on the Weather and Climate Enterprise, has been critical.

Increasingly, the private sector understands the important role of NWS both as a source of basic data and forecasts and as the nation's authoritative weather information source and the NWS understands the value of the private sector as both a channel for effectively distributing weather information and a source for innovative added value. As an estimated 90 percent of weather information used by individuals and businesses originates with NWS but is transformed and delivered by the private sector, this has been an important accomplishment (Myers, 2011). With the private sector leading implementation of emerging technologies such as social networking and smart phones, its position as an interface to users will likely expand further. In this decade's budget environment, it is also increasingly recognized that a synergistic relationship can extend and leverage the NWS budget, providing better value for the nation.

This relationship is still fragile, depending largely on individual attitudes and informal agreements. The NRC's *Fair Weather* report concluded that there should not be a well-defined separation of NWS and the private sector (NRC, 2003a), but rather a process for promoting the partnership, and a *de facto* distinction has been emerging. One means of stabilizing the roles is to document successful examples of public-private collaboration and to use this literature to define the overlapping domains of each (Myers, 2011). Issues remain, such as broader access to data by the private sector, which is both a technology and a policy issue. It is generally recognized that neither the private sector nor the NWS can do all things for all people, so extracting the best of both groups is critical for the success of the enterprise. Accomplishing this requires ongoing improvements in relationships and collaboration methods along with direct inclusion of the private sector in R&D and operational improvement planning.

**Research Community**

Several of the new WFOs have been located on or near university campuses. This enhances the interactions between NWS staff and university faculty and students. The NWS staff (particularly the SOOs) generally benefit from closer contact with developments in the research field. This leads to earlier implementation of advances in scientific understanding of weather phenomena as well as improved forecasting techniques. Often the SOOs and university staff collaborate in research efforts pointed in those directions. Students have opportunities to see close hand what goes on in a WFO; some work as volunteers alongside NWS staff, enhancing their experiences and preparation for jobs. Some students (and staff) undertake research that can lead to results benefitting the local forecasting staff. A series of regional meetings generally organized by a group of SOOs brings the NWS staff and members of the research community together to talk about current problems and learn about recent advances that can help the NWS improve their performance. Students often participate in these meetings as well.

The MAR resulted in an improved relationship between the NWS and the academic and research communities. However, there are still concerns that the structure put in place after the MAR is still not as open or as collaborative as it could be. Insufficient support for collaborative weather research programs such as the U.S. Weather Research Program (USWRP) or the Collaborative Science, Technology, and Applied Research (CSTAR) Program suggests that the NWS is not fully engaged with the research community. Greater support for such programs would aid the transition of research-to-operations.

To further assess the impact of colocation of NWS offices with universities, and to determine how well this arrangement has worked for the offices concerned and for NWS as a whole, the committee sent a questionnaire to the relevant NWS offices (including both WFOs and National Centers such as the National Hurricane Center). A detailed summary of the responses is given in Appendix D. In general, the NWS offices report that colocation has provided a positive experience with mutual benefits to both NWS and the host universities. In addition to operational, scientific, educational, and outreach benefits, the ability for NWS staff to live in a college town and work in a vibrant and forward-thinking campus environment helps to foster innovation and leads to attracting, hiring, and retaining high quality staff. Further, WFO staff report that at such locations, many students are recruited as NWS employees. It is certainly possible for NWS staff to work with researchers and universities at a distance, but the casual, more-frequent interactions easily enabled by colocation add tremendous value to the advancement of the science and the operational application of that science. When there is a lack of true colocation (as in an office being nearby, but not on campus), this appears to be a disadvantage.

Of course, the level of interaction varies from office to office. However, the achievements of the WFOs at Denver/Boulder, Colorado; Raleigh, North Carolina; Albany, New York; and Seattle, Washington stand out as positive examples of the tremendously positive benefits that can be achieved through colocation (see Appendix D for more detail). In contrast, at one reporting office (the National Hurricane Center [NHC] collocated with Florida International University) there appears to be a poor match between the university foci and operational mandate of the NWS office leading to less than optimal interactions. This suggests that more care may be needed in selecting partners for colocation.

Strong relationships with the federal and academic research communities contribute to enhanced NWS forecasting and warning capabilities. This is especially true of the NEXRAD system; research into the capabilities and advantages of polarimetric radar, summarized in Bringi and Chandrasekhar (2001) and more recently with specific reference to NEXRAD in Ryzhkov et al. (2005), has led to the implementation of a polarimetric upgrade to the NEXRAD radars. Partnerships with the National Severe Storms Laboratory (NSSL) and other research groups have introduced numerous advances in the use of the radar data, a prime example being approaches to reduce the range-velocity ambiguities in radar observations.

### Emergency Management

During the MAR, the NWS began to develop more and better partnerships with state and local emergency managers. The partnerships focused initially on better serving the emergency managers during disasters with incident meteorologists. These positions helped first responders with spot forecasts for responder safety, trends, and outlooks that may affect the needs of displaced survivors, and other tactical information.

As part of the restructuring of the workforce, the NWS expanded this emphasis to include the WCM. The WCM became the primary link between the NWS and the customers it serves. As the technological and organizational changes from the MAR began to reshape NWS products, the WCM concept began to reshape the relationships with those most affected by those products.

The NWS began to accept the philosophy that the perfect forecast and the most timely warning are worthless unless the individual and the community receive the information and take the necessary action to save lives and property. Many state and local emergency managers embraced this outreach from the NWS and integrated into plans and operations many of the new products and capabilities the MAR created.

The WCM reached out to many users who depend on rapid and dependable access to weather information, including emergency managers, fire fighters, law enforcement, and the private sector. Through this initiative, NWS products became more usable by more groups. The complexity of the MAR and all its systems could have been a detriment to its usefulness to the public. By including this human element, the NWS created and sustained effective partnerships between those who observe, forecast, and warn of the weather, and those who need those products for the safety of life and continuity of the economy.

**Finding 4-5**

**Improved relationships with other agencies and external partners have proven to be one of the more important outcomes of the Modernization and Associated Restructuring (MAR). These relationships increase the National Weather Service's societal impact and leverage its limited budget. Success of the MAR depended in part on leadership, initiative, and funding by National Oceanic and Atmospheric Administration and National Weather Service units operating outside of the MAR. Though issues remain, partnerships with academia and government research institutions have increased research-to-operation capabilities, and the MAR elevated the media and emergency management community from a customer to a partner. The relationship between the NWS and the private sector took longer to improve, but it has generally evolved into a more constructive and productive one.**

## OVERSIGHT AND ADVISORY GROUPS

The MAR was the focus of many oversight reviews and advisory reports (Appendix B). Previous sections have highlighted specific cases in which the reviews drew attention to important issues, issues whose resolution was important to the success of the MAR. In addition, there are more general benefits that flow from constructively critical expert reviews of complex system deployments. These benefits include ongoing relationships with congressional staffs, with technical colleagues in other federal agencies, and with other sectors of the weather enterprise, such as academia and the private sector. Successful reviews not only help NWS management understand and react to technical and/or schedule and budget issues, but help build communities of knowledgeable support. In large part, these benefits accrue to managements that are receptive to outside advice, and are able to avoid a defensive response to constructive criticism. During the course of the MAR, the management of NWS was generally receptive to oversight and able to benefit from it. This does not mean, however, that the committee believes more would have been better. We do believe that outside review and oversight was useful and that utility was determined primarily by the technical quality of the oversight and by NWS management's receptivity to that oversight.

**Finding 4-6**
**Expert advice and oversight from outside the National Weather Service (NWS), and the receptiveness of NWS management to such advice, contributed to the success of the Modernization and Associated Restructuring.**

## ADDITIONAL IMPACTS

The committee limited the bulk of its analysis to those aspects of weather services that were explicitly included in the MAR planning and execution. However, there are some other key areas that were significantly affected by the MAR, including hydrologic services, coastal observations and forecasts, and the climate record. NEXRAD observations of non-meteorological targets also provide data valuable to some unrelated fields of investigation.

### Hydrologic Services

The NWS has two principal service areas: meteorology and hydrology. Much of the emphasis of this assessment has been on meteorological services. However, the MAR greatly improved the observation of precipitation through the deployment of the NEXRAD network and allowed for increased coordination of WFOs with River Forecast Centers (RFCs), thus allowing NWS to expand its hydrology mission and services (NRC, 1996b). The NWS Hydrologic Services Program (HSP) had two roles within the MAR: as an integral participant in the restructuring, and as a key customer of the modernized technology (e.g., NWS, 1989). The report *Hydrometeorological Service Operations for the 1990s* describes pre-MAR hydrometeorological operations within the NWS and details plans for staged implementation, including responsibilities of the RFCs, WFOs, and national and regional headquarters (NWS, 1996b). The 1996 report reflects considerable evolution in the direction and specificity of plans from the beginning of the MAR (Fread, 1996).

The MAR restructuring of the HSP was intended to increase the integration of day-to-day hydrology and meteorology operations (NWS, 1996b). All RFCs were colocated with a WFO; in some cases, relocation moved RFCs away from key clients (e.g., the Army Corps of Engineers in Portland, Oregon). RFC staff profiles were changed to include overall management by a Hydrologist in Charge (HIC), equivalent to a MIC, science and technical development by a Development and Operations Hydrologist (DOH), similar to a SOO, and hydrologic analysis and forecasting by a substantially larger staff, up to a doubling in some RFCs, of degreed meteorologists and hydrologists with cross-disciplinary training. Selected WFOs received a degreed Service Hydrologist to support the participation of all WFO forecasters in preparation of hydrologic forecast products. The restructuring did not provide RFCs with a services coordination position similar to the WFO WCMs.

The restructuring assigned responsibility for issuance of flood and flash flood watches and warnings to the WFOs, as well as the generation of Quantitative Precipitation Forecasts (QPFs) for use by RFCs. RFCs were charged with providing hydrologic forecast guidance to the WFOs in their region at least twice daily (rather than once) over a longer service day, producing gridded hydrometeorological products that smoothly cross WFO boundaries from multiple automated sensor networks and QPFs, and assimilating high resolution datasets and QPFs into hydrologic modeling operations. NCEP units (e.g., HPC and SPC) were charged with providing routine and event-based hydrometeorological forecasts and analyses (e.g., QPFs, probabilities of exceeding RFC flash flood guidance) from NCEP modeling activities. Other NWS units (e.g., the Office of Hydrology, regional headquarters) were also assigned hydrologic services responsibilities under the MAR.

Each RFC received multiple AWIPS workstations to obtain and use the hydrometeorological information, forecasts, and guidance products from the WFOs and NCEP. Additional software tools were needed by the RFCs to interactively analyze, quality control, and assimilate the dramatically increased flow of hydrometeorological data and forecasts from multiple WFOs for use in hydrologic modeling operations. The tools were not provided as part of AWIPS, although they were needed to fulfill RFC responsibilities to support WFO operations.

The RFCs were also key customers of the MAR. The intent was for the NWS hydrological services program to capitalize on the MAR's technological improvements to increase the specificity and accuracy of flood and flash flood guidance to WFOs, and to develop a significantly expanded suite of hydrometeorological products and services. During the MAR, NWS was engaged in planning and early implementation of the Advanced Hydrologic Prediction Service (AHPS), which also aimed to improve and expand hydrologic forecasts and services. The MAR and AHPS were very much intertwined, with the MAR being considered as one of four components of AHPS, and AHPS as an integral component of a modernized NWS. Hydrologic model development, calibration, and forecast verification were considered activities under the MAR and AHPS. Although AHPS wasn't funded until midway through the MAR, it was essential for enabling the RFCs to capitalize on MAR advancements.

The MAR clearly improved coordination among hydrologic and meteorological operations, and enabled significant expansion of products and services. For example, the RFCs moved from forecasting only the traditional peak flows at select forecast points to 6- to 10-day hydrographs that predict the continuous flow at points within a specific watershed. Improvements began even pre-MAR, as some RFCs and the Office of Hydrology participated in early demonstrations of the complementary aspects of operational hydrology and meteorology planned under the MAR (e.g., QPFs, flash flood guidance, through the Prototype RFC Operational Test, Evaluation, and User Simulation [PROTEUS] project).

It appears that MAR planning did not fully account for the unique characteristics of RFCs and hydrologic operations compared to WFOs, NCEP, and meteorological operations. Collectively, RFCs were intended to serve the WFOs in a manner similar to NCEP, but at a regional scale (NRC, 1996b). However, the MAR did not provide the RFCs with the full complement of information processing tools required to fulfill those functions. Nor did it include any assessment of RFC needs for AWIPS capabilities, limiting the capability of RFCs to request additional capabilities, such as storage or processing speed. RFCs use dynamic hydrologic models that must be calibrated, requiring large archives of data much like the National Centers, and substantial data analysis and quality control. RFCs must also consider unique hydrometeorological processes within their region, and they have unique partnerships, such as agencies with regulatory responsibilities and hydropower production entities that need highly interactive access to RFC forecasts, products, and even computing resources. The RFCs shifted personnel hired or trained through the restructuring to information technology software development, delaying development of advanced hydrologic model capabilities, calibration, forecast verification, and probabilistic and ensemble forecasts. For example, RFC hydrologic professionals developed hardware configurations and software for producing gridded products, remote ensemble processors, and massive relational databases with high speed performance. In one RFC, 7 out of 10 hydrologic staff were focused on information technology rather than hydrologic science and development during the MAR.

An ongoing, challenging legacy of the MAR is that the qualifications for hydrologist positions were not upgraded to require degreed hydrologists, but instead allowed meteorologists to move into hydrology positions, even within RFCs. While much work of the RFCs (70 to 90 percent in recent estimates across three RFCs according to onsite interviews) focuses on quality control of hydrometeorological records where meteorological training is effective, negative consequences of this staffing challenge include limitations in the capability of RFCs to calibrate their hydrologic models. This issue was noted in a mid-MAR review of hydrometeorologic operations (NRC, 1996b). The staffing profile for hydrologists is imbalanced; of 600 hydrologist positions, only about 200 are degreed hydrologists and the limited opportunities for career advancement of hydrologists create difficulty in recruiting new employees (Carter, 2011).

As a whole, the MAR had a positive impact on hydrologic forecasts and services. The hydrologic services program took some lessons from the MAR and has used them to inform the design of their institutional approach to implement AHPS and the Community Hydrologic Prediction System (CHPS). Key lessons acted upon include the need for organization and planning, the need for "full buildout of limited cases" with full interface development, and bottom-up input about the resources needed to implement the larger vision. The recent addition of Service Coordination Hydrologists (SCHs) at the RFCs was based on their evaluation of the success of the WCM in coordinating with external partners and customers. Further, the hydrologic services program desires to have a hydrologic-centric MAR, especially to address current staffing profiles.

### Coastal Observations and Forecasts

Although the MAR did not explicitly include technological enhancements and capabilities for the U.S. buoy and coastal observing network, there were aspects of marine observations and analysis that benefitted. Approximately 30 percent of the U.S. population is concentrated in coastal communities that border the ocean (Crowell et al., 2007). Because of the geographical prominence of the coastal regions, an NRC review panel (NRC, 1999a) highlighted the need for NWS assessment of the AWIPS system for coastal marine weather forecasts and warnings, which had not been part of the testing that took place within the MAR. The ASOS and NEXRAD deployments significantly enhanced the observing capabilities in coastal regions. In addition, the higher spatial and temporal observations obtained with the GOES-Next satellites over data-sparse ocean regions improved forecasts of, for example, Pacific Ocean storms approaching the west coast. Even given some of the documented shortcomings previously discussed (e.g., reliability issues associated with ASOS; siting of NEXRAD radars at high altitudes), the new capabilities provided forecasters with unprecedented observations of the mesoscale coastal weather phenomena in real time. The AWIPS capability gave the forecasters for the first time an integrated depiction of coastal mesoscale meteorology that included the new ASOS and NEXRAD observing systems and GOES-Next, blended with the existing observing network, including coastal buoys (Reynolds, 2011).

### Climate Record

Reviews of early plans for the MAR noted that little attention had been given to issues of long-term management of the vastly greater stream of observations from MAR technology or to the quality of the climate record, and the reviews repeatedly stressed the importance of preserving the climate record as ASOS was deployed (NRC, 1991, 1992b, 1993). Recommendations were clear and strongly worded, e.g., ". . . the preservation of data quality for climatic purposes should have equal priority with its mission of providing forecasts" and "[w]hen instrument sites are changed, simultaneous operation at the old and new sites should occur until adequate statistics on the difference of observations between sites can be developed. These statistics should be recorded carefully and made readily available" (NRC, 1991). The 1992 NRC report included a separate appendix about data for climate studies from a standing NRC Climate Research Committee, which expressed concern that ASOS observations of cloud types and cloud cover, present weather, snowfall and water equivalent, total sunshine, radiation, and turbidity would be insufficient for climate studies (NRC, 1992b). The 1993 NRC report noted that prior recommendations relating to the climate record had not been addressed (NRC, 1993). Those same reports, though, also noted that the MAR provided opportunities to enhance the climate record by providing new kinds of data not previously available (e.g., NEXRAD precipitation estimates).

For this assessment, comments were sought from the NWS Climate Services Division (CSD) and the National Climatic Data Center (NCDC). Siting of ASOS stations was clearly driven by aviation requirements, not considerations of the climate record. Continuity plans for concurrent observations at limited sites were developed by the NWS Office of Science and Technology, following NWS Directive 10-21, but according to the CSD, those studies were never completed. However, a series of commissioned overlapping observation studies were conducted in the 1990s at a number of sites throughout the United States for varying periods of time, in all cases less than one year. Other studies provide additional insight (Brazenec, 2005; Butler and McKee, 1998; Doesken and McKee, 2000; Kauffman, 2000; McKee et al., 2000; McKee et al., 1994a, b, 1996a; Schrumpf and McKee, 1996; Sun et al., 2005). Comparison of ASOS and manual observations are complicated by differences in gauge locations, ranging from just a few hundred feet to more than one mile, although with little elevation differences. However, local exposure and vegetation differences can be significant (Guttman and Baker, 1996; McKee et al., 1995). Many performance issues are associated with the ASOS instrumentation package. A detailed description of the ASOS impacts on the climate record for different observed variables is provided in Appendix E.

Converting to ASOS has had a significant impact on the climate record. Discontinuities in temperature data occurred due to changes in instrumentation as well as changes in the observing location that occurred at most airport locations. There was also a significant impact on the cloud record with the elimination of manual observations and use of automated ceilometers. This was especially detrimental with cloud observations limited to 12,000 feet above ground level. Relative humidity was affected as well, due to instrumentation changes. The negative impact on precipitation measurements was severe with the conversion from the universal gauge to tipping buckets, which had difficulty accurately capturing medium to high rainfall rates and solid precipitation. Alterations in wind shields also affected the continuity of precipitation measurements. Observations of snowfall, snow equivalent, total sunshine, and active weather phenomena are no longer available. These impacts have created a special challenge for climatologists. Changes in instrumentation, in the locations of these instruments, and in the observational methodology (resulting from the removal of the human observer) have created inhomogeneities in the climatic records at these NWS and FAA airport sites. Without homogeneous records, computation of long-period means and frequencies of observed variables becomes meaningless as abrupt step changes in the time series are introduced.

From another perspective, however, ASOS did offer something unprecedented within the climate observing community: near real-time data collection and archival. Data observations could now be electronically transmitted and readily available, as opposed to the historical record keeping, which took a month or longer to publish data that were hand-recorded on paper, mailed to the data center, and keyed in manually by staff. Over time, ASOS has become one of the most robust data collection systems ever fielded and the advantages of the greater number of high quality stations, the station-to-station uniformity, the improved instrument siting and the rigorous (in most cases) maintenance is providing the community with a rich dataset for future climate studies.

Further, the MAR more broadly, ultimately had a positive impact on the climate record as the emphasis on data stewardship and preserving weather observations for climate-quality records increased. Some of this improvement required adjustments that took place after the formal completion of the MAR, including quality control tools, such as NCDC's Datzilla. In addition, the NWS Climate Services training program has been used to inform NWS staff of proper data stewardship practices. Lastly, the climate services[9] outreach program has expanded the overall knowledge base of users regarding the climate data record.

### NEXRAD Observations of Non-Meteorological Targets

A weather radar receives echoes not only from hydrometeors but also from other objects suspended in the atmosphere—including dust or smoke particles if they are sufficiently dense and close enough to the radar, as well as insects and birds. Many such echoes, once referred to as "angel echoes" (Battan, 1973), have come to be recognized as arising primarily from insects (e.g., Gauthreaux et al., 2008; Russell and Wilson, 1997; Wilson et al., 1994). Those echoes can provide useful tracers of the winds (provided the insect motions do not differ greatly from the winds), and also provide data useful to entomologists studying insect movements or migrations (e.g., Chapman et al., 2004, 2011). The sensitivity of the NEXRAD system has greatly enhanced the value of the NWS network data for such investigations.

Echoes from birds are more likely to contaminate wind velocity estimates, because the birds often move with appreciable velocity differentials (e.g., Serafin and Wilson, 2000). However, those echoes have proven quite useful to biologists studying bird and bat behavior (e.g., Gauthreaux and Belser, 1998; Horn and Kunz, 2008).

[9] Climate services include observations, monitoring, forecasting, and assessments of climate.

**Finding 4-7a**
**The Modernization and Associated Restructuring (MAR) improved collaboration among hydrologic and meteorological operations within the National Weather Service, and allowed significant expansion of hydrologic forecast products and services. However, the challenges facing the River Forecast Centers were magnified because the MAR did not adequately take into account the unique requirements of hydrologic data management, modeling, and partner collaborations.**

**Finding 4-7b**
**The Automated Surface Observing System (ASOS) was not implemented in such a way that the climate record was preserved. Discontinuities that degrade computation of long-period statistics, created by changes in instrumentation and observing locations, are still a concern. However, the Modernization and Associated Restructuring continues to offer prospects for improvement of the overall national climate record over the long term.**

## FRAMEWORK FOR EVOLUTION RATHER THAN REVOLUTION

In many respects, the changes that the NWS experienced as a result of the MAR can be viewed as revolutionary. The MAR brought dramatic improvements in weather services to the nation. New technology including ASOS, NEXRAD, GOES-Next, and AWIPS provided forecasters with an unprecedented set of observational and analysis tools. The new NWS organizational strategy transformed the forecast offices into a modern national network of WFOs. The workforce transitioned from two-thirds technicians, to two-thirds professional meteorologists. Many WFO staff now have a college degree, and many SOOs have advanced degrees. It is also becoming more common for staff in other positions to possess advanced degrees (Sokich, 2011).

Following the official end of the MAR in 2000, a framework was left in place so that the technology and NWS organization could continue to grow in an evolutionary manner. Examples of this evolutionary framework are post-MAR upgrades to the ASOS, NEXRAD, and AWIPS systems, occurring in tandem with technological advances in the wider community. The testbed concept and risk reduction activities emerged out of the MAR framework as well. One of the lessons of the MAR was the value of prototypying new operational concepts (e.g., PROFS and the pre-NEXRAD and pre-AWIPS systems). This pre-operational prototype paradigm has been advanced following the MAR and embraced by the NWS, which now has a number of successful testbeds including

- the Developmental Testbed Center,
- the Hydrometeorology Testbed,
- the Hazardous Weather Testbed,
- the Joint Hurricane Testbed,
- the Aviation Weather Testbed, and
- the Joint Center for Satellite Data Assimilation.

Testbeds have accelerated the transfer of technology from research-to-operations; successful examples include the Joint Hurricane Testbed and the Hazardous Weather Testbed (jointly operated by NWS and the Office of Oceanic and Atmospheric Research [OAR]). These testbeds improved capacity and better separation between development and operational systems for running models (Hayes, 2011). Nevertheless, the testbeds primarily have a focus on transition of research-to-operations, not the broader scope needed to prototype new concepts for methods of operations that was present in the prototyping and risk-reduction activities of the MAR. The current generation of testbeds tend to operate largely independently of one another, and provide little capacity to experiment with multi-office collaboration on delivery of new services. Provision of new services will likely be an increasingly important requirement in the future. Some of the current testbeds have limited capacity to engage key stakeholder groups, including emergency managers, media, and commercial weather service providers, in developing and evaluating new service concepts.

Despite some of the shortcomings of the current testbed system, the framework established during the MAR provides the NWS excellent opportunities for new collaborations and partnerships, responding to the ever-increasing interdisciplinary nature of meteorology and hydrology. The MAR established a foundation for evolution that will allow the NWS to better meet the future needs of the United States.

# 5

# Lessons Learned

As a whole, the MAR led to greater integration of science into weather service activities and improved outreach and coordination with state and local government, emergency management, and local communities. Technological improvements provided forecasters with a wealth of new data and observations, allowing them to provide more accurate and timely forecast and warning services to the nation. This chapter examines whether the execution objectives of the MAR were met, and whether the promised benefits were achieved. It presents the committee's key findings about the MAR as a whole and an assessment of the lessons learned from the committee's analysis of the execution and impact of the MAR. The committee recognizes that many of the lessons presented in this report would apply to any large, complex project. However, this does not make the lessons any less useful. The fact that they are common makes it even more important that they be considered in future planning.

The stated objective of the MAR in the *Strategic Plan* (NWS, 1989) was

> *to modernize the NWS through the deployment of proven observational, information processing and communications technologies, and to establish an associated cost effective operational structure. The modernization and associated restructuring of NWS shall assure that the major advances which have been made in our ability to observe and understand the atmosphere are applied to the practical problems of providing weather and hydrologic services to the Nation.*

It is clear that the NWS succeeded in the deployment of observational, information processing, and communications technologies that have improved weather and hydrologic services. The MAR significantly increased the amount of data and information available to field forecasters. The forecast and warning products produced by the post-MAR NWS are greater in both quantity and quality. The cost-effectiveness of the operational structure is more difficult to assess, because of the challenges involved in assessing the value of decreased loss of life and property as a result of improved forecasts and warnings. Understanding of the economic impacts of weather events still needs improvement and the benefit of weather forecasts and warnings cannot be measured only in economic terms. However, recent work has estimated the annualized value of public weather forecasts and warnings to be about $31.5 billion, compared to an annual cost of $5.1 billion to produce the information (Lazo et al., 2009). Variations in weather have been shown to cause variations of $485 billion in U.S. annual economic output (Lazo et al., 2011). Because weather services clearly have great value, it is hard to argue that an increase in both the quantity and quality of forecasts, and a decrease in the total number of staff, has not yielded a more cost effective operational structure.

The *Strategic Plan* (NWS, 1989) also set forth the specific benefits the NWS hoped to achieve with the MAR

- *More uniform weather services across the Nation.* This was achieved, as summarized in Findings 3-3a, 4-2a, and 4-3a.
- *Improved forecasts*. This was achieved for local area forecasts issued by Weather Forecast Offices and regional forecasts issued by centers such as the Storm

Prediction Center, as well as the guidance products produced by the National Centers (Findings 3-3a, 4-2b, and 4-3a). Global model forecasts (e.g., the Global Forecast System) improved, but their skill still lags behind some of the other leading global models (Finding 4-4).

- *More reliable detection and prediction of severe weather and flooding*. This was achieved, as summarized in Findings 3-3a and 4-2b.
- *More cost effective NWS*. As noted above, the challenges involved in assessing the value of decreased loss of life and property as a result of improved forecasts and warnings make it difficult to quantitatively assess whether a more cost effective NWS was achieved. However, estimates of the value of weather information seem to support the notion that the post-MAR NWS is indeed cost effective. The MAR significantly increased the quantity and quality of NWS products while decreasing the total number of staff.
- *Higher productivity for NWS employees*. This promised benefit is also difficult to assess quantitatively. With a greater number of higher quality products produced by a smaller workforce with more technical capabilities, and with a greater amount of higher quality data and information available to them, productivity of NWS employees has certainly increased (Finding 4-3a).

The initial *National Implementation Plan* (NWS, 1990) expanded and clarified the list of promised benefits:

- *Operational realization of a predictive warning program focusing on mesoscale meteorology and hydrology*. This was achieved, as summarized in Findings 3-3a and 4-2.
- *Advancement of the science of meteorology and hydrology*. This was achieved although there were some issues with the application of science and technology to operational hydrology (Findings 3-4 and 4-7a). While numerical weather prediction improved steadily, there are still some cases where capabilities could be improved (Finding 4-4).
- *Development of NWS human resources to achieve maximum benefit from recent scientific and technical advances*. The scientific and technical capabilities of the workforce increased as a result of the MAR (Findings 4-3a and 4-3c), but whether maximum benefit was achieved cannot be determined.
- *User acceptance and support of NWS modernization and associated restructuring service improvement objectives*. There was some initial resistance from employees (Finding 3-3b), as well as the general public and Congress in some regions, but this goal was eventually achieved.
- *Strengthening cooperation with the mass media, universities, the research community and the private hydrometeorological sector to collectively fulfill the Nation's weather information needs from provision of severe weather warnings and general forecasts for the public as a whole, which is a Government responsibility; to provision of detailed and customer specific weather information, which is a private sector responsibility*. This was achieved, although improvement in the relationship between the NWS and the private sector took longer. Collaborations with academia and government laboratories are beneficial, with some exceptions where the colocation is not optimal (Findings 3-5, 4-3c, and 4-5).
- *Achievement of productivity gains through automation and replacement of obsolete technological systems*. Observations were automated and obsolete technological systems were replaced (Findings 3-2 and 4-2a), leading to more products and new capabilities.
- *Operation of the optimum NWS warning and forecast system consistent with service requirements, user acceptability, and affordability*. It is not possible to assess whether the post-MAR NWS operates optimally. Operations certainly improved dramatically, and this goal, with some exceptions (e.g., the tornado and flash flood warning False Alarm Ratios remains high), was largely met.

**Key Finding 1**

**The National Weather Service (NWS) had been unable to keep up with the pace of technological advances and had nearly become obsolete by the 1980s. Therefore the NWS was not utilizing the full potential available to provide the best possible meteorological services to the nation. The $4.5 billion national investment in the Modernization and Associated Restructuring (MAR) was both needed and generally well spent. Overall, the MAR was successful in achieving major improvements for the weather enterprise.**

The MAR was large and complex in terms of both breadth and magnitude. The NWS was reengineered in a revolutionary manner. Many critical technologies were replaced, the field office structure was changed, and the workforce was retrained. This was necessary at the time because the NWS had fallen behind the pace of technological growth. Given that the pace is increasing, it is critical for the NWS to develop the capability to keep up with technological change in a more evolutionary manner, so that a transition the size and complexity of the MAR will not be necessary in the future.

Risk reduction activities were an important part of the MAR, and one of the key facets of the MAR was the prototyping of new operational concepts. This pre-operational prototype paradigm has been advanced following the MAR and embraced by the NWS, which now has a number of testbeds that support risk reduction and the transition of research-to-operations. The MAR created a framework that allows the NWS to be more capable of evolution, and decreases the need for revolution. One example of this evolutionary framework is the NEXRAD Product Improvement Program and the further development of AWIPS. The further development and improvement of guidance products and their applications, as well as the increasing use of research results from the social sciences, are also examples of continued improvement facilitated by the framework put in place by the MAR. However, issues remain. Some of the current-generation testbeds are too narrow in scope to adequately prototype new operational concepts, while others fail to engage key stakeholder groups such as emergency management. Finally, apparent issues with the deployment of AWIPS-II and upgrading the NEXRAD system to dual-polarization radars indicate that lingering process issues, particularly with large procurements, may hinder the evolution of the NWS.

**Key Finding 2**

**A framework was created and left in place following the Modernization and Associated Restructuring that allows and encourages the technology and to some extent the workforce composition and culture of the National Weather Service to continue to evolve.**

Based on input from a range of stakeholders and participants in the MAR; a review of the literature, oversight reports, NWS documents, and other relevant information; and interactions with staff at several WFOs, the committee identified six lessons that resulted from the MAR, that will be helpful to the NWS as it plans future improvements.

**Lesson 1**

**If a science-based agency like the National Weather Service, which provides critical services to the nation, waits until it is close to becoming obsolete, it will require a complex and very expensive program to modernize.**

Implementation of the MAR occurred during a period of rapid technological change, and involved a number of major systems deployed across a geographically diverse nation, as well as involving several federal agencies and the direct participation of three NOAA line offices (NWS, the National Environmental Satellite, Data, and Information Service [NESDIS], and the Office of Oceanic and Atmospheric Research [OAR]). Any such undertaking requires rigorous management to be successfully executed. In addition to the planned system improvements that were the objective of the MAR, execution of the project itself left a legacy of institutional and cultural changes at NWS, largely for the betterment of the organization.

**Lesson 2 – Management and Planning**

**The budget, schedule, and technological issues encountered during execution of the Modernization and Associated Restructuring of the National Weather Service (NWS) reflected traditional challenges of large projects: inexperience of the government project-level leadership, shifting budget constraints, ambitious technology leaps, multiparty stakeholder pressures, cultural inertia, contractor shortcomings, and oversight burdens. Each represents important lessons for the NWS with regard to future projects of a similar nature:**

**- Expertise in system design, procurement, and deployment is essential to successful implementation of any complex technical upgrade.**
**- Dedicated leaders are crucial for resolving roadblocks and ensuring ultimate project success.**
**- Clearly defined system-level requirements, and competent management of those requirements, are**

**essential to any contractual acquisition of a major system.**
**- Statistical performance indicators are a major element for gaining and maintaining support for implementing changes.**
**- It is necessary to establish comprehensive performance metrics at the beginning of a process, evaluate them throughout the process, and reevaluate them after the process is complete.**

The MAR included the development, procurement, and deployment of technologies in five major areas: surface observations, the radar network, satellites, computing upgrades, and a forecaster interface to integrate the data and information available by the other elements of the modernization. It was among the largest and most complex procurements ever undertaken in the Department of Commerce. While the technologies involved in the MAR all had scheduling or budget issues, they contributed to the capability of the NWS to provide improved weather services to the nation. This is particularly true for the forecasting and detection of severe weather such as tornadoes and flash floods.

**Lesson 3 – Modernization of Technology**
**The time scale for implementing major change in government systems is very long compared to the time scale for major technological change. The pace of technological progress complicates the planning, procurement, and deployment of large, complex systems. While technology is changing so rapidly, in every aspect of the project where it is feasible, it is crucial to**

**- establish clear metrics for evaluating improvement in forecasts and warnings at the beginning of a major technological upgrade;**
**- use rapid prototyping and system demonstrations. An example includes the Program for Regional Observing and Forecasting Service (PROFS) and their Denver AWIPS Risk Reduction and Requirements Evaluation ($DAR^3E$) effort, which proved critical to the success of the Modernization and Associated Restructuring;**
**- evaluate such prototype systems under a variety of actual operational situations with multiple classes of users and stakeholders in order to refine the system design;**
**- establish the capacity for continual upgrades of complex systems, particularly those involving digital technology (e.g., high performance computing, communications);**
**- continually assess and apply the lessons of past systems, whether successful or unsuccessful.**

The MAR brought significant changes to the NWS workforce. It closed offices and moved others. Great amounts of training were necessary to familiarize staff with the new technologies. Professional meteorology training was provided for technicians who wanted to qualify for a position in the new workforce structure. While many of these changes were viewed negatively by some NWS employees during the MAR period (NRC, 1994a), hindsight has shown that they have greatly improved the capability of the NWS to provide weather services to the nation, and are now viewed favorably by the staff.

**Lesson 4 – Restructuring of Forecast Offices and Staff**

**The Modernization and Associated Restructuring (MAR) of the National Weather Service (NWS) faced initial resistance from NWS employees and, to some extent, the general public. This resistance could have been lessened by, very early in the planning stages:**

**- Engaging those whose career and livelihood were to be affected in planning the changes**
**- Better engaging a diffuse public, and to some extent Congress, regarding the benefits of improved weather forecasts and warnings as opposed to the perceived cost of losing a forecast office in their community**

**The restructuring dictated a degree of standardization between forecast offices, however it has become apparent that this needs to be effectively balanced with the flexibility needed to allow for customization at individual offices to respond to local requirements.**

**The MAR increased the overall education level of the workforce and set in place the need for routine training to keep the staff on pace with technological**

**and meteorological advancements in the community. Staff development through in-person, hands-on training in a centralized classroom or laboratory of the type that occurred during the MAR has great value. Where relevant, online courses or self-directed study can be a useful supplement, but can sacrifice quality of learning and the connections made with colleagues that are essential to the overall operations of the NWS.**

While the MAR was a reengineering of the NWS, its execution depended on the involvement of many partners. Development and deployment of all the observational systems of the MAR involved other NOAA line offices (e.g., NESDIS, OAR) as well as other federal agencies. The NWS worked with the private sector through contracted work, and the research community played a large role in the development and demonstration of MAR technologies. In general, the MAR strengthened the relationships between the NWS and other members of the weather enterprise, although in the case of the private sector, it took some time after the MAR to develop these strengthened relationships.

**Lesson 5 – Partnerships**
**The execution of the Modernization and Associated Restructuring required working with many partners, which provided cost-sharing and improved understanding of user needs. However, the relationships with the partners were not always as well conceived or managed as would have been desirable. This could have been avoided by involving all known stakeholders (e.g., other agencies, academia and the research community, the private sector, media, and emergency management) from the outset. The National Weather Service (NWS) operational staff is also a stakeholder, and need to be involved early in the design and procurement process to ensure system functionality and practicality. Engagement with stakeholders from both inside and outside the NWS would help the NWS better understand user needs and secure 'buy-in' to new initiatives.**

Throughout the execution of the MAR, the NWS received a large amount of oversight and technical advice both from within and outside the government. In many cases, the reviews drew attention to important issues, issues whose resolution was important to the success of the MAR. Successful reviews not only help management understand and react to technical, schedule, and budget issues, but help build communities of knowledgeable support.

**Lesson 6 – Oversight and Advice**
**The Modernization and Associated Restructuring of the National Weather Service (NWS) showed that candid yet non-adversarial advice from outside experts and other interested parties was useful in the design and deployment of a large complex system. Because NWS management was receptive to such oversight and advice, the outside input was effective.**

The MAR was a large, complex process that lasted a decade, and cost an estimated $4.5 billion. Despite issues, some more significant than others, in the end the MAR was a success. New technologies deployed during the MAR now provide forecasters with more observations of higher quality. NWS forecast and warning products were dramatically improved, in both quality and quantity. NWS now has stronger relationships with many of its partners in the weather enterprise. Changes in the distribution of field offices have allowed stronger connections with local communities. Weather services have great value to the nation, and the MAR was clearly well worth the investment. In Phase II of its study, the committee will build on the lessons presented in this report to develop actionable recommendations for the NWS to best plan, deploy, and oversee future improvements.

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# A

# Acronyms and Abbreviations

| | |
|---|---|
| ACARS | Aircraft Communications Addressing and Reporting System |
| ACN | AWIPS Communications Network |
| AFOS | Automation of Field Operations and Services |
| AHPS | Advanced Hydrologic Prediction Service |
| AMS | American Meteorological Society |
| ARTT | AWIPS Requirements Task Team |
| ASOS | Automated Surface Observing System |
| ATS-1 | Applications Technology Satellite |
| AVN | Aviation Model |
| AWC | Aviation Weather Center |
| AWCIA | American Weather and Climate Industry Association |
| AWIPS | Advanced Weather Interactive Processing System |
| BLM | U.S. Bureau of Land Management |
| CDAS | Coordinated Data Analysis System |
| CHI | cloud height indicator |
| CHPS | Community Hydrologic Prediction System |
| CMC | Canadian Meteorological Centre |
| COMET | Cooperative Program for Operational Meteorology, Education, and Training |
| CONUS | Contiguous United States |
| CPC | Climate Prediction Center |
| CSD | Climate Services Division |
| CSTAR | Collaborative Science, Technology, and Applied Research |
| CWA | County Warning Area |
| CW | Continuous Wave |
| $DAR^3E$ | Denver AWIPS Risk Reduction and Requirements Evaluation |
| DCS | Data Collection System |
| DMIC | Deputy Meteorologist in Charge |
| DMSP | Defense Meteorological Satellite Program |
| DOC | U.S. Department of Commerce |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOH | Development and Operations Hydrologist |
| DOT | U.S. Department of Transportation |
| ECMWF | European Centre for Medium-range Weather Forecasts |
| EM | Emergency Manager |
| EMC | Environmental Modeling Center |
| EPA | U.S. Environmental Protection Agency |
| ERL | Environmental Research Laboratories |
| FAA | Federal Aviation Administration |
| FAR | False Alarm Ratio |
| FAWN | Florida Automated Weather Network |

| | |
|---|---|
| FEMA | Federal Emergency Management Agency |
| FHWA | Federal Highway Administration |
| flops | floating point operations per second |
| FNMOC | Fleet Numerical Meteorology and Oceanography Center |
| FPS-77 | Weather radar system used by USAF Air Weather Service |
| FSL | Forecast Systems Laboratory |
| FTE | Full Time Equivalent |
| GAO | General Accounting Office (Government Accountability Office after July 7, 2004) |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GFE | Graphical Forecast Editor |
| GFS | Global Forecast System |
| GOES | Geostationary Operational Environmental Satellite |
| GOES-Next | Next Generation Geostationary Operational Environmental Satellite |
| HIC | Hydrologist in Charge |
| HPC | Hydrometeorological Prediction Center |
| HSP | Hydrologic Services Program |
| HTB | Heated Tipping Bucket |
| IG | Inspector General |
| IGFOV | Instantaneous Geometric Field of View |
| IR | Infrared |
| IRT | Independent Review Team |
| ITO | Information Technology Officer |
| JDOP | Joint Doppler Operational Project |
| JSPO | Joint System Program Office |
| LFM-II | Limited Area Fine Mesh-II |
| MAR | Modernization and Associated Restructuring |
| MARD | Modernization and Associated Restructuring Demonstration |
| METAR | Aviation Routine Weather Report |
| MIC | Meteorologist in Charge |
| MOS | Model Output Statistics |
| MOU | Memorandum of Understanding |
| MSC | Meteorological Service of Canada |
| MTC | Modernization Transition Committee |
| NAM | North American Mesoscale |
| $NAR^3E$ | Norman AWIPS Risk Reduction and Requirements Evaluation |
| NASA | National Aeronautics and Space Administration |
| NBS | National Bureau of Standards |
| NCDC | National Climatic Data Center |
| NCEP | National Centers for Environmental Prediction |
| NCIM | National Council of Industrial Meteorologists |
| NCO | NCEP Central Operations |
| NESDIS | National Environmental Satellite, Data, and Information Service |
| NEXRAD | Next Generation Weather Radar |
| NGM | Nested Grid Model |
| NHC | National Hurricane Center |
| NIDS | NEXRAD Information Dissemination Service |
| NIP | National Implementation Plan |
| NMC | National Meteorological Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NPC | NEXRAD Program Council |
| NPOESS | National Polar-orbiting Operational Environmental Satellite System |
| NPS | National Park Service |
| NRC | National Research Council |
| NSSL | National Severe Storms Laboratory |
| NTR | NEXRAD Technical Requirements |
| NWP | Numerical Weather Prediction |
| NWS | National Weather Service |
| NWSEO | National Weather Service Employees Organization |
| OAR | Office of Oceanic and Atmospheric Research |
| OD | Office of the Director |
| OFCM | Office of the Federal Coordinator for Meteorological Services and Supporting Research |

| | |
|---|---|
| OH | Office of Hydrology |
| OMB | Office of Management and Budget |
| OPC | Ocean Prediction Center |
| OSF | Operational Support Facility (Renamed later to Radar Operations Center) |
| OSIP | Operational Satellite Improvement Program |
| | |
| PI | Precipitation Identification |
| POD | Probability of Detection |
| POES | Polar Operational Environmental Satellite |
| POP | Probability of Precipitation |
| PROFS | Program for Regional Observing and Forecasting Service |
| PROTEUS | Prototype RFC Operational Test, Evaluation, and User Simulation |
| | |
| QPF | Quantitative Precipitation Forecast |
| | |
| RDA | Radar Data Acquisition |
| RFC | River Forecast Center |
| RFI | Radio Frequency Interference |
| RFP | Request for Proposals |
| RPG | Radar Product Generator |
| | |
| SAO | Surface Airway Observations |
| SCH | Service Coordination Hydrologist |
| SOO | Science Operations Officer |
| SPC | Storm Prediction Center |
| SPECI | Aviation Selected Special Weather Report |
| SSR | Sampled Subpoint Resolution |
| SWPC | Space Weather Prediction Center |
| | |
| TAC | Technical Advisory Committee |
| TIROS | Television Infrared Observation Satellite |
| | |
| UCAR | University Corporation for Atmospheric Research |
| UKMO | United Kingdom Meteorological Office |
| USAF | United States Air Force |
| USFS | United States Forest Service |
| USGS | United States Geological Survey |
| USWRP | United States Weather Research Program |
| | |
| WCM | Warning Coordination Meteorologist |
| WFO | Weather Forecast Office |
| WMO | World Meteorological Organization |
| WSFO | Weather Service Forecast Office |
| WSO | Weather Service Office |
| WSR-57 | Weather Surveillance Radar, 1957 |
| WSR-74 | Weather Surveillance Radar, 1974 |
| WSR-88D | Weather Surveillance Radar, 1988, Doppler |
| WWW | World Weather Watch |

# B

# Prior Assessments of the Modernization and Associated Restructuring

**TABLE B.1** National Research Council reports related to the Modernization and Associated Restructuring

| Report Title | Publication Year |
|---|---|
| Toward a New National Weather Service: A First Report | 1991 |
| Revised Standards for Entry-Level Meteorologists in Federal Government: A Letter Report | 1992 |
| Toward a New National Weather Service: Second Report | 1992 |
| Review of Modernization Criteria | 1993 |
| National Weather Service Employee Feedback | 1994 |
| Weather for Those Who Fly | 1994 |
| Assessment of NEXRAD Coverage and Associated Weather Services | 1995 |
| Aviation Weather Services: A Call for Federal Leadership and Action | 1995 |
| The Importance of the U.S. Weather Research Program for NWS Modernization | 1996 |
| Preliminary Assessment of the Operational Test and Evaluation Process for the Advanced Weather Interactive Processing System | 1996 |
| Assessment of Hydrologic and Hydrometeorological Operations and Services | 1996 |
| Continuity of NOAA Satellites | 1997 |
| An Assessment of the Advanced Weather Interactive Processing System | 1997 |
| Future of the National Weather Service Cooperative Observer Network | 1998 |
| A Vision for the National Weather Service; Road Map for the Future | 1999 |
| Review of the Draft Plan for the Modernization and Associated Restructuring Demonstration | 1999 |

**TABLE B.2** U.S. General Accounting Office reports related to the Modernization and Associated Restructuring

| Report Title | Report Number | Publication Date |
|---|---|---|
| Weather Satellites: Cost Growth and Development Delays Jeopardize U.S. Forecasting Ability | GAO/NSIAD-89-169 | June 1989 |
| Weather Satellites: Action Needed to Resolve Status of the U.S. Geostationary Satellite Program | GAO/NSIAD-91-252 | July 1991 |
| Cost Growth and Delays in Billion-Dollar Weather Service Modernization | GAO/IMTEC-92-12FS | December 1991 |
| Weather Forecasting: Important Issues on Automated Weather Processing System Need Resolution | GAO/IMTEC-93-12BR | January 1993 |
| Weather Forecasting: Systems Architecture Needed for National Weather Service Modernization | GAO/AIMD-94-28 | March 1994 |
| Weather Forecasting: Improvements Needed in Laboratory Software Development Processes | GAO/AIMD-95-24 | December 1994 |
| Meteorological Satellites | GAO/NSIAD-95-87R | February 1995 |
| Weather Service Modernization: Despite Progress, Significant Problems and Risks Remain | GAO/T-AIMD-95-87 | February 1995 |
| High-Risk Series : An Overview | GAO/HR-95-1 | February 1995 |
| Weather Service Modernization Questions | GAO/AIMD-95-106R | March 1995 |
| Weather Forecasting: Unmet Needs and Unknown Costs Warrant Reassessment of Observing System Plans | GAO/AIMD-95-81 | April 1995 |
| Weather Forecasting: Radar Availability Requirements Not Being Met | GAO/AIMD-95-132 | May 1995 |
| Weather Service Modernization Staffing | GAO/AIMD-95-239R | September 1995 |
| Weather Forecasting: Radars Far Superior to Predecessors, but Location and Availability Questions Remain | GAO/T-AIMD-96-2 | October 1995 |
| Weather Forecasting: New Processing System Faces Uncertainties and Risks | GAO/T-AIMD-96-47 | February 1996 |
| Weather Forecasting: NWS has not Demonstrated that New Processing System Will Improve Mission Effectiveness | GAO/AIMD-96-29 | February 1996 |
| Processing Systems Development Risks | GAO/AIMD-96-74 | May 1996 |
| NOAA Satellites | GAO/AIMD-96-141R | September 1996 |
| High-Risk Series: Information Management and Technology | GAO/HR-97-9 | February 1997 |
| Weather Satellites: Planning for the Geostationary Satellite Program Needs More Attention | GAO/AIMD-97-37 | March 1997 |
| Weather Service Modernization and NOAA Corps Issues | GAO/T-AIMD/GGD-97-63 | March 1997 |
| National Oceanic and Atmospheric Administration: Follow-up on Weather Service Modernization and NOAA Corps Issues | GAO/AIMD/GGD-97-75R | April 1997 |
| Weather Service Modernization: Risks Remain that Full Systems Potential Will Not be Achieved | GAO/T-AIMD-97-85 | April 1997 |
| National Weather Service: Budget Events and Continuing Risks of Systems Modernization | GAO/T-AIMD-98-97 | March 1998 |
| NWS Sulphur Mountain Radar Performance | GAO/AIMD-99-7 | October 1998 |
| Department of Commerce: National Weather Service Modernization and NOAA Fleet Issues | GAO/T-AIMD/GGD-99-97 | February 1999 |
| NOAA: National Weather Service Modernization and Weather Satellite Program | GAO/T-AIMD-00-86 | March 2000 |

# C

# Weather Forecast Office Site Visits

**Alaskan Region**
Anchorage (Alaska)

**Central Region**
Denver/Boulder (Colorado)
Rapid City (South Dakota)

**Eastern Region**
Boston/Taunton (Massachusetts)
Baltimore/Washington (Virginia)

**Southern Region**
Norman (Oklahoma)
Houston/Galveston (Texas)
Miami/South Florida (Florida)

**Western Region**
San Francisco/Bay Area (California)
Los Angeles/Oxnard (California)
Tucson (Arizona)
Portland (Oregon)
Seattle (Washington)

# D

# National Weather Service Offices Collocated with Academic Institutions: Summary of Questionnaire Responses

**When Colocation Occurred:** Colocation of National Weather Service (NWS) offices on or near the campuses of universities occurred between 1993 and 1998 with the earliest being in State College, PA, around 1993 (Middle Atlantic River Forecast Center [RFC] and Weather Forecast Office [WFO] State College) and the most recent being WFO Fairbanks in 1998. In some of these cases, interactions had already begun prior to colocation, in the 1980s, and had progressively increased through COMET, internship, and other programs.

**How Close NWS Offices Are to Campus:** Five of the NWS offices interviewed are located on campus (National Hurricane Center [NHC] Florida, WFO Fairbanks, WFO Honolulu, WFO Raleigh, and WFO Tucson). Three offices are located adjacent or close to campus from a few blocks to a 25-minute walk (NWS Albany, WFO Rapid City, and WFO Denver/Boulder). Five offices are located in the same city (Middle Atlantic RFC, WFO Reno, WFO San Francisco, WFO Seattle, and WFO State College)—though technically on campus they are in a research park or annex about one to three miles away. In cases where there is lack of true colocation, this appears to be a disadvantage, as discussed later.

**How Successful Colocation Is with Regard to Regular Interaction:** The results here appear to be somewhat varied but, overall, the responses indicate successful sustained, regular, and beneficial bidirectional interactions at 9 of the 12 NWS offices. The extent of these does not appear to be correlated with how close the NWS offices are to the campuses, although true colocation seems to have provided clear benefits.

Three of the five "On Campus Offices" (WFO Honolulu, WFO Raleigh, and WFO Tucson) report very extensive bidirectional interactions, while the other two (WFO Fairbanks and NHC Florida) report no "regular" interactions, with interactions being more on an as-needed basis.

Very strong, mutually beneficial interactions appear to have developed at WFO Raleigh (North Carolina State University). These include NWS-hosted internship courses offered for credit and with competitive selection of students (the course was highlighted in the Bulletin of the American Meteorological Society in October 2005), monthly integration of students into NWS activities and projects, participation of NWS staff in the NCSU student chapter of AMS, collaborative projects funded through CSTAR and COMET, and research meetings/workshops many times a year to discuss successes and challenges of funded research, meteorological challenges for focus in future research proposals, data gathering efforts, etc. Beneficial interactions at WFO Tucson (University of Arizona) include research collaboration, communicating weather, water and climate issues to the community, and providing an academic institution easy access to an operationally oriented organization. Within any one year period, WFO Tucson is usually involved in two research projects with faculty and graduate students, jointly conducts press conferences on science issues and participates in three to five meetings associated with integrating advances in science into an operational setting. Similar benefits appear to be realized at WFO Honolulu (University of Hawaii).

Similarly the three "Near Campus Offices" report fairly successful interactions. WFO Denver/Boulder reports multiple daily interactions ranging from weather briefings to side-by-side work in the forecast operations area, regular interactions such as project and science presentations and participation in seminars and workshops at NCAR, UCAR, CIRES (University of Colorado) and CIRA (Colorado State University) providing strong educational experiences for NWS staff. NWS Albany is engaged in active CSTAR grants, hosts 16 University of Albany interns each year, employs two to three students per year, and benefits from University conference facilities. The WFO Rapid City reports participation in seminars, substitute teaching, a severe weather spotter class by the WCM, collaborative research meetings, and the SOO serving on thesis and dissertation committees.

Three of the four "Same City" offices in Pennsylvania (Middle Atlantic RFC, WFO Reno, and WFO State College) report extensive student engagement (some leading to careers with the NWS) that provides "hydrologic familiarization training" to meteorology students, including some teaching. WFO San Francisco reports limited interactions. WFO Seattle benefitted from and contributed to the collaboration with University of Washington atmospheric scientists on the science of weather forecasting. This led to improvements in the understanding of the local weather of the Pacific Northwest. University of Washington atmospheric scientists did a lot to improve weather observations locally and WFO Seattle benefitted from this.

**How Colocation Impacts NWS Functions:** Colocation appears to benefit NWS functions at most of the offices, through (1) improved precipitation forecasts during some heavy rainfall events; (2) feedback from faculty; (3) student involvement in operational forecasting and data collection; (4) shared research projects (resulting in more rapid integration of science findings into NWS operations thereby improving forecasts and warnings); (5) access to unique datasets (imagery and high-resolution/ensemble model runs) that would not otherwise be available; (6) access to robust Internet connections; (7) being able to identify top students for recruitment; and (8) continuing education of NWS employees. However the latter suffers from inadequate funding support. Outreach is also improved by being able to take advantage of university outreach programs and career fairs. In the case of WFO Honolulu, the collaboration results in Hawaii-specific research on issues that would not be studied without University participation and resources.

Again, the most extensive benefits appear to be at WFO Albany, WFO Denver/Boulder, WFO Raleigh, and WFO Tucson, these being the ones reporting the most active and extensive interactions. In fact, WFO Denver/Boulder reports that one academic actually works a forecast shift once a month under the supervision of a lead forecaster and often joins the discussion of the forecast on other days. In another vein, Raleigh reports being able to take advantage of the NCSU recycling program to properly dispose of an estimated one-half ton of recycled materials.

**How Colocation Impacts University Functions:** Colocation appears to benefit University functions at most of the locations, through (1) guest lectures and/or teaching provided by NWS staff; (2) participation in collaborative research opportunities and grant proposals—both directly and through letters of support; (3) participation on student thesis committees; (4) participation in (and providing data and projects for) student term projects; (5) easier student/faculty access to radar/precipitation products; (6) internships, career experiences, and employment opportunities provided to students; (7) input provided regarding faculty hires; and (8) ability of University to tout the nearby NWS forecasting facilities and internship opportunities to help them recruit and retain top students. Conversely, it appears that numerous students at collocated Universities take advantage of NWS career opportunities.

Again, WFO Raleigh reports very extensive benefits from the close partnership including sharing of data and building of critical datasets used by the North Carolina State Climate office (also collocated). WFO

Tucson reports that colocation brings expertise in applying research in an operational setting to the university. WFO Rapid City reports an interesting student volunteer program that is run as a course for credit. In an interesting arrangement, rent monies paid by WFO Honolulu to the University of Hawaii are used to support a full time Graduate Research Assistant, two summer teaching assistants, six undergraduate student assistants and some operational costs.

**Other Benefits of Colocation:** In general, colocation offers excellent working facilities with good security, an easy commute, a nice campus atmosphere, and an unparalleled opportunity for the NWS staff to interact with the academic community. In many cases such colocation provided early access to advanced Internet connectivity, this being instrumental in the development of operational research programs. WFO Rapid City reports that the interaction helps keep the NWS staff from becoming too internally focused. WFO Fairbanks reports that colocation enhances outreach and facilitates collaborations that would otherwise be difficult to accomplish. Further, students get unique access to the forecast office and staff, and are often able to gain insights into operational forecast decision making that are not easily taught in the classroom. Active discussion/debate between forecasters and faculty during significant weather events (such as tropical cyclones) benefits both sides. WFO Denver/Boulder reports that the ability of the WFO to provide input at early stages in the research-to-operations process helps to ensure a better product for the National Weather Service and the weather enterprise at large. WFO Raleigh reports that recruits note that the benefits of collaborative research, professional development, educational opportunities, and/or increased activity or energy are important reasons for their interest in the office.

**Challenges/Difficulties Reported with Respect to Colocation:** While challenges with respect to colocation differ from site-to-site, one common theme is the lack of sufficient funding to support the activities that benefit from colocation. In almost every case, more benefits would likely accrue if more moneys and/or FTEs could be devoted to university collaborative activities. WFO Rapid City would like to dedicate more of an FTE to collaboration. The Middle Atlantic RFC would like to offer paid student internships on a regular basis and provide more opportunities for Middle Atlantic RFC staff to take course work at Pennsylvania State University.

In a different vein, there can be difficulties related to the nature of the facilities. For example, the experience of WFO Honolulu indicates that colocation can raise difficulties with regards to access to staff and visitor parking. This can cause security issues for shift workers. Meanwhile WFO Raleigh points out that in a facility directly-owned by NWS, the office is more able to solve facilities-related problems on its own or through providers of its choosing. In a facility leased from a campus, facilities issues must usually be directed to campus facilities personnel with more complex procedures to be followed (work orders, facilities modification form completion and approvals, etc.) to get work accomplished. Sometimes, apparently very simple work needs to be completed by University personnel at a cost, due to the need to comply with state law and liability issues. On the other hand, when colocation is not directly on campus, the lack of close proximity poses a real drawback because it does not allow for the kind of valuable informal gatherings that are critical to true interaction.

A unique challenge appears to exist in regard to the colocation of the NHC at Florida International University. In this case, the basic problem seems to be that the University foci do not include ones that are directly related to what NHC or NWS does, so collaboration has been difficult. This may point to the need for more careful attention when pairing NWS offices with Universities. The colocation of WFO San Francisco with the Naval Postgraduate School has also been less than optimal. Interaction between the WFO and the University has been minimal, and the location is very inconvenient. Most constituents and partners of WFO San Francisco are now a one to three hour drive away. The WFO reports losing interaction with the San Francisco media market since moving to Monterey.

# E

# Automated Surface Observing System Impact on the Climate Record

The ASOS hygrothermometer (McKee et al., 1996b) is cooler than the conventional HO-83 hygrothermometer for both maximum and minimum temperatures and also has a smaller diurnal temperature range (McKee and Doesken, 1997; McKee et al., 1996b; Schrumpf and McKee, 1996). The maximum temperature differences are larger in magnitude (compared to minimums) and vary more with varying weather conditions. Individual test sites showed wide variation in ASOS-conventional differences, possibly due to differences in instrument siting and surroundings, as well as variable changes in the solar heating effects; this local effect can vary from day to night, and the effect of instrument location change can sometimes be as large as that resulting from the change in instrument. These local effects introduce a nonlinear relationship between the ASOS and pre-ASOS data. Large ASOS-conventional differences in dew point temperature can occur from station to station, but without systematic bias (McKee et al., 1996b). The cool temperature bias of ASOS means that relative humidity estimates are slightly higher than before, with seasonal averages being one to three percent higher (McKee et al., 1996b).

The ASOS Heated Tipping Bucket (HTB) gauge consistently undermeasured precipitation compared to the standard universal weighing gauge, during heavy rain events (McKee et al., 1996b) and snow events (McKee et al., 1995). This difference showed a nonlinear seasonal pattern in the central United States, with ASOS measuring significantly less precipitation during winter and summer when compared to spring and autumn (McKee et al., 1995). The HTB gauge also reported too many days with 0.01 inch resulting from dew condensation, not precipitation. ASOS precipitation undercatch ranged from two to 10 percent compared to traditional manual observation. Further, the HTB evaporated or sublimated precipitation falling below 15°F, recording almost no cold weather precipitation. The introduction into service, beginning in 1996, of a modified heated tipping bucket gauge for ASOS resulted in an improved comparison between the ASOS and conventional measurements (McKee and Doesken, 1997). However, according to the CSD, the nearly 10 years of undercatch reported from the HTB gauge is still in the extant climate record. The phased introduction of this new ASOS gauge will complicate future precipitation comparison studies and any adjustments that may be made to the data for normal computation. Further, ASOS is not equipped to measure snowfall and snow depth amounts (NWS, 1992a).

Conventional NWS wind measurements use a three-cup design with a continuous output to drive a dial indicator or a strip chart recorder; ASOS uses a light chopper rather than a voltage generator resulting in a lower starting threshold and an accurate one-second average sample speed. The conventional wind vane reports in 10-degree steps or a resolution of ± five degrees, while the ASOS wind vane reports to the nearest whole degree (Lockhart, 1995). ASOS also introduces a significant change in the way wind speed is measured. All applications of maximum wind speed which relate to warnings have been based in the past on "instantaneous" values equivalent to an averaging time of 2 seconds, whereas ASOS uses a five-second (soon to be changed to three-second) average peak gust. ASOS provides a two-minute average, continuously updated each minute, for the hourly observation (Lockhart, 1995, 1996a, 1996b). Possible sources for differences in wind direction (Lockhart, 1996b) are that measurements may not be taken at exactly the same time, the instruments are not co-located which would affect the character of the wind flow, and the wind direction is determined differently. ASOS provides unweighted (objective) averages (scalar or unit vector) from one-second samples taken for two minutes, whereas the conventional observation is the (subjective) average direction and speed inferred by an observer watching a dial for one minute. Analysis of five-second wind averaging indicates ASOS peak winds are lower than the previous subjective measurements (Lockhart, 1996b; McKee et al., 1996a). Differences in the hourly wind speed observation show a nonlinear wind speed-dependent bias (Lockhart, 1996b). A comparison of the wind direction distributions at two sites indicated that there was no significant difference between the ASOS and conventional hourly observations (Lockhart, 1996b).

The ASOS cloud height indicator (CHI) is a laser ceilometer that differs from the standard NWS ceilometer in the way it processes returns for low cloud base and total obscuration. Both ceiling height and cloud coverage (up to 12,000 feet only) are determined by time averaging over a 30-minute period the conditions directly overhead. In manual observations, the observer subjectively evaluates the ceilometer trace at a single point in time to determine ceiling height, and the cloud coverage is determined by visual examination of the cloud conditions over the entire sky then subjectively forming a spatial average (Cornick and McKee, 1993). ASOS ceiling reports were highly correlated to conventional ceiling reports most of the time (92.7 percent), but the high level of equality drops during periods of active weather (Cornick and McKee, 1993).

ASOS is not equipped to measure sunshine duration (NWS, 1992a). Conventional pressure observations are based on an aneroid altimeter indicator or a precision aneroid barometer with observations made at hourly and special observation times (NWS, 1992a, 1994a). The ASOS barometers consist of redundant digital pressure transducers utilizing capacitive sensors, which compute and update the pressure report once every minute from readings obtained every 10 seconds (NWS, 1992a).

Manual observation of weather phenomena, including obstructions to vision, has been based on personal interpretation of the human senses (NWS, 1994a) for almost all of history (Cornick and McKee, 1993), with intensity being based on visibility criteria. These phenomena include (a) rain, snow, fog, haze, and freezing precipitation; and (b) tornadoes, funnel clouds, water spouts, thunderstorms, hail, ice crystals, snow pellets, snow grains, ice pellets, drizzle, blowing obstructions (snow, sand, dust, spray), and smoke. The automated observation of these elements required a fundamental change in observational technique and perspective. The ASOS Precipitation Identification (PI) sensor can discriminate between the occurrence of rain and snow (and identify intensity) from an algorithm based on sensor response (Cornick and McKee, 1993). Fog is reported if visibility drops below seven statute miles and dew point depression is 4°F or less. If the dew point depression is greater than four degrees and no present weather is indicated, then haze is reported. ASOS cannot report the weather phenomena from group (b) above (NWS, 1992a). In a study of 13 sites, ASOS and human observers reported approximately the same number of total minutes of freezing rain, however the coincidence rate (ASOS and human reporting freezing rain at the same time) was about 66 percent (Ramsay, 1997).

# F

# Statement of Task

During the 1980s and 1990s, NOAA launched a major program to modernize the National Weather Service (NWS), investing $4.5 billion to modernize NWS technologies to advance weather forecasting. No complete assessment of the entire end-to-end NWS modernization enterprise has been done, thus Congress has asked the National Academy of Sciences to conduct an assessment of the now-completed National Weather Service modernization. The project should not only address the past modernization, but also focus on lessons learned to support future improvements to NWS capabilities. It should address high-impact weather and new science and technologies that allow for even better forecasts; the integration of new technologies and better models into NWS operations; workforce composition and structure; and improving current partnerships with private industry, academia, and other governmental agencies. Finally, the project should provide advice on how NWS can best plan, deploy, and oversee these future improvements based on lessons learned from the NWS modernization.

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# Biographical Sketches of Committee Members

**John A. Armstrong** (NAE, Chair) retired from IBM after a 30-year career with the world's largest manufacturer of computers. He is internationally recognized as an expert in nonlinear optics, the statistical properties of laser light, picosecond pulse measurements and the multiphoton laser spectroscopy of atoms. He previously chaired the Committee on Partnerships in Weather and Climate Services, which produced the 2003 NRC Report, Fair Weather: Effective Partnership in Weather and Climate Services. Dr. Armstrong holds an A.B. in physics from Harvard College (1956) and a Ph.D. (1961) from Harvard University for research in nuclear magnetic resonance at high pressures. He joined IBM in 1963 as a research staff member. In 1976 he became Director of Physical Sciences for the company and was responsible for a major part of IBM research in physics, chemistry, and materials science. In 1980 he was appointed to the IBM Corporate Technical Committee. In 1983 he was named Vice President of logic and memory in the Research Division. In 1986 he became director of research and the following year was elected IBM Vice President and Director of research. In 1989 he was elected a member of the Corporate Management Board and named Vice president of Science and Technology. Dr. Armstrong is a Fellow of the Optical Society of America, the American Physical Society, the American Association for the Advancement of Science, the American Academy of Arts and Sciences, and the Institute of Electrical and Electronic Engineers. He is a member of the National Academy of Engineering and a foreign member of the Royal Swedish Academy of Engineering Sciences. In 1989 he was awarded the George E. Pake Prize of the American Physical Society.

**James D. Doyle** earned his B.S. degree in atmospheric science and mathematics from the University of Wisconsin at Milwaukee in 1983 and M.S. and Ph.D. from the Pennsylvania State University in 1986 and 1991, respectively, in meteorology with an emphasis on mesoscale dynamics and numerical weather prediction. He joined the Mesoscale Modeling Section of the Naval Research Laboratory's Marine Meteorology Division in 1992 and has served as the head of the group since 1998. Since joining NRL, he has conducted research on atmospheric processes over complex terrain, coastal air-sea interaction, and the development of high-resolution numerical weather prediction models. He is one of the primary developers of the Navy's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), which is used to support operational Navy and Department of Defense interests globally, as well as basic research at NRL and numerous other universities and laboratories. Currently, he is leading efforts for improving the physical understanding and prediction of mesoscale phenomena using both deterministic and probabilistic approaches. He is a past Chairman of the American Meteorological Society Committee on Mesoscale Processes and has served as an editor for the Monthly Weather Review and subject matter editor for the Bulletin of the American Meteorological Society. He is a recipient of the 2008 Top Navy Scientists and Engineers of the Year Award and is a Fellow of the American Meteorological Society. He has over 100 peer-reviewed publications.

**Pamela Emch** is a Senior Staff Engineer/Scientist with Northrop Grumman Aerospace Systems in Redondo Beach, California. She works in Northrop's Space Systems business area on weather, climate, and environmental remote sensing and information technology activities supporting the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Defense, and international customers. From 2005 to 2007 she was System Engineering, Integration, and Test Lead on Northrop's GOES-R PDRR Program. Before working on GOES-R, Dr. Emch spent eight years on Northrop's NPOESS Program effort, the last two years of which she relocated to Washington, D.C. to serve as Northrop's system engineering and science interface to the NPOESS government program office in Silver Spring, Maryland. Prior to that Dr. Emch managed development of end-to-end physics/instrument/satellite remote sensing simulations, archives for environmental multimedia data, and led environmental data-collection and application activities for hyperspectral airborne instruments. Dr. Emch holds an M.S. degree in aerospace engineering from the University of Southern California and a B.A. in mathematics and a Ph.D. in civil and environmental engineering from the University of California, Los Angeles, specializing in water resources with a minor in atmospheric sciences. She is the current Past Chair of the American Meteorological Society (AMS) Board on Enterprise Economic Development, a member of the Executive Committee of the AMS Commission on the Weather and Climate Enterprise, and a Cochair of the Weather Coalition.

**William Gail** is a Director in the Startup Business Group at Microsoft with responsibility for enabling breakthroughs in consumer software, having held similar positions within the Public Sector and Virtual Earth organizations. He is also cofounder and Chief Technology Officer of Global Weather Corporation, a private-label provider of precision weather forecast information. He was previously Vice President of the mapping products division at Vexcel Corporation (where he initiated Vexcel's 2006 acquisition by Microsoft) and Director of Earth Science programs at Ball Aerospace, where he was responsible for developing spaceborne instruments/missions for Earth science and meteorology. Dr. Gail received his undergraduate degree in physics and his Ph.D. in electrical engineering from Stanford University, where his research focused on plasma physics in Earth's magnetosphere. During this period, he spent a year as cosmic ray field scientist at South Pole Station. Dr. Gail has served on a number of National Research Council committees including the "Decadal Survey for Earth Science and Applications from Space." He serves on a variety of corporate and organizational boards including Peak Weather Resources Inc., Women in Aerospace, Imaging Notes magazine, the National Oceanic and Atmospheric Administration Advisory Committee on Commercial Remote Sensing (acting), and the National Aeronautics and Space Administration Applied Sciences Program Advisory Group. He has published extensively on both technical and policy issues, and serves as Associate Editor for the SPIE Journal of Applied Remote Sensing and Director of Industry Relations for the IEEE Geoscience and Remote Sensing Society. Dr. Gail received recent awards from GITA for best conference speaker and AGU for excellence in scientific journal review.

**David Gochis** is currently a Scientist-II at the National Center for Atmospheric Research in Boulder, Colorado. Dr. Gochis is based in NCAR's Research Applications Laboratory, a group that looks for research and engineering solutions to problems relevant to society. As a hydrometeorologist, he serves as a liaison between hydrologists, who traditionally have strong engineering backgrounds, and atmospheric scientists, who are typically oriented toward scientific research. His research focuses on coupled hydrological and meteorological forecasting problems. Dr. Gochis earned an M.S. in bioresources engineering from Oregon State University, with an emphasis on water resources and the agricultural applications of meteorology and atmospheric sciences. Afterward, he worked briefly for an engineering firm, designing irrigation systems and assessing water resources. He earned his Ph.D. in hydrology and water resources from the University of Arizona. From Arizona, he moved to NCAR to work as a postdoctoral researcher, and later became part of the organization's permanent scientific staff. Dr. Gochis also serves as co-chair of the International CLIVAR panel on Variability of American Monsoon Systems.

**Hoshin Gupta** specializes in systems analysis and modeling for environmental science. His research is focused on the methods for reconciling models with data, and on methods for dealing with predictive uncertainty. His team has made contributions to hydrology and hydrometeorology for the National Science Foundation (NSF), National Weather Service, and National Aeronautics and Space Administration. He also works with economists and social scientists to develop coupled models that support improved decision making under uncertainty, particularly future (scenario) uncertainty, and is co-leader of the first-ever graduate program in hydrometeorology. Dr. Gupta holds a B. Tech degree in civil engineering (1979) from the Indian Institute of Technology and M.S. (1982) and Ph.D. (1984) degrees in system engineering from Case Western Reserve University. He is a Fellow of the American Geophysical Union and current Editor of Water Resources Research. He leads the New Model Approaches and Model Diagnostics groups of the International Association of Hydrologic Sciences (IAHS), is special Editor for Journal of Hydrology, and is on the Editorial Board of Benchmark Papers in Hydrology. In the past he was Executive Director of Semi-Arid Hydrology and Riparian Areas (SAHRA), the first NSF Center in hydrological science, which coordinated the activities of 400 scientists and 110 students from 17 institutions, and served as President of the IAHS Commission on Coupled Land-Atmosphere System (ICCLAS), and as Chair of the American Geophysical Union Surface Water Committee.

**Holly Hartmann** is Director of the Arid Lands Information Center at the University of Arizona, where she is a coinvestigator at the Climate Assessment for the Southwest (CLIMAS) and led the scenario development team at the Science and Technology Center for the Sustainability of SAHRA. Dr. Hartmann's research has focused on making climate and water research more usable, based on engagement with stakeholders, development of decision support resources and tools, and transition of decision support into sustainable operations. Current projects address climate and hydrologic forecasts, climate change scenario planning and risk management, water policy in the U.S. West, and collaborative software development. She is a member of the American Meteorological Society (AMS) Committee on Climate Services, the AMS Board of Economic Enterprise Development, the Board of the International Environmental Modeling and Software Society, the Editorial Board of the journal Environmental Modeling and Software, and the Executive Committee of Carpe Diem West. She also serves on the Climate Working Group of the National Oceanic and Atmospheric Administration Science Advisory Board. Dr. Hartmann received her M.S. degree in water resources management from the University of Michigan, and her Ph.D. in hydrology and water resources from the University of Arizona.

**Kevin Kloesel** is Associate Dean for Public Service and Outreach in the College of Atmospheric and Geographic Sciences at the University of Oklahoma. He is responsible for outreach programs and tours for the 50,000 people that visit the National Weather Center facility in Norman annually. In addition, he is an Associate Professor in the College of Atmospheric and Geographic Sciences with teaching and research interests ranging from synoptic meteorology to societal impacts and decision making in weather-impacted situations. He led the team that won the Innovations in American Government Award from Harvard University and the Ford Foundation for their work with the emergency management community in Oklahoma. Currently, he works directly with thousands of K-12 students and teachers, as well as hundreds of emergency management agencies in finding appropriate applications for weather data in local education and decision making. He also serves as Director for the largest state climate office in the country, the Oklahoma Climatological Survey, and previously served as Director of the Florida Climate Center in Tallahassee, Florida. He has a B.S. in engineering science from the University of Texas at Austin and an M.S. and Ph.D. (1990) in meteorology from The Pennsylvania State University.

**Nicholas Lampson** served as a member of the U.S. House of Representatives in Texas' Districts 9 and 22 from 1997 to 2009. During his five terms in Congress, Lampson was Chairman of the House Science Committee's Subcommittee on Energy and the Environment which has oversight of the National Weather Service. He has a strong focus on energy issues, particularly alternative energy and acknowledges the important role weather observations and forecasting play in managing an energy grid heavily reliant on alternative energy. Congressman Lampson's diverse background provides a unique perspective on the social aspect of weather forecasting. He is an active proponent of business and economic growth. Both before and after his tenure in Congress, Congressman Lampson advocated for issues of planetary concern and now serves in advisory positions to a green energy company and a company aiming to launch a satellite to measure solar flares to warn Earth of pending damage. As a Congressman, he was active in many issue-oriented Congressional caucuses.

**John W. Madden** was appointed in January 2007 as the Director of the Division of Homeland Security and Emergency Management for the State of Alaska. This followed a year as the Deputy Director for Homeland Security within the division. His mission is to protect lives and property from all hazards including terrorism as well as to provide response and comprehensive recovery from all disasters. His state service follows a distinguished career in seven federal agencies. Most recently, he served with the Transportation Security Administration as Assistant Federal Security Director for Operations. He coordinated security policies, procedures, plans, and exercises with federal, state, and local agencies throughout Alaska. Mr. Madden served in the U.S. Army for three years including twenty months in Vietnam performing aviation direct support. After his military service, he joined the U.S. civil service with the Department of the Navy. He worked in program and project management with the Naval Weapons Engineering Support Activity, Naval Electronic Systems Command, and the Joint Cruise Missile Project Office. After earning his degree in political science, he joined the Department of Energy working on fossil fuels programs and research and development into alternative fuels. In 1982, he elected to move to Alaska with the National Weather Service. He supported their operations throughout Alaska and traveled extensively to maintain the remote weather observation sites. He next worked for the Alaskan Region of the Federal Aviation Administration as the Executive Staff to the Regional Administrator. He also ensured continuity of operations for all FAA operations under all hazards. He supported FEMA in several exercises and served in several Disaster Field Offices, most notably to Puerto Rico and Florida in response to Hurricane Georges.

**Gordon McBean** is a Canadian atmospheric scientist and Professor at the University of Western Ontario, and Chair for Policy in the Institute for Catastrophic Loss Reduction. Previously Gordon Dr. McBean was the Assistant Deputy Minister, Meteorological Service of Canada (MSC); Professor and Head, Department of Oceanography, University of British Columbia; Professor and Chairman, Atmospheric Science Programme, University of British Columbia; and Senior Scientist, Canadian Climate Centre, MSC. Dr. McBean has received many distinguished awards including the Order of Canada, the MSC Patterson Medal and CMOS President's Prize and has been elected a Fellow of the Royal Society of Canada, the Canadian Meteorological and Oceanographic Society and the American Meteorological Society. Dr. McBean has chaired and been a member of enumerable national and international scientific committees, including the National Research Council Committee on Partnerships in Weather and Climate Services and Chair of the International Scientific Committee for the World Climate Research Programme. He is now chair of the ICSU-ISSC-UNISDR Science Committee for Integrated Research on Disaster Risk program and President of START International. He has published extensively. Dr. McBean received his Ph.D. in physics and oceanography from the University of British Columbia.

**David J. McLaughlin** is Professor of electrical and computer engineering at the University of Massachusetts, Amherst and Director of the National Science Foundation Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA). CASA is a partnership among academic, industry, and government researchers from 20 different organizations pursuing the fundamental knowledge, enabling technologies, and system-level prototypes behind a new dense radar network technology that has the potential to revolutionize how we detect, track, forecast, warn, and respond to hazardous weather events. Dr. McLaughlin received his B.S. and Ph.D. degrees from the University of Massachusetts, Amherst, in

1984 and 1989, respectively. He spent the period from 1989 through 1999 on the engineering faculty at Northeastern University and joined the University of Massachusetts electrical and computer engineering faculty in January of 2000 where he was the first recipient of the UMass College of Engineering Armstrong Professional Development Professorship and he served as Director of the Microwave Remote Sensing Laboratory (MIRSL). His research and teaching interests include radar design, systems engineering, and policy-mediated dense radar networks. He is a Distinguished Lecturer for the American Institute of Aeronautics and Astronautics (AIAA) and was named a Distinguished Faculty member by the University of Massachusetts, Amherst Alumni Association. He has held research fellowships at the U.S. Naval Research Laboratory and the U.S. Air Force Rome Laboratory and recently completed a sabbatical as an Engineering Fellow at Raytheon Integrated Defense Systems.

**Adrian E. Raftery** (NAS) is Professor of Statistics and Sociology at the University of Washington in Seattle. He was born in Ireland, and obtained a B.A. in mathematics (1976) and an M.Sc. in statistics and operations research (1977) at Trinity College Dublin. He obtained a Doctorate in mathematical statistics in 1980 from the Université Pierre et Marie Curie in Paris, France. Dr. Raftery has published over 150 refereed articles in statistical, meteorological, and other journals. His research focuses on the development of new statistical methods for the social, environmental, and health sciences, including methods for probabilistic weather forecasting and the evaluation of weather forecasts. He is a member of the U.S. National Academy of Sciences, a Fellow of the American Academy of Arts and Sciences, a Fellow of the American Statistical Association, and a Fellow of the Institute of Mathematical Statistics. He is a former Coordinating and Applications Editor of the Journal of the American Statistical Association.

**James L. Rasmussen** spent three years as a weather officer in the U.S. Air Force following his graduation from St. Olaf College in 1958. Assigned to the Air Force Institute of Technology he graduated with a B.S. in meteorology from the University of Utah (1959) and served as a weather officer at the 8th Air Force Forecast Center at Westover Air Force Base from 1959 to 1961. Upon discharge he entered graduate school at Colorado State University (CSU), Department of Atmospheric Science, earning his Ph.D. in 1968 with research interests in hydrometeorology, tropical meteorology, and climate studies. He remained at CSU as a faculty member until 1972 when he joined the National Oceanic and Atmospheric Administration's (NOAA) Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) project office as the science coordinator for the U.S. contribution to this international field project involving some 13 countries. He was awarded the Department of Commerce Gold Medal for his work on GATE. In 1976 he moved to the World Meteorological Organization (WMO) in Geneva, Switzerland, to participate in the International Joint Planning Staff for GARP and to undertake the task as manager of the International Operations Center for the First GARP Global Experiment, an effort involving virtually every country in the world. He returned to NOAA in 1981 as Director of the National Weather Service (NWS) Climate Analysis Center at the National Meteorological Center. He was elected President of the WMO Commission for Climatology serving for 8 years in this capacity. In 1982 he took the position of Director of the Office of Meteorology in the NWS. This office oversaw the NWS service programs and was responsible for planning and coordination with, and between, the six regional offices. In 1989 he returned to WMO as the Director of the World Weather Watch (WWW) Department which was responsible for organizing and coordinating all Member States to implement WMO's Basic Systems comprised of the Global Observing System, the Global Telecommunications System, and the Global Data Processing System and WMO's associated service programs. In 1994 he was appointed Director of NOAA's Environmental Research Laboratories (ERL). After retiring from NOAA in 1999 he has been a consultant internationally on topics including the Global Climate Observing System, the continued development of the World Weather Watch, and the organization and management of meteorological and climate services. He has served in various capacities in the American Meteorology Society (Counselor, Commissioner, and Fellow). He was awarded the CSU William E. Morgan Alumni Achievement Award.

**Paul L. Smith** is Interim Director of the Institute of Atmospheric Sciences (IAS) at the South Dakota School of Mines and Technology. He started as a research engineer in the IAS, working his way up the ladder as chief engineer to engineering group head and senior scientist, to become the Director of the Institute in 1981. He served in that position until 1996, at which time he retired from full-time duties and was designated Professor Emeritus. Dr. Smith was also named the facility manager for the National Science Foundation supported T-28 Research Aircraft Facility, which was housed at the IAS, and served in that position from 1985 to 2005. He then retired but was called back to duty as Interim Director for the South Dakota 2011 fiscal year. He has taught radar meteorology, physical meteorology, and microwave engineering. Dr. Smith's major research interests are in radar meteorology, cloud physics, and weather modification. He chaired the National Research Council Committee on Weather Radar Technology Beyond NEXRAD, the Committee to Assess NEXRAD Flash Flood Forecasting Capabilities at Sulphur Mountain, California, and the Committee on the Evaluation of the Multifunction Phased Array Radar Planning Process. Paul Smith has received the Award for Meritorious Civilian Service, U.S. Air Force Air Weather Service (1975); the Editor's Award, Journal of Applied Meteorology, American Meteorological Society (1992); the Thunderbird Award, Weather Modification Association (1995), and was named a National Associate by the National Research Council (2004). He was selected as the American Meteorological Society's Remote Sensing Lecturer for 2006. Dr. Smith has more than 70 refereed publications in engineering and scientific journals or books and presented more than 100 papers at professional society meetings.

**John Toohey-Morales** is chief meteorologist at WTVJ-TV NBC-6 in Miami, Florida. He is also founder and president of ClimaData Corporation, a commercial weather firm providing specialized forecasts for government, industry, and media. Mr. Toohey-Morales is a Fellow of the American Meteorological Society (AMS) and currently serves on the AMS Fellows Committee. From 2004 to 2010 he served as AMS Commissioner on Professional Affairs, overseeing the Society's certification programs, its continuing education efforts, as well as the private and public sector meteorologist boards. He is part of the National Oceanic and Atmospheric Administration Science Advisory Board's Environmental Information Services Working Group. During his 27-year professional career, Mr. Toohey-Morales has worked in the public sector (as a forecaster for the National Weather Service) and in the private sector (as a Certified Consulting Meteorologist and a broadcast meteorologist). He also participates within the academic sector as an adjunct professor of meteorology. He attained his B.S. in atmospheric sciences from Cornell University in 1984. World Meteorological Organization (WMO)-sponsored training at the National Hurricane Center and the University of Miami in 1988 garnered him several credits of masters-level meteorology courses. He attained his AMS Certified Consulting Meteorologist (CCM) designation in 1997. He is one of only a handful of AMS members with both the CCM and Certified Broadcast Meteorologist (CBM) accreditations. Mr. Toohey-Morales is Past-President of the National Council of Industrial Meteorologists (NCIM), as well as a member of the National Weather Association (NWA) and the International Association of Broadcast Meteorologists. In 2005, he served as private-sector envoy to the U.S. Delegation at the 57th WMO Executive Council meeting in Geneva, Switzerland. He won the AMS Award for Outstanding Contribution to Applied Meteorology in 2007, the AMS Award for Broadcast Meteorology in 2004, and the NWA Broadcaster of the Year Awar