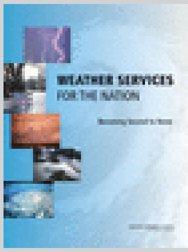

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WEATHER SERVICES FOR THE NATION

Becoming Second to None

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

Board on Atmospheric Sciences and Climate

Division on Earth and Life Studies

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Preface

The Modernization and Associated Restructuring (MAR) of the National Weather Service (NWS) was completed in 2000. This Committee was formed to conduct a comprehensive assessment of the MAR. In its first report, the Committee concluded that the MAR was a success and worth the investment. This report contains the second part of the Committee's work, advice for the NWS on how best to plan, deploy, and oversee future improvements, based on lessons learned from the MAR. It is the Committee's hope that the recommendations in this report will aid the NWS in becoming second to none in integrating advances in science and technology into their operations and meeting user needs.

To carry out the second part of its charge, the Committee held four in-person meetings during which they heard input from a range of NWS staff and stakeholders in the larger weather, water, and climate enterprise. The Committee reviewed the literature, NWS documents, and other relevant information, and met by phone. In addition, the Committee hosted a Town Hall Meeting at the 92nd Annual Meeting of the American Meteorological Society as a way of gathering input from the community. The Town Hall Meeting attendees represented the public, private, and academic sectors.

This report would not have been possible without the assistance of many of our colleagues in the enterprise. The Committee would like to acknowledge the many individuals who briefed us, provided written information, or other technical information. They include Rick Anthes, Ray Ban, Stan Benjamin, Rit Carbone, Fred Carr, Don Cline, John Cortinas, Walt Dabberdt, Julie Demuth, Dan Eleuterio, Doug Forsyth, Mike Foster, Robert Gall, Mike Hudson, Jack Hayes, Pam Heinselman, Susan Joslyn, Kevin Kelleher, Mary Kicza, Jeff Lazo, Frank Marks, Curtis Marshall, Cliff Mass, Berrien Moore, Rebecca Morss, Liz Quoetone, Ed Rappaport, Bill Read, Gary Reisner, Tim Spangler, Travis Smith, Dave Stensrud, Fred Toepfer, and Louis Uccellini.

The Committee would also like to thank all those who have firsthand experience with the MAR who briefed us as we prepared our first report. Their input was equally valuable as we prepared this report. The individuals who briefed the Committee or provided information as we prepared our first report 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. Our sincerest thanks are extended to Edward Johnson and John Sokich for their help and support throughout the study process. The Committee is grateful for the insights provided by John

Snow, who served as the liaison from the NRC Board on Atmospheric Sciences and Climate. 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:

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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. Shuyi Chen, University of Miami, Florida, appointed by the Division on Earth and Life Studies, and Dr. Neal Lane, Rice University, Houston, Texas, appointed by the Report Review Committee, who were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Institutional oversight for this project was provided by:

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Summary

During the 1980s and 1990s, the National Weather Service (NWS) undertook a major program called the Modernization and Associated Restructuring (MAR). 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, had ever been conducted. Therefore, Congress asked the National Academy of Sciences to conduct an end-to-end assessment. That report, *The National Weather Service Modernization and Associated Restructuring: A Retrospective Assessment*, concluded that the MAR was a success: "weather services have great value to the Nation, and the MAR was well worth the investment" (NRC, 2012a).

TODAY'S KEY CHALLENGES

Now, twelve years after the official completion of the MAR, the challenges faced by the NWS are no less important than those of the pre-MAR era. The three key challenges are

- *Keeping Pace* with accelerating scientific and technological advancement.
- *Meeting Expanding and Evolving User Needs* in an increasingly information-centric society.
- *Partnering with an Increasingly Capable Enterprise*[1] that has grown considerably since the time of the MAR.

THE EVOLVING CONTEXT

These challenges are made more difficult by the external context, two areas of which are of particular importance:

- *Budget resources* are uncertain and will likely be constrained for the next decade.
- *Operational performance* s*tandards* against which NWS is measured, including those set by international weather service counterparts and private-sector entities, are increasingly high.

Additional important contextual issues include: the rapid, transformative pace of technological change will continue; the number and type of observational data will expand greatly; there will be continued concentration of infrastructure investment and population growth in vulnerable areas; climate change implies the possibility of changing weather patterns; and the international dimensions will continue to evolve.

RESPONDING TO THE CHALLENGES

Meeting the key challenges within the contextual drivers will require NWS to evolve its role and how it operates, making it more agile and effective. This report

[1] The "enterprise" includes all entities in the public, private, nonprofit, research, and academic sectors that provide information, services, and infrastructure in the areas of weather, water, and climate. For the purposes of this report, "enterprise" is often used as shorthand to refer to those enterprise elements outside the National Oceanic and Atmospheric Administration (NOAA) that it can draw on in its mission. The non-NOAA portion of the enterprise is now of equal or greater economic size compared to the NOAA portion.

presents three main recommendations for responding to these challenges.

Prioritize Core Capabilities

The NWS needs to prioritize the core capabilities that only the NWS can provide so as to deliver the products and services upon which the public and the entire weather, water, and climate enterprise depend. These core capabilities include creating foundational datasets, performing essential functions such as issuing forecasts, watches, and warnings, and conducting operationally-related research. Because the quality of NWS core capabilities underlies the relationship of trust and reliance among the NWS, the public, and the rest of the enterprise, and consistent with Lessons 1, 2, 3, and 5 from NRC (2012a), the Committee makes the following overarching recommendation.

Recommendation I: Prioritize Core Capabilities

The National Weather Service (NWS) should

1. Evaluate all aspects of its work that contribute to its foundational datasets, with the explicit goal of ensuring that those foundational datasets are of the highest quality and that improvements are driven by user needs and scientific advances. As part of this initial and ongoing evaluation effort, clear quality and performance metrics should be established. Such metrics would address the technical components of NWS operations, as well as the efficiency and effectiveness of the flow of weather information to end users.

2. Ensure that a similarly high priority is given to (a) product generation and dissemination, (b) the brokering and provision of data services, and (c) development and enhancement of analysis tools for maintaining a common operating picture (COP).

3. Engage the entire enterprise to develop and implement a national strategy for a systematic approach to research-to-operations and operations-to-research.

To aid the NWS in implementing Recommendation I, the Committee makes the following supporting recommendations:

Recommendation I.a: Technology Infusion

The National Weather Service (NWS) should continue technology infusion programs that have been effective subsequent to the Modernization and Associated Restructuring. Parallel support from the National Environmental Satellite, Data, and Information Service (NESDIS) is needed to continually upgrade satellite capabilities. Such infusion programs should include both hardware and software development.

Recommendation I.b: Numerical Weather Prediction

The National Weather Service (NWS) global and regional numerical weather prediction systems should be of the highest quality and accuracy, with improvements driven by user needs and scientific advances. To achieve this goal, the NWS should give priority to upgrading its data assimilation system and increasing the resolution of its deterministic and ensemble modeling systems. The product development process can be improved by developing a systematic approach to research-to-operations through collaboration with users and partners in the entire weather, water, and climate enterprise, both in the United States and around the world.

Recommendation I.c: Observational Data Metrics

To increase the capability of its numerical weather prediction systems to keep up with technological advances and prioritize investments in data assimilation and observations systems, the National Weather Service (NWS) should develop and advance software tools to monitor the impact of observations on numerical weather prediction and downstream forecast systems.

Recommendation I.d: Probabilistic Forecasts

The National Weather Service (NWS) should take the lead in a community effort to provide products that effectively communicate forecast uncertainty information. The format for communicating probabilistic forecasts requires careful design using cognitive research. Calibrated probabilistic forecasts would be produced by statistical post-processing of forecast ensembles, and improvement efforts should focus on increasing the resolution and accuracy of the ensemble forecasts.

Recommendation I.e: Hydrologic Prediction Metrics

The National Weather Service (NWS) hydrologic prediction services should coordinate with other entities in the hydrologic prediction community to continue and expand a set of common, objective model metrics from which operational and experimental models may be inter-compared and continually assessed.

Recommendation I.f: Incremental Upgrades

As an absolutely necessary condition for success, although insufficient by itself, the National Weather Service (NWS) should have an ongoing capability for development and testing of its incremental technical upgrades. This will allow the NWS to advance its capabilities to respond to new scientific and technological possibilities and to enhance its service to the nation.

Evaluate Function and Structure

The current structure of the NWS primarily reflects the functions of the weather, water, and climate enterprise in the 1990s. Technology, including improvements in communications and computer forecast models, has changed much of the rationale for the present organizational structure of the NWS. In view of the directions outlined in the *Weather-Ready Nation Roadmap* for expanding the role of forecasters and other NWS staff (NWS, 2012), it would be prudent to evaluate the NWS's organizational and functional structure. Based on these considerations, Lesson 4 from NRC (2012a), and a Congressional request for a new study to examine potential efficiencies in NWS operations, the Committee makes the following overarching recommendation.

Recommendation II: Evaluate Function and Structure

In light of evolving technology, and because the work of the National Weather Service (NWS) has major science and technology components, the NWS should evaluate its function and structure, seeking areas for improvement. Any examination of potential changes in the function and organizational structure of the NWS requires significant technical input and expertise, and should include metrics to evaluate the process of structural evolution. Such an examination would include individual NWS field offices, regional and national headquarters and management, as well as the National Centers and the weather-related parts of the National Oceanic and Atmospheric Administration (NOAA) such as the National Environmental Satellite, Data, and Information Service (NESDIS) and the Office of Oceanic and Atmospheric Research (OAR).

To aid the NWS in implementing Recommendation II, the Committee makes the following supporting recommendations:

Recommendation II.a: Post-Event Evaluations

The National Weather Service (NWS) should broaden the scope of the system for evaluating its forecasts and warnings to include false alarms that result in substantial public and/or emergency management response as well as significant hydrometeorological, oceanographic, or geological events. It should consider whether having an independent entity conduct all post-event evaluations of performance after false alarms and significant events would be more effective. These evaluations should address the full scope of response issues, from forecasts and warnings to communication and public response, and be conducted by an appropriate mix of individuals from within and outside the NWS. They should also include instances of relative success (minimal or no loss of life) to learn valuable lessons from these episodes as well.

Recommendation II.b: Forecast Offices

Because it is impractical to expect each individual at the Weather Forecast Office level to possess all of the requisite skills to capitalize on the quantity and quality of new foundational data being produced, the National Weather Service (NWS) management should consider expanding its vision of team structures and functions within individual offices and between local offices and regional offices and national centers.

Recommendation II.c: Workforce Evolution

To create a workforce that is fully able to utilize improved core capabilities and optimally serve the public, the National Weather Service (NWS) should develop performance metrics-based approaches to assessing staff skill sets to identify areas where enhanced capabilities are needed. The NWS should involve the entire enterprise in working with the academic and research communities to design new curricula to address pre-employment and during-employment education and training needs. The NWS should also work with the American Meteorological Society to update and expand the credential criteria to reflect the future educational needs of NWS personnel. The National Weather Service Employee Organization should be engaged as early as possible in the development of both performance-based metrics and improved curricula.

Recommendation II.d: Hydrologist Staff

The National Weather Service (NWS) service-hydrologist staff requires reeducation and continual retraining if NWS hydrologic prediction services are to be able to adopt current state-of-the-science prediction methodologies and instill the evolutionary culture required for optimal hydrologic services.

Leverage the Entire Enterprise

The weather, water, and climate enterprise has evolved considerably since the beginning of the MAR in the 1980s. At that time, NWS was viewed as the primary source of all weather, hydrology, and climate information. Today, the private sector and other non-NWS organizations generate and deliver a wide variety of information that complements what is available from NWS.

The Committee views improved NWS-enterprise interaction as a way to enhance the NWS's capability to accomplish its mission of serving the public. The Committee thinks this is especially important at a time when it is seeking to enhance its service (NWS, 2012). Leveraging the entire enterprise provides one means to further NWS's mission of serving the public. Regarding the role of the NWS within the broader enterprise, and consistent with Lesson 5 from NRC (2012a), the Committee makes the following overarching recommendation.

Recommendation III: Leverage the Entire Enterprise

The National Weather Service (NWS) should broaden collaboration and cooperation with other parts of the weather, water, and climate enterprise. The greatest national good is achieved when all parts of the enterprise function optimally to serve the public and businesses. This process starts with the quality of core NWS capabilities but is realized through the effectiveness of NWS-enterprise relationships. A well-formulated enterprise strategy will also return direct benefit from the enterprise to the NWS, especially in areas of shared research, technology development, observational data sources, and improved end-user access to NWS-generated information.

To aid the NWS in implementing Recommendation III, the Committee makes the following supporting recommendations:

Recommendation III.a: Secondary Value-Chain

The National Weather Service (NWS) should seek to better understand the functioning of the secondary value-chain, including ways in which it complements the primary value-chain. When appropriate, it should identify new or evolved NWS data and services that can enhance public value delivered through the secondary value-chain, the benefits associated with such services, and any challenges or risks in implementing them. To the greatest extent possible, this should be accomplished through collaborative efforts with corresponding enterprise partners.

Recommendation III.b: Major Systems Procurement

The National Oceanic and Atmospheric Administration (NOAA) as a whole should strengthen its systems engineering and procurement processes for major systems, including ground-based sensor, gauge, and radar networks, satellites and ground processing, and major communications and processing systems so as to achieve more productive and cost-effective interactions with the enterprise partners developing and building such systems.

THE OUTCOME: A NATIONAL WEATHER SERVICE SECOND TO NONE

Meeting today's challenges will require changes over as much as a decade. Fortunately, the MAR established a solid foundation as a starting point. The recommendations presented in this report will help the NWS address these challenges, making it more agile and effective. This will put it on a path to becoming second to none at integrating advances in science and technology into its operations and at meeting user needs, leading in some areas and keeping pace in others. It will have the highest quality core capabilities among national weather services. It will have a more agile organizational structure and workforce that will allow it to directly or indirectly reach more end users, save more lives, and help more businesses. And it will have leveraged these capabilities through the broader enterprise. This approach will make possible societal benefits beyond what the NWS budget alone allows.

1

The Rationale for Further Evolution of the National Weather Service

During the 1980s and 1990s, the National Weather Service (NWS) undertook a major program called the Modernization and Associated Restructuring (MAR). 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, had ever been conducted. Therefore, Congress asked the National Academy of Sciences to conduct an end-to-end assessment (see Appendix A for Statement of Task). The Committee's first report, *The National Weather Service Modernization and Associated Restructuring: A Retrospective Assessment*, documented how these challenges were met and identified lessons learned (Box 1.1). Detailed information about the background, execution, and impact of the MAR are provided in that report. In short, that report (NRC, 2012a) concluded:

> The MAR was a large and 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.

Accelerating improvements in technology and the science of meteorology and hydrology favor a continuing modernization of the NWS and its partners in the weather, water, and climate enterprise.[1] This report presents guidance, based on the lessons of the MAR, for the NWS as it plans future improvements. This report builds on the Committee's first report, and all information gathered in the process of drafting the first report, including speaker presentations and reviews of the literature and materials provided by the NWS, was equally useful in the drafting of this report. With the exception of the Committee's recommendations on hydrologic services and numerical weather prediction, topics not covered by the MAR, all of the recommendations in this report are reinforced by the lessons learned from the MAR identified by the Committee in its first report.

TODAY'S KEY CHALLENGES

Twelve years after the official completion of the MAR, the challenges faced by the NWS are no less important than were those of the pre-MAR era. The

[1] The "enterprise" includes all entities in the public, private, nonprofit, research, and academic sectors that provide information, services, and infrastructure in the areas of weather, water, and climate. The public sector includes the NWS as well as other weather-related line offices within NOAA, other federal agencies, and state and local governments. For the purposes of this report, "enterprise" is often used as shorthand to refer to those enterprise elements outside NOAA that it can draw on in its mission. Within this, the private sector is present in two major areas: (1) services companies providing a broad range of data, forecasts, warnings, and value-added products to consumers and businesses, and (2) infrastructure companies providing systems such as satellites. The non-NOAA portion of the enterprise is now of equal or greater economic size compared to the NOAA portion.

BOX 1.1
Lessons Learned from the Modernization and Associated Restructuring

The following are the lessons from the Modernization and Associated Restructuring, identified in the first report from this Committee, *The National Weather Service Modernization and Associated Restructuring: A Retrospective Assessment* (NRC, 2012a).

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.

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, multi-party 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.

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.

key challenges include keeping pace, meeting expanding and evolving user needs, and partnering with an increasingly capable enterprise. Mass (2012) provides an excellent example of how these challenges have converged to frame directions for the future of the NWS.

Keeping Pace. The pace of scientific and technological advancement in the atmospheric and hydrologic sciences continues to accelerate. As an outgrowth of public- and private-sector investment in weather, climate, and hydrologic research, new observational, data assimilation, prediction, and other technology advancements are exceeding the capacity of the NWS to optimally acquire, integrate, and communicate critical forecast and warning information based on these technological achievements. The MAR focused on NWS observational and warning functions and instituted an operational framework appropriate for that time. Now, as scientific and technological progress continues, critical components within the NWS are lagging behind the state of the science. Furthermore, enormous amounts of data generated by new surface networks, radars, satellites, and numerical models need to be rapidly distilled into actionable information in order to create and communicate effective public forecasts and warnings. The skills required to comprehend, manage, and optimize this decision-making process go beyond traditional meteorological and hydrologic curricula. Hence, the NWS workforce skill set will need to evolve appropriately.

- 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.

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.

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.

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.

Meeting Expanding and Evolving User Needs. Increasingly, the United States is an information-centric society. Meteorological and hydrologic information in particular is central to societal security and welfare (Lazo et al., 2009, 2011). Unlike some other industries, weather is largely an information-based enterprise. The public expects continuous improvement in public safety and property protection related to severe weather. To succeed, the NWS needs to not only improve forecast and warning capabilities but also do so faster than the rates of construction and population increase in at-risk locations. With broad adoption of the internet and mobile technology, people have found many new ways to access and use weather and water information in their daily lives. The evolution of business processes, such as just-in-time manufacturing, has made the economy more dependent on weather and water information. New business uses have emerged, such as the energy sector's investment in weather-sensitive renewable sources.

Partnering with an Increasingly Capable Enterprise. At the time of the MAR, delivery of weather information was largely synonymous with the NWS, the broadcasting sector, and the private-sector suppliers of weather data and services that supported the broadcasting sector. Outside of this, the weather, water, and climate enterprise had limited capacity. Today, the enterprise has grown considerably, and now the NWS has many important partners. Private-sector and other organizations provide sensor data, weather forecasts, and value-added, end-user weather, water, and climate services to a broad set of customers encompassing both businesses and the public, with multiple sources available in many cases. All of these entities rely on core NWS infrastructure and capabilities to provide customized services. Together this combination of the NWS and third parties serves the nation better than the NWS could on its own.

THE EVOLVING CONTEXT

These challenges are made more difficult by the external context, two areas of which are of particular importance:

- *Budget resources* are uncertain and will likely be constrained for the next decade.
- *Operational performance standards* against which the NWS is measured, including those set by international weather service counterparts and private-sector entities, are increasingly high. For example, skill[2] measures of NWS global numerical weather prediction models are often compared to the performance of corresponding entities around the world. The European Centre for Medium-range Weather Forecasts (ECMWF) is just one of several for which model skill is arguably equal to or better than that of the NWS (NRC, 2012a). Such competition can be deemed positive, as it motivates all to improve performance and integrate the latest advances in science and technology. But it can introduce organizational tension when the pressure to meet the competition is not balanced by resources to do so.

There are many uncertainties in the evolution of the external context within which the NWS will function. The NWS will need to consider many factors that will affect the way in which it undertakes its core functions, and possibly even redefine those core functions. The evolving context increases the need for greater agility within the NWS. The Committee foresees the following future developments.

The rapid, transformative pace of technological change will continue. This implies that there will be as-yet unimagined technical applications, as well as unexpected disruptions of the current context and arrangements for the provision of weather- and water-related services. The scale of computing that is affordably available to the NWS and the rest of the weather, water, and climate enterprise will continue its exponential increase. This will make higher spatial and temporal resolution models possible, with ensemble forecasting and probabilistic products becoming increasingly utilized. There is likely to be a continual increase in the number and diversity of services provided by the private sector, fueled by expected improvements in computing and telecommunications technology.

The volume and types of observational data will expand greatly. This is due to availability of data from increasingly powerful satellites (including international sources); the explosion of data from new sensor networks (including the oceans); the proliferation of sensors on devices in the hands of individuals; and new sensors used to support transportation. This will provide opportunities for more coverage and more types of information on the present state of the weather-water-climate system, but it will also present challenges as to how to most effectively integrate and use this information in the service-delivery system.

There will be continued concentration of infrastructure investment and population growth in coastal and riverine floodplain areas subject to severe weather and flooding, a circumstance that will continue to produce the potential for increasing losses of property, and perhaps of life, regardless of whether there are changes in the frequency of severe weather events and improvements in weather and flood forecast and warning skill.

Climate change implies the possibility of changing weather patterns with forecast regimes not well matched to historical expectations (IPCC, 2012). The NWS will need to maintain and improve forecast and warning skill in the face of such change.

The international dimensions will continue to evolve. The World Meteorological Organization's (WMO's) World Weather Watch (WWW) and Global Atmosphere Watch (GAW) programs will continue to provide the basis for the global collection, analysis, and distribution of weather, water, and other environmental information. The NWS, NESDIS, and the relevant parts of OAR will continue to provide the major part of the United States' contribution to the WMO programs.

[2] "Skill" is a statistical evaluation of the accuracy of forecasts or the effectiveness of detection techniques (AMS, 2000).

The basic concept of the WMO/WWW/GAW is that each of the 183 member countries undertakes, according to its means, to meet certain responsibilities in the agreed global scheme so that all countries may benefit from the consolidated effort. This is a major achievement in international cooperation that requires protection so that the operational work of individual national meteorological hydrological services (NMHS) can continue to evolve and improve. Recent initiatives such as the Global Earth Observation System of Systems (GEOSS) are being developed to provide system architectures for data acquisition and dissemination that include, but also expand beyond, the WMO programs (GEO, 2005). These efforts will also be important as observation requirements and applications evolve. Although there may be increasing interplay between countries and their own NMHS and private sectors, the concepts upon which the international cooperation is based are important. The relationships within the U.S. weather, water, and climate enterprise need to reflect and respect these agreements and their standards.

RESPONDING TO THE CHALLENGES

This report presents three main recommendations for responding to these challenges within the evolving context:

1. Prioritize Core Capabilities
2. Evaluate Function and Structure
3. Leverage the Entire Enterprise

Meeting today's challenges will require large changes over as much as a decade. Fortunately, the MAR established a solid foundation as a starting point, but new methods of tackling these challenges are necessary. The Committee feels their recommendations will guide the NWS in establishing such new methods, going beyond what they are already doing to tackle today's challenges. The recommendations presented in this report will help the NWS become more agile and effective. This will put it on a path to becoming second to none at integrating scientific and technological advances into its operations and at meeting user needs, leading in some areas and keeping pace in others. It will have the highest quality core capabilities among national weather services. It will have a structure and organization that allows it to directly or indirectly reach more end users, save more lives, and help more businesses. And it will have leveraged these capabilities through the broader enterprise. This approach will make possible societal benefits beyond what the NWS budget alone allows. This report suggests how this can be accomplished, in part building on the lessons from the MAR identified in the first report from this Committee.

Prioritize Core Capabilities

The NWS needs to prioritize the core capabilities that generate products and services only the NWS can provide. Figure 1.1 illustrates the relationships among different elements of the overall enterprise. Central to a successful enterprise is a set of NWS *core capabilities*, defined as

- Creating foundational datasets,
- Performing essential functions, and
- Conducting operationally related research.

Foundational datasets include collected and integrated observations, advanced analyses either from modern data assimilation or other objective methods, and predictions obtained from deterministic and probabilistic models. *Essential functions* constitute those activities and services that are mandated by the NWS mission and include product generation (e.g., general weather forecasts, watches, warnings, advisories, and guidance) and dissemination; brokering and provision of weather and water data; international responsibilities to WMO programs; and the creation of critical analysis tools that enable NWS staff to execute its functions. *Operationally related research* refers to activities that continually invigorate NWS core capabilities with new understanding and improved techniques from OAR and the broader research community (e.g., research-to-operations, or R2O), allowing the NWS to better keep pace with rapidly evolving technology. Such activities also include new research priorities based on issues that inhibit analysis and prediction skill or the production of forecast and warning products (e.g., operations-to-research, or O2R).

As illustrated in Figure 1.1, enterprise partners from the private sector, academia, and other domestic

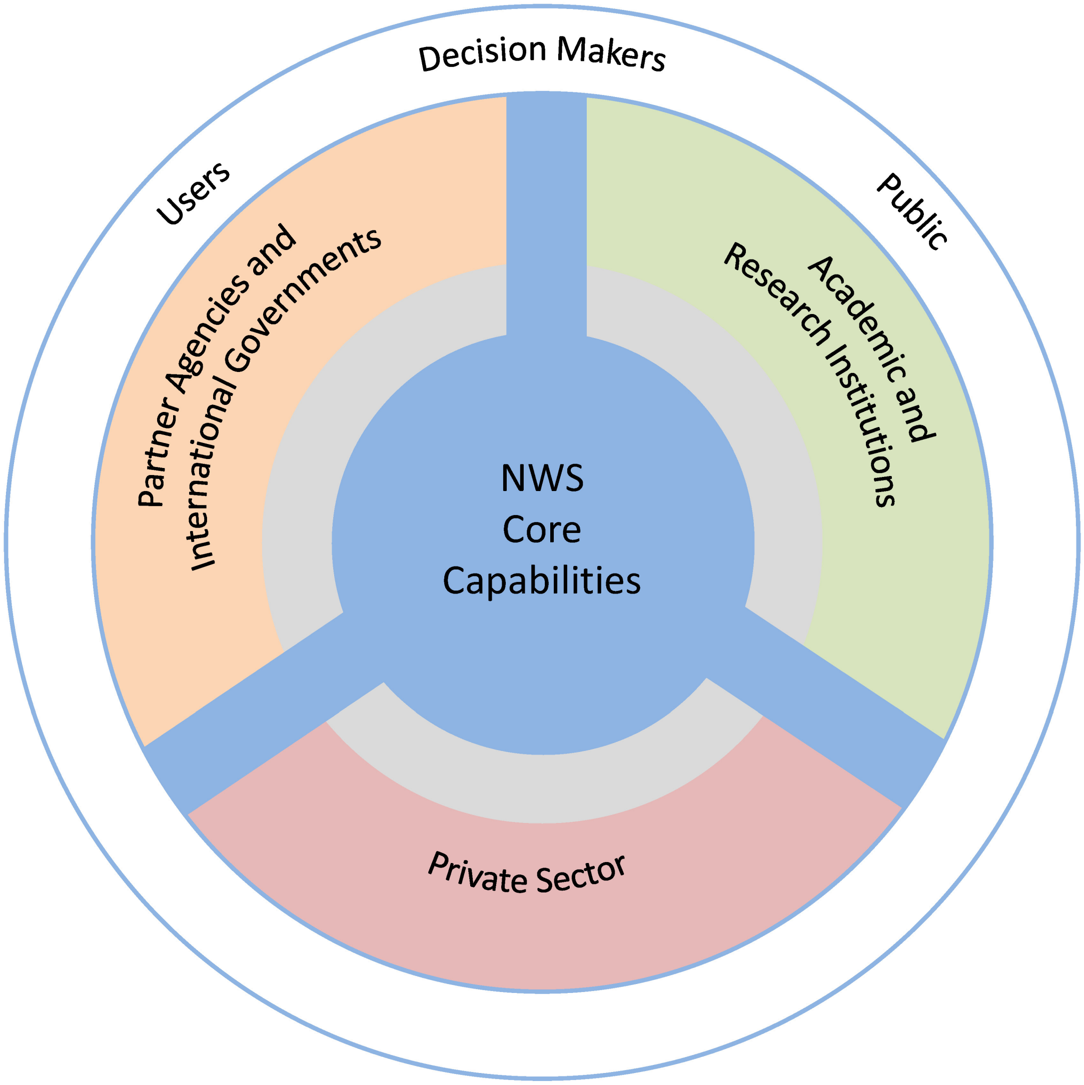

FIGURE 1.1 Conceptual "hub-spoke-rim" paradigm for defining the relationships between core NWS capabilities (hub and spokes), its partners in the broader enterprise (the spaces between the hub, spokes, and rim), and end users of weather services (the rim). The gray ring around the hub represents the gray areas of responsibility between the NWS and the rest of the enterprise. The intention of this conceptual framework is to articulate how various entities connect to and support weather information services that emerge from core NWS capabilities.

and international organizations help the NWS serve its overall mission by feeding NWS core capabilities with data and services and then help transfer NWS core products and foundational data to the public, decision makers, and other stakeholders. The size and scope of the "hub" of core capabilities is constantly in flux based on the needs, capabilities, and constraints of the enterprise and its users.

Prioritizing roles and defining the breadth and scope of NWS core capabilities require the NWS to make four key distinctions: (1) roles that only the NWS can perform; (2) roles that partners can perform reliably; (3) roles that the NWS performs, but which partners could perform if any partners were available; and (4) roles that initially are performed by partners, but which develop technology such that the NWS could perform the role at little or no cost. This is an ongoing process that will always involve gray areas. The Committee is not suggesting that such prioritization resolve gray areas, but rather that those areas clearly core to the NWS be prioritized as such, and those that are clearly best performed elsewhere in the enterprise receive recognition and technical and data support—as needed and as possible—from the NWS.

Because the quality of NWS core capabilities underlies the relationship of trust and reliance among the NWS, the public, and the rest of the enterprise, and consistent with Lessons 1, 2, 3, and 5 from NRC (2012a), the Committee makes the following overarching recommendation. (Specific, supporting recommendations for improving the various aspects of NWS core capabilities are discussed in detail in Chapter 2.)

Recommendation I: Prioritize Core Capabilities

The National Weather Service (NWS) should

1. Evaluate all aspects of its work that contribute to its foundational datasets, with the explicit goal of ensuring that those foundational datasets are of the highest quality and that improvements are driven by user needs and scientific advances. As part of this initial and ongoing evaluation effort, clear quality and performance metrics should be established. Such metrics would address the technical components of NWS operations, as well as the efficiency and effectiveness of the flow of weather information to end users.

2. Ensure that a similarly high priority is given to (a) product generation and dissemination, (b) the brokering and provision of data services, and (c) development and enhancement of analysis tools for maintaining a common operating picture (COP).[3]

3. Engage the entire enterprise to develop and implement a national strategy for a systematic approach to research-to-operations and operations-to-research.

Evaluate Function and Structure

The current structure of the NWS primarily reflects the function of the weather, water, and climate enterprise in the 1990s. Technology, including improvements in communications and computer forecast models, has changed much of the rationale for the present organizational structure of the NWS. For example, marked improvements in computer forecast models and increased efficiency in translating model output into public forecasts may allow NWS meteorologists to increasingly focus their attention on high-impact weather events and rapid response, as well as improving cooperation with the core partners[4] of the NWS. An in-depth statistical evaluation of performance of the field-forecaster product compared to the numerical model guidance could be used to help define priorities, workloads, and assignments for field office personnel and to optimize the overall performance of the NWS.

The impact from extreme weather and water events is increasing due in part to increasing population, buildings, and infrastructure in vulnerable areas. Being aware of this challenge, the NWS has launched the *Weather-Ready Nation* paradigm, which emphasizes a broader concept of services and interactions with other partners in the enterprise—from emergency managers to the academic and private sectors.

Meanwhile, the emergence of the rest of the enterprise beyond the NWS has led to multiple outlets through which the general public accesses weather forecasts and information. These outlets, generally in the private sector, are greatly dependent on the core capabilities of the NWS, from data acquisition to accurate model forecast output. Collectively, they have become the primary source of weather and water forecast information for the general public (Lazo et al., 2009).

In view of the directions outlined in the *Weather-Ready Nation Roadmap* of expanding the role of forecasters and other NWS staff (NWS, 2012), it would be prudent to evaluate the structure of the NWS and the weather-related parts of NOAA, including the development and deployment of satellites in NESDIS[5] and the role and structure of basic research in OAR. Based on these considerations, Lesson 4 from NRC (2012a), and a Congressional request for a new study to

[3] The *Weather-Ready Nation Roadmap* defines common operating picture as "a repository of digital, extensible environmental data and forecasts, where all types of information are integrated and related to each other to facilitate their full use" (NWS, 2012).

[4] "Core partners" include the emergency management community, other government agencies, and broadcast and electronic media outlets that provide weather and water warning information to the public.

[5] There have been policy discussions regarding moving NESDIS procurement programs from NOAA to NASA. Regardless of the outcome of these discussions, the Committee thinks that the development and deployment of weather satellites needs to be included in any evaluation of NWS function and structure.

examine potential efficiencies in NWS operations (U.S. Congress, 2012), the Committee makes the following overarching recommendation. (Specific, supporting recommendations for examining the various aspects of the NWS organizational structure and workforce are discussed in detail in Chapter 3.)

Recommendation II: Evaluate Function and Structure

In light of evolving technology, and because the work of the National Weather Service (NWS) has major science and technology components, the NWS should evaluate its function and structure, seeking areas for improvement. Any examination of potential changes in the function and organizational structure of the NWS requires significant technical input and expertise, and should include metrics to evaluate the process of structural evolution. Such an examination would include individual NWS field offices, regional and national headquarters and management, as well as the National Centers and the weather-related parts of the National Oceanic and Atmospheric Administration (NOAA) such as the National Environmental Satellite, Data, and Information Service (NESDIS) and the Office of Oceanic and Atmospheric Research (OAR).

Leverage the Entire Enterprise

The weather, water, and climate enterprise has evolved considerably since the beginning of the MAR in the 1980s. At that time, the NWS was viewed as the primary source of all weather information. Today, the private sector dedicated to generating and delivering weather information is about twice the size of the NWS; the overall non-NOAA portion of the enterprise (including state and local governments as well as academia) is likely equal in size to the weather-related portion of NOAA and other federal agencies—each perhaps on the order of $4 to $5 billion.[6]

The traditional NWS value-chain (what might be called the "primary value-chain") delivers weather information to the public from the NWS through core partners. The NWS identifies these three categories of core partners: (1) emergency managers, (2) state and local governments requiring close cooperation, and (3) the broadcast and electronic media. These partners are considered core on the basis of their need for ensured access to unaltered NWS information (NWS, 2012). Yet today, there is an increasingly important "secondary value-chain"[7] by which the public receives weather and water information originating from the NWS but altered or enhanced to improve its accuracy or usability.

- The majority of forecasts received by the public arrive from third parties rather than directly from the NWS (Lazo et al., 2009). To the extent that this information is altered before reaching the public, it can be considered to have gone through the secondary value-chain.
- Increasingly, weather- and water-related decision making involves integrating NWS-originated weather and water information with information from other sources through the secondary value-chain. Many needs, including some associated with the core NWS mission of protecting life and property, are thus not served by the primary value-chain alone.

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[6] These figures are rough estimates, as definitive information is not readily available. The most authoritative recent information on the size of the weather enterprise is about five years old (for example, see Lazo et al. (2009), which cites sources from about 2007) and suffers from incompleteness. The total federal-sector budgets for FY2007 were estimated at $3.4 billion. In FY2006, the NWS budget was $852 million, the NESDIS budget was $943 million, and an additional $200 to $400 million from the research and program support budgets might be attributed to serving NOAA's weather, water, and climate mission. Of the NESDIS budget, $769 million went to procurement, largely for private-sector services associated with satellite and other observing system development. Within the private sector, based on a survey for this same year, Spiegler (2007) identifies $1.65 to $1.8 billion of activity associated with weather-based services. Based on the growth rate from the prior ten years, the private-sector services market was expected to be around $2.5 billion by 2012. When coupled with the amount spent in the private sector by NOAA (and other federal agencies) on infrastructure (primarily observing systems), the total private-sector market is now more than $4 billion. No figures for other nonfederal expenditures, such as state and local governments, are available. Extrapolating this information to 2012 for federal and nonfederal enterprise sectors leads to an estimated $4 to $5 billion each.

[7] The terms "primary value-chain" and "secondary value-chain" are not intended to reflect superiority or inferiority of either chain. Instead, "primary" is meant to reflect the mission of the NWS to be the authoritative source of weather, water, and climate information for the nation. The capability of the NWS to reach the public through the primary chain, when an authoritative perspective is required, cannot be compromised. The term "primary" is meant to reflect this critical NWS role.

- Even core partners, including emergency managers and broadcast and electronic media, now receive substantial portions of their decision-making information from the secondary value-chain. Nearly all television channels, for example, utilize private-sector forecast service providers to prepare their weather information; unaltered NWS information is presented typically only in the case of watches and warnings.

Prior to the MAR, the NWS perceived the secondary value-chain and its constituent organizations largely as competition. The MAR and the subsequent *Fair Weather* report (NRC, 2003a) changed this. The NWS instituted new policies to avoid competing with or replicating capabilities robustly available within the secondary value-chain. As stated in the Committee's first report, efforts from professional weather associations—including the American Weather and Climate Industry Association (AWCIA), the National Council of Industrial Meteorologists (NCIM), the National Weather Association (NWA), and the American Meteorological Society (AMS), specifically its Commission on the Weather and Climate Enterprise (CWCE)—have been critical in improving the relationship between the NWS and the private sector (NRC, 2012a).

In the Committee's opinion, that change has been positive for the nation. Today, the enterprise has developed new capabilities and alternate means for accessing weather and water information. Yet the entire secondary value-chain is built on a foundation of NWS data and services. If NWS core capabilities were to be compromised, this value-chain would be severely degraded. Moreover, the primary value-chain is critical for ensuring a direct path to the public when public safety is at risk. This, too, cannot be compromised. For these reasons, the Committee carefully couples its recommendation to leverage the enterprise with a recommendation for the NWS to prioritize core capabilities supporting both value-chains.

The Committee views the objective of an enhanced NWS-enterprise interaction as a way to enhance the NWS's ability to accomplish its mission of serving the public. The Committee thinks this is especially important at a time when it is seeking to enhance its service (NWS, 2012). Leveraging the secondary value-chain provides one means to further the NWS's mission of serving the public.

Achieving this added benefit to the nation requires a fundamental change in how the NWS and the overall enterprise interact with each other. It is not a simple change. The enterprise is not a single entity with clear authorities and responsibilities. Its capabilities may change with time. Therefore, change would need to proceed cautiously and in collaboration with the NWS. The paradigm of enterprise collaboration is not entirely new. The NWS has long relied on the broadcasting sector as a primary means of communicating with the public. Over the past decade, the NWS has begun to extend such collaboration to other areas, such as sensor networks and digital media. The Committee confirms the need to expand the productive interaction of the NWS with the rest of the enterprise.

Regarding the role of the NWS within the broader enterprise, and consistent with Lesson 5 from NRC (2012a), the Committee makes the following overarching recommendation. (Specific, supporting recommendations for how this change could be accomplished are described in Chapter 4).

Recommendation III: Leverage the Entire Enterprise

The National Weather Service (NWS) should broaden collaboration and cooperation with other parts of the weather, water, and climate enterprise. The greatest national good is achieved when all parts of the enterprise function optimally to serve the public and businesses. This process starts with the quality of core NWS capabilities but is realized through the effectiveness of NWS-enterprise relationships. A well-formulated enterprise strategy will also return direct benefit from the enterprise to the NWS, especially in areas of shared research, technology development, observational data sources, and improved end-user access to NWS-generated information.

2

Prioritize Core Capabilities

The entire weather, water, and climate enterprise is built on a foundation anchored by the core capabilities of the National Weather Service (NWS). These core capabilities include foundational datasets, essential functions, and operationally related research. Prioritization will allow the NWS to focus time and resources on those things it does best and are most needed. This chapter provides details and sub-recommendations in support of Recommendation I and as guidance to the NWS as it attempts to prioritize its core capabilities. Above all, the Committee feels that clear performance metrics and evaluation of the impact of scientific and technological advances on those performance metrics will best guide the NWS in prioritizing its investments.

Recommendation I: Prioritize Core Capabilities

The National Weather Service (NWS) should

1. Evaluate all aspects of its work that contribute to its foundational datasets, with the explicit goal of ensuring that those foundational datasets are of the highest quality and that improvements are driven by user needs and scientific advances. As part of this initial and ongoing evaluation effort, clear quality and performance metrics should be established. Such metrics would address the technical components of NWS operations, as well as the efficiency and effectiveness of the flow of weather information to end users.

2. Ensure that a similarly high priority is given to (a) product generation and dissemination, (b) the brokering and provision of data services, and (c) development and enhancement of analysis tools for maintaining a common operating picture (COP).

3. Engage the entire enterprise to develop and implement a national strategy for a systematic approach to research-to-operations and operations-to-research.

FOUNDATIONAL DATASETS

Foundational datasets include collected and integrated observations, advanced analyses either from modern data assimilation or other objective methods, and predictions obtained from deterministic and probabilistic models. As indicated in the first bullet of Recommendation I, evaluation of the NWS's foundational datasets with the goal of improving their quality will necessitate unambiguous quality and performance metrics. These would include existing metrics such as probability of detection and lead time for severe weather (e.g., tornadoes, flash floods), hurricane track and intensity forecast skill, quantitative precipitation forecast skill, and hydrologic prediction forecast skill. For numerical weather prediction, such metrics include the traditional comparison of model performance at the 500 hPa level. Evaluation of these models will need to expand to include surface-level performance as well. False alarm ratios are currently included for most severe weather events, but the strict definition of this metric will need to be reevaluated to expand its usefulness. Finally, as the NWS moves away from deterministic forecasts toward probabilistic forecasts, metrics will need to move toward more appropriate measures of performance, such as reliability, calibration, and sharpness. The NWS will also need to develop a systematic method for evaluating the effectiveness of communicating warnings to the public.

Maintaining Infrastructure Through Technology Infusion

Keeping up with advances in technology requires a continual NWS program of technology infusion. Areas to be covered by such a program include major communications and processing systems, satellites and ground processing, and ground-based radar, sensor, and gauge networks.

In each of these areas, a well-organized program of technology infusion would provide a means for the NWS to avoid becoming obsolete and requiring another massive overhaul like the MAR. This is consistent with Lesson 1 of NRC (2012a). Lesson 2 of that report found that such a technology program requires established systems engineering processes, including setting system-level requirements and performance metrics for evaluating progress toward meeting those requirements. The capability for development and testing, and a process for rapid field-testing of prototype systems, would also be an important part of the program and is discussed in further detail later in this chapter.

In the computing area, five-year-old hardware is obsolete in today's world of rapidly advancing technology. Thus, planning and budgeting for replacement needs to begin as soon as a new generation has been deployed, if not sooner. For example, during the MAR, the information technology (IT) systems for both the Advanced Weather Interactive Processing System (AWIPS) and Next Generation Weather Radar (NEXRAD) were upgraded, in some cases before the systems were fully commissioned. These upgrades were developed through prototyping and involved interaction with the research community and the contractor. The AWIPS-II program is an example of a computing upgrade that addresses the need for systems refreshment. However, AWIPS-II is also an example of a failure to draw upon what was learned during the development and deployment of the major systems of the MAR. Rather than making continual upgrades, all upgrades were stopped almost ten years ago in anticipation of the large AWIPS-II upgrade. An example of success in the area of computing technology has been the leasing of research and operational high-performance computing assets. Leasing allows for more rapid updating of computing infrastructure and prevents the procurement of out-of-date technology.

The NWS is only one part of NOAA that feeds requirements to, and utilizes data from, the NOAA satellite systems. Therefore, processes for technology infusion related to the satellite programs need to involve NOAA management, NESDIS, and other branches, along with the NWS. It is also important to note that a "satellite system" typically consists of multiple segments, or elements, including space vehicle; instruments; launch vehicle; command, control, and communications (C3); and data processing hardware and software. Costs for each of these elements can be substantial, as can costs for development of the science versions of the data processing algorithms and program management. (These last two elements can include a large portion of government personnel.) Each of the system elements alone can be quite complex and therefore costly. These disparate elements of the system need to be specified, acquired, built, and activated synergistically as they work together to provide data and products. Exercising a well-established systems engineering process is therefore critical both for existing data observation and product continuity and for planned technology infusion.

NOAA has a relatively well-established approach to the acquisition of its satellite system elements that typically includes a process for developing instrument requirements, study and risk reduction phases involving preliminary designs, and possibly early component-builds from competitors.[1] These phases of the program include both space and ground segment elements that apply to spacecraft, instruments, ground algorithms, and processing. NOAA also typically requests detailed

[1] This assessment applies primarily to NOAA's Geostationary Operational Environmental Satellite (GOES) and Polar Operational Environmental Satellite (POES) series. As noted in the Committee's first report, the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program, while following a similar procurement process, was not managed directly by NOAA but by a tri-agency Integrated Program Office, of which NOAA was a member (GAO, 1995). NOAA, the NWS, the other agencies involved, and the enterprise as a whole have been affected by the issues encountered by the NPOESS procurement approach. The full range of lessons to be learned from that approach is beyond the scope of this report.

life-cycle cost estimates for elements of various system architectures. With these standard procurement processes, the government can obtain a "rack and stack" of an assortment of sizes and designs of spacecraft, instrument designs, and data processing approaches—with the associated cost, risk, performance, and schedule metrics. With respect to data products, NOAA has, on various programs, endeavored to group the products into categories that indicate a prioritization. These techniques all show recognition of the importance of the systems engineering process, including top-level requirements development.

Infusion of new technology into the NOAA satellite programs requires an even more rigorous approach to developing a clearly defined and recognized process. At the least, because the satellite system elements can be so costly and time-consuming, each planned infusion of new technology requires metrics that illustrate the potential benefit. NOAA has at times included in the requirement set "pre-planned improvements" grouped in a lower-priority category. This is a good way to encourage competitors to strive for new approaches in design while keeping the primary focus on higher-priority requirements.

It would serve NOAA to make the connection between specific products and metrics that illustrate the importance of these products even more clear. The products are linked to observations and thus instrument and other element designs as well as processing algorithms. Although the trade-offs needed to develop some of these metrics can be difficult and costly, they can be useful for directing resources most efficiently and potentially eliminating some less-critical observations. As an example, methods for determining impacts of various measurements on numerical weather prediction are described later in this chapter. NOAA provided a good visual example of impact metrics when it compared the "Snowmageddon" weather forecast with and without the polar afternoon orbit satellite data (Sullivan, 2011). In this case, however, no distinction was made as to which instruments on the polar platform made the most critical difference. A further level of detail would be needed to adequately prioritize among instruments or instrument designs.

Another very important distinction to be made in technology infusion (and indeed in general product prioritization) is between the operational mission and products and research mission and products. Both aspects are critical to NOAA and to the nation. But the distinction needs to be made very clearly. An operational mission and the observations required to accomplish that mission are presumably thus identified because of their very criticality to the nation and its more immediate security and well-being. A well-planned research program and the associated requirements and products serve a different purpose; indeed, it is the cornerstone of technology improvement and infusion. Operations and research are synergistic, but the goals and metrics of each need to be clearly stated and differentiated. NOAA's current approach is to include a select group of lower-priority "product improvement" requirements along with the higher-priority product requirements. Although this allows for some research infusion, perhaps a clearer distinction needs to be made, if possible, with a separate, well-recognized national approach to research satellite missions that feed specifically into NOAA operational missions. In this way, there is a synergistic process yet a clear distinction between missions.

This has been a part of the process in prior years: an example is the Operational Satellite Improvement Program (OSIP), a NOAA-National Aeronautics and Space Administration (NASA) agreement in effect from 1973 to 1981, in which the results from the NASA research missions were fed into requirements development for the NOAA operational missions (GAO, 1997). It should also be noted that part of the original intent of the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) was to facilitate risk reduction for NPOESS in areas including sensors, algorithms, and ground processing. NPP was not intended to be an operational mission itself. NOAA, along with the other members of the tri-agency NPOESS Integrated Program Office, embraced this approach.

In the area of radar observations, the just-being-completed NEXRAD polarimetric upgrade is bringing new and valuable capabilities to the field. At the same time, the basic NEXRAD design is nearly 25 years old, and the other major apparatus (apart from data and signal processing equipment) is more than 15 years old. Given the long development, design, procurement, and deployment cycle for such a large system, as well as the need for multiagency requirements development and approval, the time is already here to plan for the next generation of radar surveillance equipment.

Various avenues are open. The simplest and perhaps least costly option (at least in the short run) would be a Service Life Extension Program (SLEP). Assuming regular replacement and upgrading of signal and data processing facilities and data display equipment, the major NEXRAD components that would need SLEP attention are electromechanical—such things as motors, gears, and bearings. A second, more expensive, option would involve wholesale replacement of the NEXRAD radars with new equipment of similar design. A third option is to collaborate with the Federal Aviation Administration (FAA) (and perhaps other agencies) in the development and deployment of a multifunction surveillance radar system. Work toward that goal is ongoing, with emphasis on phased array radar (PAR) technology. At this point, however, the ability of a PAR system to provide NEXRAD-like polarimetric capabilities has not been established. Moreover, the likely procurement and life-cycle costs of such a system are not yet known. Another potential obstacle lies in the frequency allocations required for such a PAR system. According to current design concepts, the bandwidth required is substantially greater than that of the NEXRAD system, but there is already great pressure to dedicate more of the S-band spectrum to communications applications.

Any of the preceding options leaves unresolved the issue of comprehensive low-level coverage. Good low-level coverage is important for many severe-storm warning and precipitation-estimation applications as well as in complex-terrain situations. Dealing with such issues would require radars that are more closely spaced, particularly in regions of mountainous terrain, which would have to be more numerous than the NEXRAD radars but could be smaller and less expensive (because of the overlapping coverage). Here the Collaborative Adaptive Sensing of the Atmosphere (CASA) experience demonstrates much of the needed capability (McLaughlin et al., 2009). Here again, however, the procurement, deployment, and life-cycle costs of a practical system are not yet known. It may well be that benefit-cost considerations would favor a hybrid system, including a mix of NEXRAD-like surveillance capabilities with smaller local networks of CASA-like radars to deal with areas where the NEXRAD coverage is insufficient, such as urban areas or mountainous regions.

In addition to hardware platforms, the NWS will also need to address technique and algorithm development, which will be critical to maximizing the use of radar data. In the past, the development and evolution of data processing algorithms has been done in collaboration with the National Severe Storms Laboratory (NSSL), the Department of Defense (DOD), and the FAA. In order to avoid a large and expensive upgrade, as noted in Lesson 1 of the Committee's first report, incremental, collaborative advances in data algorithms will need to continue.

For surface observations, the NWS currently relies on the joint NWS/FAA Automated Surface Observing System (ASOS) network. As noted in this Committee's first report, the ASOS network was designed primarily to support aviation needs. Because of issues with ASOS sensor performance many scientists have developed their own networks for surface observing needs (NRC, 2012a). It has become commonplace that surface observations from private or public mesoscale networks (mesonets) are utilized in conjunction with, or instead of, data from ASOS. Mesonets have proven to be far more agile in terms of evolving sensor suites than has the ASOS network. The sensor suite and the spatial and temporal resolution of ASOS data have seen little improvement since the end of the MAR. Despite the relative maturity of surface observing technology, critical gaps remain. Land-surface properties important to numerical weather prediction, particularly soil moisture, lack the necessary spatial resolution (NRC, 2009). Urban areas, mountains, and coastal zones all present unique observing and forecasting challenges. A recent NRC report addressed the unique needs of the urban environment (NRC, 2012b). As the NWS expands the range of users it serves under the *Weather-Ready Nation* paradigm, it will be necessary to consider whether the surface observation data collected by the ASOS network is sufficient to meet user needs or whether other surface observing systems would provide the needed agility.

Similar challenges exist with respect to hydrologic observation and forecasting activities. Presently, the observational infrastructure for hydrologic forecasting is fragmented across such different agencies as the U.S. Geological Survey (USGS), the Natural Resources Conservation Service, NASA, and the NWS, in addition to various state and regional entities. The lack of standards between these networks combined with nonuniform acquisition quality control standards for merging these datasets translates into significant probability that use of existing observations is suboptimal. Such new technologies as multi-scale estimates of soil moisture or skin temperature or satellite altimetry of river and reservoir levels are not easily or readily being integrated into the existing data assimilation and forecasting workflows. Finally, a preliminary plan was presented to the Committee on how to address these issues, though these topics were raised in discussion related to the development of the new National Water Center being constructed in Tuscaloosa, Alabama. A thorough, integrated assessment of observational, data assimilation, and data management needs for hydrologic prediction activities would provide much-needed guidance to address current challenges in developing and adopting the hydrologic prediction components of the NWS (these challenges are elaborated on in Chapter 3).

Recommendation I.a

The National Weather Service (NWS) should continue technology infusion programs that have been effective subsequent to the Modernization and Associated Restructuring. Parallel support from the National Environmental Satellite, Data, and Information Service (NESDIS) is needed to provide continuing upgrade of satellite capabilities. Such infusion programs should include both hardware and software development.

Numerical Weather Prediction

Numerical weather prediction guidance affects nearly every facet of the NWS's mission. The NOAA Global Forecast System (GFS)[2] is one of the centerpieces of the NWS modeling enterprise. Not only is the GFS a key model used for short- and medium-range forecasting, it is also used to initialize or provide boundary conditions for many downstream models, applications, and products. Those include the North American Mesoscale Model (NAM)[3]; the Wave Watch III wave model[4]; the global Real Time Ocean Forecast System (RTOFS)[5] (based on the Hybrid Coordinate Ocean Model [HYCOM][6]); hurricane models (Hurricane Weather Research and Forecasting [HWRF][7], Geophysical Fluid Dynamics Laboratory [GFDL][8]); air quality applications and models (Hybrid Single Particle Lagrangian Integrated Trajectory [HYSPLIT][9]); aviation applications; and many specialized products. The numerical model used by the medium-range ensemble system is the GFS. Additionally, the GFS code and development are closely linked with the Climate Forecast System (CFS). It follows that the performance of the GFS has a crucial impact on many downstream models and products.

Performance in numerical weather prediction at the National Centers for Environmental Prediction (NCEP), including medium-range modeling, has been steadily improving and NCEP is widely considered one of the world leaders in weather and climate prediction. However, global forecast models run by several other national centers consistently outperform NCEP by established metrics of numerical modeling skill. The performance of the GFS was partially addressed in the Committee's first report (Finding 4-4) and is discussed in more detail in this section.

One method to assess the performance of the NWS global medium-range forecast model is to compare its accuracy to that of model-based forecasts made by other operational weather centers of the state of the atmosphere at approximately 18,000 ft (500 hPa). This metric is often considered the gold standard for medium-range prediction models because the 18,000-ft level is a dynamically significant region near the vertical midpoint of the troposphere that contains signatures of weather systems from the surface up through the jet stream aloft. Thus, this integrative metric is widely used for evaluation of the overall model performance. Many centers have a long history of this metric that tracks the model performance and improvements over the years, and this is one of the WMO standard statistics for model inter-comparisons. Weather prediction

[2] http://www.srh.noaa.gov/ssd/nwpmodel/html/gfs.htm
[3] http://www.srh.noaa.gov/ssd/nwpmodel/html/nam.htm

[4] http://polar.ncep.noaa.gov/waves/index2.shtml
[5] http://polar.ncep.noaa.gov/ofs/
[6] http://hycom.org/
[7] http://www.emc.ncep.noaa.gov/index.php?branch=HWRF
[8] http://www.gfdl.noaa.gov/hurricane-portal
[9] http://www.arl.noaa.gov/HYSPLIT_info.php

centers evaluate many other metrics as well (such as precipitation, low-level winds, tropical cyclone tracks and intensity, and surface pressure).

Figure 2.1 compares the 5-day forecast performance of several operational centers, including the NCEP GFS, for the time period 1996 through the present, averaged over the Northern and Southern Hemispheres. The leading models, including the GFS, have exhibited steadily increasing skill over the past 15 years. However, the European Centre for Medium-range Weather Forecasts (ECMWF) and more recently the UK Meteorological Office (UKMO) consistently outperform the GFS (and all other operational global medium-range forecast models). Additionally, it is apparent that the GFS has not closed the gap in terms of forecast skill with ECMWF over the past decade or more. Environment Canada and Japan have also shown significantly positive trends in predictive skill over the past decade.

Systematic comparison using metrics other than overall accuracy at 500 hPa, particularly at the surface, is more limited. However, the conclusions are similar. 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. Froude et al. (2007) and Froude (2010) compared the performance of the NCEP and ECMWF ensemble forecasts in forecasting extratropical cyclones in the Northern Hemisphere. Again, the ECMWF consistently produced better forecasts than did NCEP.

The Committee believes that a dedicated, community R2O effort, based on lessons from other centers, would aid the NWS in improving its numerical weather prediction skill (for example, the efforts of the Navy as described later in this chapter). Additionally, the UKMO and ECMWF systems have more advanced data assimilation systems than the current NWS GFS has, which may partially explain some of the differences in the performance of the systems. For example, both the UKMO and the ECMWF make use of an advanced data assimilation method, namely, four-dimensional variational (4DVar) assimilation. And both the UKMO and the ECMWF have made various improvements to their 4DVar systems, including recent advances to achieve a hybrid assimilation

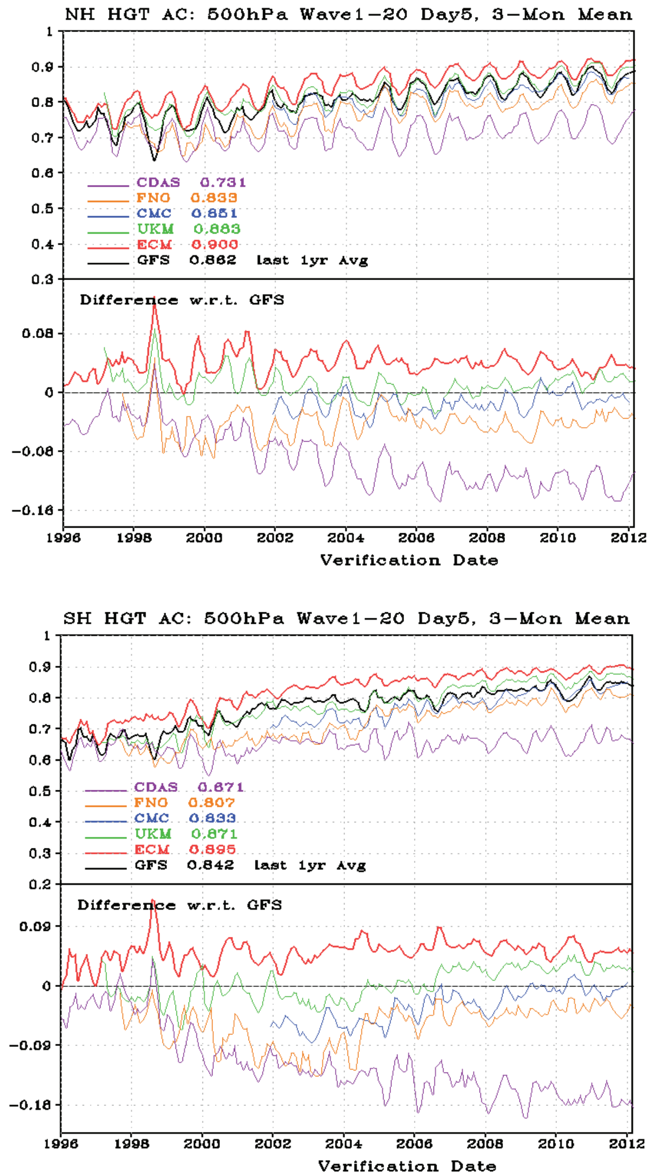

FIGURE 2.1 Five-day forecast 500 hPa anomaly correlation (top panels) for different forecast models (NCEP's Global Forecast System [GFS], European Center for Medium-range Weather Forecasting [ECM in figure legend], UK Meteorological Office [UKM in figure legend], Fleet Numerical Meteorology and Oceanography Center [FNO], the baseline Coordinated Data Analysis System [CDAS], and Canadian Meteorological Centre [CMC]) from 1996 to 2012 for the Northern (top) and Southern (bottom) Hemispheres. A higher anomaly correlation indicates better model forecast performance. The differences with respect to the GFS system are shown along the bottom panels, with positive values indicative of higher forecast skill than the GFS. SOURCE: National Centers for Environmental Prediction.

capability using synergistic variational and ensemble approaches. Recently, NCEP has also pursued a hybrid data assimilation approach and implemented a major upgrade in May 2012 to their three-dimensional variational (3DVar) system using a hybrid approach, which is intended to improve the overall performance (Lapenta, W., NWS Environmental Modeling Center, personal communication to member of the Committee). However, NCEP can further improve the GFS through implementing existing data assimilation technology, such as 4DVar, that is already being used at other leading centers.

Given the central role of the NCEP GFS, improvements made to its skill translate to improved products and performance in downstream models. An example of the relationship between the GFS performance and a downstream model is seen in the performance of the HWRF modeling system. It is estimated that the forthcoming improved hybrid (3DVar/ensemble) data assimilation system in GFS alone will lead to a significant improvement in the track prediction skill of the HWRF, based on a large sample of cases from the past several years (Tallapragada, V., NWS Environmental Modeling Center, personal communication to member of the Committee).

Another major difference between the leading operational center modeling systems and the GFS is the horizontal resolution in the models. The ECMWF uses a horizontal resolution of 17 km, while the GFS uses 27 km. Increases in resolution need to remain a high priority not only for the GFS but for downstream models as well.

Trade-offs might be considered between the number of numerical models being currently run by NCEP, the frequency with which these models are run, and the horizontal resolution in the models. Fewer models (either through consolidation or replacement with unified models that can address multiple scales and applications) being executed less frequently (within requirement limits) would allow for higher resolution to be achieved, as well as more sophisticated data assimilation and physical parameterization approaches to be used. Furthermore, within the NWS the concept of a unified modeling system—a single model for local, regional, global, and climate scales, which has been embraced by the UKMO—needs to be considered. Such a system minimizes duplicative developmental and software infrastructure efforts that are needed to maintain multiple numerical modeling systems. A new generation of numerical techniques and dynamical cores that are sufficiently flexible to address the multiple needs of the NWS ranging from high-resolution limited areas to global weather and climate applications are rapidly maturing and becoming available, suggesting the time is right to consider such a unified model approach. The use of cloud computing technology could help the NWS acquire computational flexibility to address changing priorities, and possibly reduce computing costs.

New community efforts are now emerging that will attempt to unify research and operational prediction systems and capabilities across a number of U.S. agencies. An inclusive and holistic approach (uniting nations, agencies, and disciplines) to Earth system science and numerical prediction is essential to realize much-needed major advances in observations, analysis, data assimilation, and prediction of high-impact weather and climate (Brunet et al., 2010; Shapiro et al., 2010; Shukla et al., 2009, 2010). Some of the challenges include infrastructure issues related to national computational resources, especially operational computing capacity, required for high-resolution weather and climate forecasting; the importance of collaboration between the weather and climate research communities for advances in seamless prediction; and improved end-user products produced by forecast systems. The Earth System Prediction Capability (ESPC) represents the national response to this need and many challenges. The International Council for Science (ICSU) and international partners, including the Belmont Forum of funding agencies (the National Science Foundation is a lead member), have developed a new international initiative—Future Earth: Research for Global Sustainability—and this demonstrates the importance of linking improved predictions of weather and climate with a broad range of societal issues such as food, water, energy, health, and human security.

The Committee notes that improving NWS's numerical weather prediction capabilities will require a systematic approach to transitioning research to operations. In designing such an approach, useful lessons can be drawn from the success of the R2O systems of the Navy and ECMWF programs.

Recommendation I.b

The National Weather Service (NWS) global and regional numerical weather prediction systems should be of the highest quality and accuracy, with improvements driven by user needs and scientific advances. To achieve this goal, the NWS should give priority to upgrading its data assimilation system and increasing the resolution of its deterministic and ensemble modeling systems. The product development process can be improved by developing a systematic approach for research-to-operations through collaboration with users and partners in the entire weather, water, and climate enterprise, both in the United States and around the world.

Current and Future Observing Needs for Numerical Weather Prediction Models

To better anticipate future observing needs and requirements, it is beneficial to consider the impact of the various current generation observation types on numerical weather forecasts. Furthermore, analysis of the relative value of observation systems can be useful for prioritizing investments. A plethora of surface, aircraft, radiosonde, satellite, and radar observations are used to initialize numerical weather prediction models. The impacts of these observations on numerical weather forecasts have been quantified traditionally through observing system experiments (OSEs), in which observations are removed from (or added to) a data assimilation system and the resulting forecasts are compared to a control set of forecasts. Such OSEs can provide an indication of a gross impact of observations on forecasts. However, OSEs are expensive because of the number of experiments required to test the large number of observation types, including such things as multiple individual sensing channels on satellite sounding instruments.

New approaches have recently been developed based on adjoint[10] sensitivities through the linking of the adjoint for the data assimilation and modeling systems (Langland, R.H., and N.L. Baker, Naval Research Laboratory, and Gelaro, R., NASA, personal communication to member of the Committee; Errico, 2007; Gelaro et al., 2007). These methods can provide detailed information about the impact of various observations and can help to identify problems with any given observation or the way that observation is assimilated. One caveat is that the estimate is subject to assumptions and limitations inherent in the use of adjoint models (i.e., the so-called tangent linear assumption). The adjoint observation impact method can quantify information related to the observation type and location. Similar observation impact information can be obtained from ensemble-based approaches as well.

In the last decade, adjoints for the modeling and data assimilation systems have been developed and applied at many centers around the world, including NASA, the U.S. Navy, ECMWF, UKMO, Meteo-France, and Environment Canada. NCEP has closely collaborated with NASA to develop an adjoint for the data assimilation systems because they share similar data assimilation methodology. However, it would be useful for the NWS to develop an adjoint for the prediction systems as well, such as the GFS, to enhance the monitoring and guidance of the impact of observations on their own Numerical Weather Prediction (NWP) systems (and downstream forecast systems). The observation impact tool can be especially valuable for the evaluation of hyper-spectral satellite sounders (with thousands of channels) since the methodology provides quantitative guidance on the selection of which channels to assimilate (given one only has sufficient resources to assimilate a fraction of them).

An example of the daily average observation impacts for January 2007 is shown in Figure 2.2. The results compare the observation impact on analysis and prediction systems from the NASA (GEOS-5), U.S. Navy (NOGAPS), and the ECMWF (EC-MSGFS) operational systems. The Advanced Microwave Sounding Unit (AMSU-A), radiosondes, satellite winds, and aircraft observations all have the largest impact in all of the systems for 24-hour forecasts using a synoptic-scale metric.

One can also compare the impact per observation that reduces the forecast error. On a per observation basis, some of the surface observations such as ships and land surface data become more important.

[10] The adjoint—the transpose of the forecast model's forward tangent propagator—provides a particular forecast output's sensitivity to initial state changes in a mathematically rigorous and computationally feasible manner.

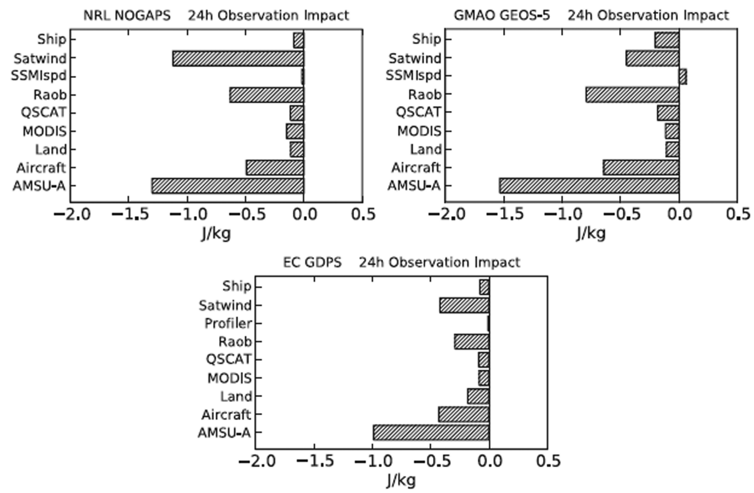

FIGURE 2.2 Daily average impacts of various observation types on 24-hour forecasts from January 2007 in U.S. Navy NOGAPS (top left), NASA GEOS-5 (top right), and ECMWF GDPS (bottom left). The results are presented as an energy-based measure of forecast error, and the units are J kg^{-1}. Larger negative numbers imply that the observation types are reducing the forecast error. The observation types include ships and buoys (Ship), geostationary satellite winds (Satwind), radiosondes and dropsondes (Raob), QuikSCAT winds (QSCAT), MODIS satellite winds (MODIS), land surface-pressure observations (Land), commercial aircraft (Aircraft), and AMSU-A radiances (AMSU-A). Results are also shown for SSM/I wind speeds (SSMIspd) in NOGAPS and GEOS-5 as opposed to profiler winds (Profiler) in GDPS, but both those observations types have the smaller overall impact in the respective forecast systems. In all systems, the AMSU-A, radiosondes, satellite winds, and aircraft observations have the largest impact on the forecast. SOURCE: Gelaro et al. (2010). ©American Meteorological Society. Reprinted with permission.

The impact of individual satellite channels can be assessed as well.

Several key aspects are emerging from these studies that are important for the future directions of observing systems used for NWP models. The radiosondes are still important, and degradation to the global radiosonde network could be detrimental to synoptic-scale and mesoscale forecasts. There are large differences in NWP analyses where models assimilate radiances from satellite sensors; the differences are small where they assimilate radiosonde data (Langland, R.H., and N.L. Baker, Naval Research Laboratory, personal communication to member of the Committee). While radiosondes are essential and necessary to anchor the satellite observing systems, the number of daily radiosonde observations has decreased during the same time period that the skill of global forecast models has increased. Further analysis is needed to determine how many radiosondes are needed and how they can be optimally distributed. The results of such an analysis could differ based on whether the goal is improving the skill of regional or global forecasts.

Radiosondes provide direct measurements of temperature, moisture, and winds, in contrast to satellites that typically provide vertically layered radiance information that is often more difficult to assimilate. NWP models likely suffer from a lack of accurate wind data, particularly in the troposphere. Cloud track winds are typically one of the most important satellite observations for NWP models; however, their positive impact may be mitigated by inaccurate estimates of cloud height assignments. Radiances are now available from sensors on several different satellites (AMSU-A, IASI, AIRS) and the data may currently be somewhat redundant from a modeling perspective (but may not be in the future as some key satellites expire). Although NWP models are thought to be especially sensitive to moisture observations, these observations are often more limited and very difficult to use. For example, water vapor channels from satellite infrared sounders are quite challenging to use in current data assimilation systems.

One major caveat is that most of these data impact studies have been made with medium-range prediction models, and the results may not necessarily translate to the mesoscale and high-impact severe weather. Moisture and boundary layer wind field observations are likely to be even more important on the mesoscale.

Accurate tropospheric wind measurement is considered one of the highest observation priorities to improve weather prediction and climate (Hays et al., 2005). One critical future observing system is satellite LIDAR (LIght Detection and Ranging); LIDAR-derived winds would fulfill a vital national need for high-resolution global tropospheric wind observation and will lead to improved long-range weather forecasting and more accurate hurricane landfall prediction (e.g., Baker et al., 1995; Hays et al., 2005). Currently available radiosonde wind measurements are sparse. The Atmospheric Dynamics Mission (ADM-Aeolus) of the European Space Agency (Stoffelen et al., 2005), set to be launched in 2013, will provide global observations of vertical wind profiles with the aim of demonstrating improvement in atmospheric wind analyses for NWP and climate studies.

Adaptive or targeted observations have been explored for applications such as tropical cyclones (Harnisch and Weissmann, 2010; Weissmann et al., 2010, 2012) and winter storms (Szunyogh et al., 2000). Targeted observations refer to data collected in specific areas at specific times with the aim of improving the quality of pre-selected NWP forecast aspects or metrics. The NOAA Winter Storm Reconnaissance (WSR) program (Szunyogh et al., 2000) goal is to reduce forecast errors for significant winter weather events over the contiguous United States and Alaska in the one- to four-day forecast lead time through the use of adaptive observations over the data-sparse northeast Pacific. Targeting by satellite observations (e.g., using rapid scan capabilities selectively) can be very effective and might be considered by the NWS as an important priority.

Additionally, the emergence of Unmanned Aircraft Systems (UAS) will provide an unprecedented future opportunity for targeted observations and an observing and monitoring network that is adaptive to meet NWS needs (based on weather or end-user requirements), further providing agility. These UAS have a variety of capabilities that are amenable to a multitude of meteorological situations and applications, including collection of vital offshore data. A potential UAS platform of interest is the Global Hawk, which has a long duration allowing for expansive data coverage and a large payload for meteorological instruments. The NASA Hurricane and Severe Storm Sentinel (HS3) is a five-year mission that will use two NASA Global Hawks to investigate processes that lead to hurricane formation and intensity change in the Atlantic Ocean basin. One Global Hawk will have an instrument suite designed to observe the environment around the hurricane, and the other will have instruments aimed at measuring the inner-core structure and processes. Field measurements will take place for one month each during the hurricane seasons of 2012 to 2014 and will be an excellent opportunity to assess the capabilities of such systems.

Recommendation I.c

To increase the capability of its numerical weather prediction systems to keep up with technological advances and prioritize investments in data assimilation and observations systems, the National Weather Service (NWS) should develop and advance software tools to monitor the impact of observations on numerical weather prediction and downstream forecast systems.

Probabilistic Forecasting

There is now a wide consensus that assessing and communicating uncertainty needs to be considered as an essential part of weather and water forecasting. This has been expressed in a range of reports from the National Research Council and the American Meteorological Society (AMS, 2008; Hirschberg et al., 2011; NRC, 2006, 2010).

Probabilistic weather and water forecasts benefit many areas of society. Dutton (2002) estimated that more than $3 trillion in annual private industry activities in the United States is subject to weather-related risk. Probabilistic forecasting allows for optimal decision making in a wide range of applications (Krzysztofowicz, 2001; Palmer, 2002; Zhu et al., 2002). For example, extreme low temperatures, extreme precipitation, or high winds can force the transportation industry to cancel flights or reroute ships and can cause authorities to salt roads or clear snow. In mountainous regions, sudden heavy localized precipitation can lead to flash floods. Locally accurate forecasts are also an important tool in agricultural planning, such as to take measures to avoid damage to crops when there is a risk of low temperatures, or to avoid unnecessary irrigation when sufficient precipitation is anticipated (Katz and Murphy, 1997; Stern and Coe, 1982).

The most widespread information about forecast uncertainty takes the form of probabilistic weather forecasts. These forecasts provide probabilities of future weather events (such as probability of precipitation) and probability distributions of future weather quantities (such as temperature or amount of precipitation). Probabilistic weather forecasts have been shown to improve weather-related decisions, to increase trust in the forecast, and to reduce the effects of forecast error (Joslyn and LeClerc, 2012). They are particularly important for forecasting in very-high-impact weather situations (NRC, 2010).

The NWS has regularly issued probability of precipitation forecasts for about 40 years, much longer than most other national weather agencies. There is some evidence that, perhaps as a result, the American public is used to probabilities in the forecast and reacts better to such information than does the public in some other countries (Gigerenzer et al., 2005). However, the NWS does not routinely issue probabilistic forecasts of other weather quantities of public interest, such as surface temperature, amount of precipitation, or wind speeds.

The dominant approach to probabilistic forecasting uses ensemble forecasts. Ensemble forecasts consist of multiple runs of one or more numerical weather prediction models, varying the initial conditions and/or model physics (Palmer, 2002). The NWS has produced ensemble numerical weather forecasts since December 1992 (Toth and Kalnay, 1993). Ensemble forecasts often exhibit a spread-error correlation, in which the spread of the ensemble is correlated with the absolute error of the forecast compared to the verifying observation (Buizza et al., 2005).

Nevertheless, most ensemble forecasts underestimate the size of the forecast errors and hence are not calibrated (Buizza et al., 2005).[11] This is especially the case for the surface weather quantities that are most important for practical forecasting. In their 2011 report on forecast uncertainty, the AMS Board on Enterprise Communication summarized the situation this way: "Current-generation ensemble prediction systems produce uncertainty forecasts that are biased and underestimate the forecast uncertainty (i.e., underdispersion of the ensemble members collectively). This is partly because of the low resolution of the forecast models, partly because of improper initial conditions, and partly because the ensemble prediction systems do not include effective treatments for the error introduced by model deficiencies" (Hirschberg et al., 2011). Possibly as a result, the NWS and most other national weather agencies do not yet routinely issue public probabilistic forecasts of most meteorological and hydrologic variables, 20 years after ensemble forecasts of such variables started being produced on a regular basis.

Over the past decade or so, there has been intense research on the development of methods for producing calibrated probabilistic forecasts based on forecast ensembles. These use various kinds of statistical post-processing, and vary according to the quantity being forecast. The research on these methods is now fairly mature, but they have not yet been widely integrated into operational forecasting.

The most straightforward variable to forecast probabilistically is temperature, for which probabilistic forecasting methods include the rank histogram adjustment method (Hamill and Colucci, 1997), the best member dressing method (Roulston and Smith, 2003), Bayesian model averaging (BMA; Raftery et al., 2005), and ensemble model output statistics, also called non-homogeneous regression (Gneiting et al., 2005).

Probabilistic forecasting of quantitative precipitation is more difficult, because precipitation has a high probability of being zero, and because the observed distribution of the amount of precipitation is typically highly skewed. The probabilities of exceeding specific thresholds can be found by model output statistics (MOS; Glahn and Lowry, 1972). More recent research has shown that logistic regression gives better results for quantitative precipitation than do the linear regression methods on which MOS is based (Applequist et al., 2002; Hamill et al., 2004). A full predictive probability distribution of the amount of precipitation can be found by rank histogram adjustment (Hamill

[11] A probabilistic forecast is said to be calibrated when events forecast to happen with probability x% actually happen x% of the time on average. For example, a probabilistic forecasting system that issues forecasts of the probability of freezing is calibrated if, of the times when it forecasts freezing with probability 20%, it actually freezes on average about 20% of the time.

and Colucci, 1998), BMA (Sloughter et al., 2007), or extended logistic regression (Wilks, 2009).

For wind speed, quantiles can be found by quantile regression (Bremnes, 2004). One major reason for the probabilistic forecasting of wind speeds is the management of wind energy systems, and for this, as for other applications calling for a cost-loss analysis, a full predictive probability distribution is needed. Such a distribution can be found by BMA (Sloughter et al., 2010) or ensemble model output statistics (Thorarinsdottir and Gneiting, 2010).

Generally, these probabilistic forecasting methods have been found to be calibrated and to give forecast intervals that are narrow enough to be useful in a variety of experiments. The different methods perform similarly, but all clearly outperform probabilistic forecasts based on the raw ensemble with no post-processing. They work for different types of ensembles, including ensembles whose members are all distinct, ensembles with subsets of exchangeable members, and multi-model ensembles (Fraley et al., 2010). They have the advantage of typically requiring only short data training periods. They may be improved by being used in conjunction with reforecasts (Hamill et al., 2004), although these can be computationally expensive to produce.

An important challenge is effective communication of probabilistic forecasts. Recent research in this area is encouraging, suggesting that it is possible to communicate uncertainty in the forecast in a way the public can understand. The communication format has to be carefully designed, however, and cognitive research is proving useful in showing how to do this.

Research has shown that decision making by non-experts can be better when they are given uncertainty information than when they are given traditional deterministic forecasts only (Nadav-Greenberg and Joslyn, 2009). The format is important. For example, box plots and uncertainty charts enhance reading accuracy and awareness of the degree of uncertainty, while showing a visualization of the worst-case scenario can cause bias (Nadav-Greenberg et al., 2008). Uncertainty information can make people less reluctant to act in situations in which precautionary action is required at low probabilities, which is often the case with rare events (Joslyn and LeClerc, 2012). A website[12] showing probabilistic forecasts of temperature and precipitation for the Pacific Northwest was designed using results from cognitive research (Mass et al., 2009). An earlier version of the website was cited as an example of how probabilistic forecasting could be done (NRC, 2006).

Overall, the research of the past decade on probabilistic forecasting has three implications. One is that the NWS needs to employ statistical methods to post-process its ensemble forecasts so as to obtain calibrated probabilistic forecasts—these are now within reach. Other national agencies have not yet started issuing probabilistic forecasts of the main weather and water elements, such as temperature, precipitation, and wind speed, on a regular basis, so this is an area in which the NWS has an opportunity to take the lead globally. Statistical post-processing may be best developed through collaboration with the broader weather, water, and climate enterprise.

The second implication is that increasing the size of the ensembles used, which is quite expensive computationally, will not by itself yield calibrated probabilistic forecasts. Increasing the resolution of the ensemble members and statistical post-processing are more likely to yield sharper and better calibrated probabilistic forecasts than increasing ensemble size, and are thus a better investment in the context of limited resources.

The third implication is that probabilistic forecasts can be effectively communicated to users, but it is important that the communication format be carefully designed using cognitive research. When calibrated and well communicated, probabilistic forecasts can increase trust in the forecast and lead to better decision making in the face of uncertainty. It is possible that the design of formats for communication of probabilistic forecasts may be better done by a partner organization.

Recommendation I.d

The National Weather Service (NWS) should take the lead in a community effort to provide products that effectively communicate forecast uncertainty information. The format for communicating probabilistic forecasts requires careful design using cognitive research. Calibrated probabilistic forecasts would be produced by statistical post-processing of forecast ensembles, and improvement efforts should

[12] www.probcast.com

focus on increasing the resolution and accuracy of the ensemble forecasts.

Hydrologic Prediction Services

The MAR had a substantial impact on NWS hydrologic prediction services operations. Hydrologic prediction services were not addressed directly by the MAR, however, and the benefits to hydrologic services were co-benefits of improvements designed to benefit meteorological services. These co-benefits included the greatly improved observation of precipitation through the deployment of the NEXRAD network; the greatly increased density of surface observation with the Automated Surface Observing System (ASOS); and increased coordination of Weather Forecast Offices (WFOs) with River Forecast Centers (RFCs), thus allowing the NWS to expand its hydrology mission and services (NRC, 2012a). Although the Committee notes the need for more integrated planning and technology improvement in the meteorological and hydrologic services, hydrologic services are treated separately in this report. This is because improvements in hydrologic services have been an afterthought in the past and the Committee feels they need special attention. NWS hydrologic prediction services were partially addressed in the Committee's first report (Finding 4-7a) and are discussed in more detail in this section.

Coincident with the MAR, the Advanced Hydrologic Prediction System (AHPS) was developed and implemented, which also aimed to improve and expand hydrologic forecasts and services. Although AHPS wasn't funded until midway through the MAR, it was essential for enabling the RFCs to capitalize on MAR advancements. Hydrologic model development, calibration, and forecast verification are important functions of the RFCs. However, the MAR did not provide the RFCs with the full complement of information processing tools, through AWIPS or other tools, required to fulfill those functions.

As a whole, the MAR did have a positive impact on hydrologic forecasts and services as evidenced, in part, by a significant improvement in flash flood forecast lead time during the period of 1994 to 1998 when the NEXRAD radar system was completed (NRC, 2012a). The recent addition of Service Coordination Hydrologists (SCHs) at the RFCs was based on their evaluation of the success of the Warning Coordination Meteorologist (WCM) position at WFOs in coordinating with external partners and customers. Perhaps more importantly, the hydrologic services program presently desires to have a hydrologic-centric MAR, especially to address current staffing profiles (NRC, 2012a).

National, mutually agreed upon, quantitative hydrologic forecast performance metrics provide a clear, consistent, and objective way to track prediction service skill over time. Comparison of hydrologic forecasts from different sites or watersheds can be complicated, but this difficulty need not inhibit the development of a consistent framework for hydrologic prediction skill assessment. Because any single metric is often deficient in quantifying forecast service performance, it is commonplace to use a select set of metrics to characterize many aspects of forecast quality over time. This is particularly true for hydrologic forecasts where different hydrologic behaviors such as peak flow amount, period of inundation, duration of low flow conditions, and location of overbank flows can each have specific impacts that present threats to society. Flash flood forecast performance based on flash flood warnings issued by NWS WFOs have been monitored since the late 1980s and show a steady increase in forecast lead time and reasonable values of probability of detection of flooding events. River flow forecasts issued from RFCs have only been monitored since 2008 under a relatively new program entitled the Point-based Flood Warning Verification Program. Forecast verification statistics made available to the Committee suggest that on a national basis there have been increases in river flood forecast lead times but the skill of the forecasts, in terms of probability of detection and false alarm ratios, has remained relatively constant while there has been an increase in the absolute timing error (error in the forecast of the time of flood onset).

While still early, the Committee sees this effort as a positive step toward tracking forecast performance in NWS products and services. The Committee suggests that this effort be sustained and potentially expanded to include additional river flow levels (also known as probabilistic "exceedance" thresholds), which would allow for more complete assessment of river flow forecasts in addition to flood flows. The existing and additional metrics will provide a clear history of the benefit of past forecast innovations and provide a continuous platform from which experimental methodologies may be easily compared.

NWS hydrology is also moving toward more modern distributed, physics-based Earth system models for hydrologic prediction (Cline, 2012). If implemented, such models would gradually replace the spatially lumped conceptual hydrologic models[13] that have been used operationally for the past 20 to 30 years in NWS hydrologic prediction services. While there are numerous reasons for undertaking this modeling transformation, many of which are described below, it is important that such model development efforts be informed and guided by clear model assessment activities. Presently, it is not clear to the Committee that there is a formal, objective vetting process for different modeling systems at either the national scale or at the individual RFC level, though the aforementioned forecast evaluation efforts could be part of such an effort. The Distributed Model Intercomparison Program (DMIP) has provided some significant degree of model assessment but it is only a periodic, voluntary, and largely unfunded research activity and could be improved to include a more formal and continuous framework for model assessment. In summary, the Committee views these forecast metrics and evaluation activities as key elements in conducting continuous assessment value determination of new modeling innovations.

Recommendation I.e

The National Weather Service (NWS) hydrologic prediction services should coordinate with other entities in the hydrologic prediction community to continue and expand a set of common, objective model metrics from which operational and experimental models may be inter-compared and continually assessed.

ESSENTIAL FUNCTIONS

Essential functions constitute those activities and services that are mandated by the NWS mission and include product generation (e.g., general weather forecasts, watches, warnings, advisories, and guidance) and dissemination; brokering and provision of weather and water data; international responsibilities to WMO programs; and the creation of critical analysis tools that enable NWS staff to execute its functions.

Data Management

As outlined in *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks*, there has been a proliferation of networks designed to acquire meteorological and hydrologic data for various applications (NRC, 2009). From agriculture and transportation interests to recreation and severe weather and flood forecasting, it is commonplace that surface observations from private or public mesoscale networks (mesonets) are utilized in conjunction with, or instead of, data from the joint NWS/FAA Automated Surface Observing System (ASOS) network. Mesonets have become widespread and popular for a variety of reasons, including cost-effective and customized instrumentation and readily available communications infrastructure. These private and public networks have also proven to be far more agile in terms of evolving sensor suites than the ASOS network has. The ASOS network continues its singular focus on aviation interests. Very little in the way of modification has occurred with the ASOS network in terms of the sensor suite or enhancements in spatial and temporal resolution.

As in situ sensors are being deployed to measure conditions near the Earth's surface at mesoscale time and space scales, a similar revolution is taking place with remote sensing platforms. The dual polarization upgrade to the NWS NEXRAD radars is under way, and research continues at NSSL on multi-function phased array radar (MPAR) capabilities. However, as is the case in the surface observation realm, a myriad of non-NWS weather radars are operating with the goal of protecting life and property. Examples include the CASA radar project and radars operated by private industry, primarily the broadcasting sector. As with the case of surface mesonets, these radar networks are operated independently with dissimilar sensing protocols, spatial and temporal resolution, and quality assurance protocols.

As water quantity and quality become a more critical national resource and national security issue,

[13] A spatially lumped hydrologic model represents a drainage basin as a single entity and simulates state variables and fluxes into and out of the basin as a whole (NRC, 2010).

the next decade will likely result in the increase of new mesonet measurements focused on water, and new radar and satellite algorithms focused on precipitation estimation. New methods of determining precipitation rates, precipitation type, evaporation, soil moisture, surface moisture fluxes, and groundwater availability will result in another round of mesonet, radar, and satellite enhancements that the NWS is not well prepared to integrate into its operational mission. It is expected that this trend will continue with regard to observations throughout the troposphere.

In addition, the most recent decade has seen an increase in the use of nontraditional data as proxies for meteorological and hydrologic information. These datasets include such vehicular information as windshield wiper speeds and the use of headlights, fog lights, and antilock brakes to provide information regarding visibility and rainfall rates. There is also potential to gather useful information from the tens of thousands of networked video cameras spread throughout the country.

The NWS is better suited than entities in the private or academic sectors to play a critical leading role with respect to observation data quality requirements and standards. System of systems architecture analyses can be strengthened to prioritize data requirements and, therefore, the key design parameters of the observing instruments and platforms. In view of the increasing complexity, cost, and quantity of data, it is critical to approach this up-front activity in a rigorous fashion and is clearly a priority government role. Therefore, it is critical that the NWS carefully review the recommendations made in *Observing Weather and Climate from the Ground Up: A Nationwide Network of Networks* (NRC, 2009) and apply them to weather, water, and climate data in all of their forms. In particular, the Committee endorses the following recommendations from that report:

> **Recommendation**: Stakeholders, including all levels of government, various private-sector interests, and academia, should collectively develop and implement a plan for achieving and sustaining a mesoscale observing system to meet multiple national needs.

> **Recommendation**: To ensure progress, a centralized authority should be identified to provide or to enable essential core services for the network of networks.

> **Recommendation**: The centralized authority should require metadata of every component in an integrated, multi-use observing system (NRC, 2009).

In addition to having an infrastructure to address issues of data standards, the NWS will also need to consider an infrastructure to address issues of data security to ensure the integrity of information and data throughput to delivery in times of disaster.

OPERATIONALLY RELATED RESEARCH

Operationally related research aims to infuse NWS core capabilities with improved techniques from the research community (e.g., research-to-operations, or R2O). Such activities also include research priorities based on issues that inhibit analysis and prediction skill or the production of forecast and warning products (e.g., operations-to-research, or O2R). Achieving effective R2O processes has challenged most technology-based organizations, both public and private. The reasons for this are many, and the potential solutions are diverse. Prior NRC reports have addressed this on multiple occasions (NRC, 2000, 2003b, 2010). The issue is of sufficient importance to be a major element of Recommendation I. In particular, the Committee includes in its recommendation the new approach of reaching out to the broader weather, water, and climate enterprise to identify improved R2O techniques and to assist the NWS with making such transitions more successful. The Committee believes that a community-based, systematic approach to R2O—developed by professionals from all sectors of the enterprise and inspired by a dedicated team of experts—is likely to have wide-reaching consequences. As stated in the third bullet of Recommendation I, it is especially important that the development and implementation of a national strategy for a systematic approach to R2O/O2R involve the entire enterprise, and that the NWS lead such an effort.

Several system and research and development (R&D) activities are being conducted that contribute to the NWS infrastructure and service program. Each offers an example of the type of research partnerships that would be useful in developing a national R2O/O2R system as called for in the third bullet of Recommendation I, and each offers lessons that could be used as guidance when developing such a strategy. In addition to the specific programs and partnerships like the examples provided here, an overall improved partnership between the NWS and OAR will be critical to strengthening NWS core capabilities through R2O and O2R. These include the following.

High-capacity R&D Computing Capability

Access to computing capacity for NOAA research has significantly increased with dedicated systems located at or near research institutions and available for projects directly applicable to NWS requirements. The computer systems include GAEA (Oak Ridge, Tennessee), T-Jet (Boulder, Colorado), S4 (Madison, Wisconsin), and Zeus (Fairmont, West Virginia).

Global Data Assimilation

Researchers from NOAA/NCEP, NASA, NOAA/Earth System Research Laboratory (ESRL), and the University of Oklahoma have jointly undertaken the development and testing of an advanced 3DVar/ensemble Kalman filter (EnKF) ensemble hybrid data assimilation system using the NOAA R&D computing resource. Initial testing of the system obtained positive results in terms of standard NWP metrics, and the system was transitioned to operations in May 2012. This initial step is part of a longer NWS NWP development objective and illustrates the power of utilizing a collaborative enterprise approach to major R&D objectives.

Hurricane Forecast Improvement Program

Established in 2008, the Hurricane Forecast Improvement Program (HFIP) has aligned the interagency and scientific hurricane community at large, including a consortium of researchers from universities, NCAR, NOAA/ESRL, NOAA/Atlantic Oceanographic and Meteorological Laboratory (AOML), NOAA/NCEP/National Hurricane Center (NHC), NOAA/NCEP/EMC, DOD/NRL, as well as a hurricane specialist from NHC, to address the major challenge of improving hurricane forecasts. HFIP has assembled a computational infrastructure and implemented a focused set of cross-organizational R&D activities addressing global models, regional models, surge models, hybrid data assimilation, and statistical post processing to improve hurricane track, intensity, and storm surge forecast guidance. The goals of the HFIP are to reduce the average errors of hurricane track and intensity forecasts by 20 percent within five years and 50 percent in ten years, with a forecast period out to seven days. Among HFIP's goals is to provide research and "experimental operational" products in real time to the NHC forecasters for their use and evaluation. HFIP is an example of a community-based approach that has brought together the research and operational communities to address NWS science and service goals.

Additionally, the Developmental Testbed Center (DTC) assists in the evaluation of the real-time and retrospective HFIP forecasts. These collaborations with academia and government agencies within and outside of NOAA (e.g., the Navy) have demonstrated that increased model resolution and improved data assimilation through the application of the EnKF for both global and regional models, enhanced model physics, data assimilation of observations around the hurricane core in regional models, and new post-processing techniques, have the potential for improvements in both hurricane track and intensity prediction. The global EnKF ensembles indicate a 20 percent improvement in track guidance, while the intensity forecasts have not seen improvement over the past four years.[14] In the meantime, intensity improvements were demonstrated in a research model (the NCAR Advanced Research WRF) that continues to outperform both NWS hurricane models (GFDL and HWRF). In spite of the short-term progress forged through the HFIP effort, improvements in hurricane intensity forecasts from dynamical models continue to be a major challenge. Hurricane track forecast skill has steadily improved over the last 20 years, but the intensity forecasts have improved little if at all (NRC, 2012a). For example, in 2011 the NOAA high-resolution operational dynamical models (GFDL and HWRF) had larger intensity errors than those of the statistical models, which is a basic metric of skill. Clearly a longer-term sustained and focused effort is needed to improve hurricane intensity forecasts. The progress of the NCAR Advanced Research WRF model in reducing hurricane intensity forecast error, while the operational models have failed to show similar improvement, highlights the need for improving the transition of R2O. To meet its

[14] http://www.nhc.noaa.gov/verification/verify5.shtml

goals, HFIP will need to develop a systematic approach to R2O.

It should be noted that the Joint Hurricane Testbed (JHT), under the auspices of the USWRP, predates the HFIP and has also shown success in improving technologies for forecasting in operational centers and improving modeling and data assimilation capabilities at the EMC. The success of both the DTC and the JHT suggest that testbeds are an effective approach to facilitating R2O.

NOAA Center for Weather and Climate Prediction (NCWCP)

The construction of this new facility located near NASA Goddard and the University of Maryland will provide the infrastructure and location required to facilitate the R2O necessary to carry out a major part of the vision for the NWS outlined in this report. Included in the transition is the collocation of five of the NCEP centers, major elements of NESDIS operations and research, and OAR's Air Resources Laboratory. To facilitate collaboration between NOAA and the external science community, forty spaces in the new facility have been dedicated for visiting scientists. There is currently some funding allocated to support visiting scientists from the University Corporation for Atmospheric Research (UCAR), and the NWS is working with other tenants of the NCWCP to develop a coordinated approach to supporting an expanded visiting scientist program (Uccellini, L., NWS National Centers for Environmental Prediction, personal communication to member of the Committee). Such a program would benefit from engaging scientists from outside the NOAA labs or other federal agencies that the NWS already works with, and increasing partnerships with all parts of the weather, water, and climate enterprise and internationally. In developing such a program, the NWS could draw valuable lessons from existing visitor programs at other national centers such as ECMWF.

Severe Storm Prediction

The National Weather Center (NWC) in Norman, Oklahoma, is a multi-agency facility built in 2006 designed to bring government, academic, and private entities of the weather, water, and climate enterprise together for mutual collaboration. Over the past six years, NWS scientists, engineers, researchers, trainers, and operational forecasters from the NOAA Radar Operations Center (ROC), NOAA National Severe Storms Laboratory (NSSL), NOAA Warning Decision Training Branch (WDTB), NOAA Storm Prediction Center (SPC), and the NWS Norman Weather Forecast Office (OUN) have been collocated with the NOAA-OU Cooperative Institute for Mesoscale Meteorological Studies (CIMMS), the University of Oklahoma School of Meteorology and College of Atmospheric and Geographic Sciences, the Center for the Analysis and Prediction of Storms (CAPS), the Atmospheric Radar Research Center (ARRC), and the Oklahoma Climatological Survey, a state agency. These agencies and programs are located on the OU Research Campus with private-sector partners and OU support entities, including the Office of the Vice President for Research and the OU Office of Technology Development.

The NWC has resulted in significant opportunities for collaboration, creating an environment where each of the sectors of the enterprise can learn from, and with, the other sectors. Within the NWC, NOAA has created a Hazardous Weather Testbed (HWT) that serves as the proving ground for new technologies, forecast techniques, training regimens, and datasets. This has resulted in the real-time transfer of cutting-edge research into forecast operations to protect life and property. Regular programs within the HWT consistently transition new meteorological understanding into advances in warnings for hazardous weather events nationwide. The ability to team researchers with forecasters and students provides for a unique environment whereby existing practitioners continually develop their professional skills while working alongside the next generation of meteorologists. As the NWS seriously considers optimal future collocation of its facilities with stakeholders, the NWC could be viewed as a possible model for how to design such a collaborative facility.

NRL/FNMOC Interactions

The Navy's meteorology and oceanography enterprise differs in scope from the NWS (e.g., the Navy is focused on different applications and areas of responsibility) and the overall mission is quite different in its nature. Nevertheless, some relevant parallels between the two enterprises are illustrative. To develop leading, operationally viable technology (including models and applications) in key areas for the Navy, the Naval Research Laboratory (NRL) leverages basic and applied research programs that are among the world leaders. This is accomplished through a close relationship with national and international research partners, as well as various end users within the Navy's meteorology enterprise. The environmental prediction systems and application technologies are developed by NRL (Marine Meteorology Division in Monterey, California, and Oceanography Division in Stennis, Mississippi) and transitioned to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) and the Naval Oceanography Center (NAVO) for operational implementation and routine dissemination.

Despite fewer resources than other weather centers (e.g., personnel, financial, computational), the Navy's prediction systems are leading in some aspects or remain competitive with other efforts in many respects. One possible important reason for this success has been the collocation of the Navy's primary meteorology research entity (NRL-Monterey) with its operational partner (FNMOC). This has fostered a close working relationship and a particularly effective pathway for efficient transitions of research technology to operations. (A similarly close research-operations synergy is present on the oceanography side.) NRL has assumed the role of a developmental testbed center for the Navy in order to solely develop or harvest research and technology relevant for the Navy mission through focused interactions with the research community, and subsequent opportunities for transition to operations. This close relationship between research and operations has enabled the Navy to mitigate the so-called "Valley of Death" of R2O. Close alignment and coordination of the research and operational enterprise within the Navy has provided focus and efficiency that likely would not be achievable if these research and operational entities operated more independently with less administrative oversight.

National Center for Atmospheric Research

The National Center for Atmospheric Research (NCAR) in Boulder, Colorado, is operated under a cooperative agreement from the National Science Foundation (NSF) with the mission of conducting foundational atmospheric and related science research and serving the broader academic atmospheric and related sciences research communities. In addition to managing several state-of-the-art observational and computational research facilities, NCAR also codevelops and supports the development of a host of community-based atmospheric modeling systems. This suite of models includes the Weather Research and Forecasting model (WRF) and the Community Earth System Model. These two models, in particular, are widely used throughout both the United States and the international academic research and operational forecasting communities. By design, NCAR has deep roots in the atmospheric research community and maintains participatory observational system and modeling system development pathways. Research conducted in partnership with NCAR has led to significant technological advances in many areas, including polarimetric radar, lidar, boundary layer and surface flux measurements, regional numerical weather prediction, climate system modeling, paleoclimate modeling, solar physics, aircraft measurements, and high-performance computing applications.

Recently, NCAR has partnered with NCEP and others within NOAA and the academic community in the formation of the DTC whose mission is to evaluate new innovations in operational NWP modeling and model verification techniques. Through existing partnerships with academia and through structures like the DTC, there exist significant opportunities for the NWS to improve connectivity to the research community and to accelerate R2O activities.

Hydrologic Prediction

Presently, there is an enormous amount of active research in both the land-atmosphere-vegetation modeling communities and the catchment hydrology modeling communities. Funding for such activities has increasingly fallen outside of NOAA, being supported instead by NSF, NASA, and the Department of Energy (DOE) in recent years. This has presented barriers to transferring research into NOAA/NWS operations. The level of sophistication and representativeness of real-world processes, as well as characterizations of uncertainties, in those non-NWS research and operational communities outpace those used in NWS-hydrology operations. NWS hydrologic prediction models are simplified, often lack real physical meaning, and are limited in terms of ensemble and data assimilation capabilities. Alternatively, NWS hydrologic prediction models are fairly parsimonious from a parameter perspective, which affords convenience in terms of model calibration and the simplified structure of NWS hydrologic prediction models translates into significant computational efficiency.

The current suite of NWS hydrologic models requires numerous years of data for calibration to obtain reasonable fidelity. The broader hydrologic science community has developed numerous ways to add value to hydrologic forecasts through the use of more advanced models, through data assimilation, or through the employment of more sophisticated ensemble techniques, but there appear to be institutional and resource barriers to efficiently infusing that science and technology into NWS hydrologic prediction service operations. Evolution of NWS hydrologic prediction services in a science-based manner requires new pathways for collaboration. The NWS Office of Hydrological Development (OHD) is nominally charged with developing new forecasting methodologies and transferring those to the RFCs where operational forecasting duties are executed. Increasingly, however, it seems R2O transitions have languished, resulting in disconnects or divergence between the forecasting approaches used in RFCs and those developed by OHD. The exact reasons for this are somewhat unclear but are likely to be due in part to limited staffing and technological resources. The OHD has and continues to develop new technology and techniques and has some deep, long-standing ties with the broader academic community, but migration of technology from OHD to RFCs remains lacking.

To accelerate the transition of new observational and prediction technologies into NWS hydrologic prediction activities, a clearer set of protocols and pathways for infusing research into operations is needed. This could be achieved through an improved OHD capability or through such other means as a hydrologic prediction testbed. Such an activity would encompass and become an instrumental component of the multi-agency coordination efforts being developed at the new National Water Center in Tuscaloosa, Alabama.

The Indispensable Capability for Development and Testing

Previous sections of this chapter have detailed the many ways in which the science and technology underlying the core capabilities of the NWS continue to advance and require integration into the operations and products of the NWS. New types and new amounts of data need to be assimilated; the radars and other observation technologies need to be upgraded to provide more localized observations for feeding ever more detailed and end-user-useful forecasts; numerical weather forecasting techniques need to be enhanced so as to be state of the art; and the workstations and workstation software need to be upgraded so as to allow the forecaster to be able to use all of these enhancements.

The existing powerful NWS capability has evolved to its present state by diverse paths, in many stages, and it is very complex—much more complex than if it had all been designed at once using sophisticated systems design capability. Systems design processes are important, but making enhancements is not a matter of simply writing detailed specifications and then funding a vendor to create the required hardware or software.

The entire experience of the information technology (IT) industry to date teaches a powerful lesson: "You can't get it right the first time." Incremental improvements and additions need to be tested, while under prototype development, by being made available to selected NWS forecasters.

This capability to test during design goes by many names: development and testing; rapid prototyping; build a little, test a little, field a little; iterative design; and others. Whatever the name, the process and the capability are indispensable. This is especially true in an environment where delay in upgraded functionality means cost overruns. Note that Lesson 3 of the Committee's first report pointed to the crucial role that rapid prototyping played in the success of the MAR and the successful deployment of the AWIPS workstations in particular. This capability was a result of the Program for Regional Observing and Forecasting Service (PROFS) program and the Denver AWIPS Risk Reduction and Requirements Evaluation (DAR^{3}E) effort, which had support from NWS leadership and management and allowed for operational testing of many of the modernization concepts by prospective users.

Moreover, this development and testing capability is an essential link in the R2O and O2R processes connecting the NOAA labs and the academic meteorological communities. Although the development process could occur anywhere (within NOAA, the academic or research community, the private sector), operational testing needs to involve NWS forecasters, and the prototypes need to be modified on the basis of what is learned from the testing. Therefore, the Committee makes the following recommendation.

Recommendation I.f

As an absolutely necessary condition for success, although insufficient by itself, the National Weather Service (NWS) should have an ongoing capability for development and testing of its incremental technical upgrades. This will allow the NWS to advance its capabilities to respond to new scientific and technological possibilities and to enhance its service to the nation.

ADVISORY GROUPS FOR TECHNOLOGICAL IMPROVEMENTS

Lesson 6 of the Committee's first report was that the various scientific and technical reports from independent advisory bodies were of substantial help to the NWS during the MAR. While the Committee was unable to be specific about how much external advice was appropriate, they nevertheless concluded that it was an important input to NWS and NOAA management. The Committee notes that creation of an NWS Advisory Committee was the first recommendation of the *Fair Weather* report (NRC, 2003a) and that subsequent reports have repeated that recommendation.

The Committee has considered several ways in which ongoing independent technical advice might be provided to the NWS, and this section presents them along with what the Committee judges to be the pros and cons associated with each.

1. Institutionalize the current Environmental Information Services Working Group (EISWG) subcommittee of the NOAA Science Advisory Board (NSAB) to make it the source of technical advice for the NWS.

2. Create a separate Federal Advisory Committee Act (FACA) committee solely devoted to providing technical advice to the NWS.

3. Create an independent, standing committee charged exclusively with providing ongoing scientific and technical advice to the NWS.

The advantage of the first option is that it is probably the simplest to set up. The "overhead" of creating a FACA committee has already been incurred, and the EISWG is already functioning. A possible drawback is that the EISWG subset of the NSAB cannot, because of its rather small membership, represent all of the areas or sectors in which advice and outside perspective would be of use to the NWS. The marginal cost of this option is likely only that associated with the meetings of EISWG that are distinct from those of the NSAB itself.

One advantage of the second option is that it could be structured to include a wide range of subject expertise and a wide range of representation of the various stakeholder groups in the weather, water, and climate enterprise. A second possible advantage might be that it would interact directly with NWS management. Possible drawbacks might include the substantial overhead and delay associated with creating a new FACA committee. The cost in dollars and staff time would be borne directly by the NWS, rather than by NOAA.

The third option probably has less overhead, because setting up an independent committee is a simpler process than setting up a FACA committee. It has the advantage, compared to the first option, of a broader range of expertise and stakeholder representation, but it is, of course, not under the control of NWS management regarding committee makeup. The costs are likely to be determined primarily by the size of the committee and the expected frequency of meetings, which might be as few as one or two per year. The costs would be borne directly by the NWS.

No matter which option for technical advice the NWS pursues, the advisory body would need expertise in both the physical and social science aspects of weather, water, and climate services, as well as expertise in systems engineering and infrastructure evolution. This latter expertise would partially address Lesson 2 from the Committee's first report by helping the NWS clearly define system-level requirements (NRC, 2012a). The advisory body would also help the NWS establish clear metrics for evaluating improvement in forecasts and warnings, consistent with Lesson 3 from the Committee's first report and Recommendation I of this report. Consistent with Lesson 5, representation from all sectors and known stakeholders would also be important.

With any advisory group, advice needs to be given in a constructive manner and the recipient needs to be open to the message. As noted in Chapter 1, one of the key challenges facing the NWS is keeping pace with rapid changes in technology, user needs, and the overall enterprise context. For organizations such as government agencies, which lack the employee turnover common in the private sector, advisory groups can be an important mechanism for keeping pace and infusing new perspectives in these areas. Among other things, the Committee thinks it is important to take advantage of both majority and dissenting perspectives from advisory groups so as to understand the full range of issues and opportunities.

3

Evaluate Function and Structure

Functional and structural agility is important for the NWS. Agility enables efficient response to the evolving technological, economic, and policy environment so that the NWS can better meet user needs. Although the MAR improved NWS agility, further evolution has been limited and there is substantial room for improvement. A more flexible staffing structure does not need to be viewed as a threat to staff or the National Weather Service Employees Organization (NWSEO). Given the substantial increase in skill and responsibility envisioned in the *Weather-Ready Nation Roadmap* (NWS, 2012), it follows that the NWS might well explore ways to better instill agility in its workforce. In the future, the workforce will need an increased capability to interact with third-party providers of weather information with the goal of raising general weather awareness and improving the communication of specific weather threats.

The broad vision of the *Weather-Ready Nation* paradigm means that a thorough and objective look at the structure of the NWS is appropriate. This chapter presents ways the NWS, through an examination of the scientific and technical aspects of its structure and through workforce training, might increase its agility to face the challenges of the future. In 2012, Congress requested an additional study to examine NWS operations.[1] This chapter discusses possible realignment of NWS offices in more detail than in Chapter 1, but the Committee did not have the charge or the expertise to provide a recommendation about restructuring. Rather, several possibilities are outlined, realizing that the follow-on study requested by Congress may come up with different possibilities. This chapter provides details and sub-recommendations in support of Recommendation II. Recommendation II and its sub-recommendations are intended to inform the follow-on operations study.

Recommendation II: Evaluate Function and Structure

In light of evolving technology, and because the work of the National Weather Service (NWS) has major science and technology components, the NWS should evaluate its function and structure, seeking areas for improvement. Any examination of potential changes in the function and organizational structure of the NWS requires significant technical input and expertise, and should include metrics to evaluate the process of structural evolution. Such an examination would include individual NWS field offices, regional

[1] "NOAA shall enter into a contract with an independent organization with experience in assessing Federal agencies for the purposes of evaluating efficiencies that can be made to NWS operations. This review shall include consultations with emergency managers and other user groups as well as NWS employees. Any recommended efficiencies should not result in any degradation of service to the communities served by local forecast offices and River Forecast Centers, nor should such recommendations place the safety of the public at greater risk. This review shall not be undertaken until the National Academy of Sciences completes its review of the NWS modernization, which will include recommendations on the NWS workforce and composition and how NWS can improve current partnerships with Federal and non-Federal partners and incorporate new technologies for improved services. The findings and recommendations of the National Academy of Sciences review should inform this new independent assessment" (U.S. Congress, 2012).

and national headquarters and management, as well as the National Centers and the weather-related parts of the National Oceanic and Atmospheric Administration (NOAA) such as the National Environmental Satellite, Data, and Information Service (NESDIS) and the Office of Oceanic and Atmospheric Research (OAR).

POSSIBLE REALIGNMENT OF OFFICES

The NWS field office structure established during the MAR was designed to provide more nearly uniform coverage of service across the contiguous United States. In the broad sense, that goal has been accomplished reasonably well. Uniform service does not necessarily require uniform geographical office coverage. It does require, as much as is scientifically and technically possible, uniformity of data and information as input to and verification (for future improvement) of forecast services. For example, the spatial resolution of the NEXRAD radar beam degrades linearly with increasing distance, and the height above the ground covered by the lowest scan increases at an even faster rate. For information (other than remotely sensed data) about the situation in the more distant areas, the forecasters rely on data from ASOS-type automated sensors and reports communicated from persons in the area. Under those conditions the actual distance of the forecaster from the area being served becomes immaterial.

The NEXRAD radars are situated away from major population centers to avoid such things as beam occultation by tall buildings and the copious urban radio frequency interference (RFI) environment. At the time the MAR was planned, the costs of wideband communications dictated that the WFOs should be located at or near the NEXRAD sites. In some cases, this meant moving away from the previous Weather Service Forecast Office (WSFO) location within such a population center, with concomitant diminishing of the ease of communicating with emergency managers and other key responders in that center.

The burgeoning capability now available for low-cost wideband communications relaxes the constraint for proximate location of a WFO and NEXRAD. That makes it possible to consider some further realignment of the WFO structure. For example, in view of the increasing importance of linkages to, and communication with, key segments of local populations, it might be advantageous to relocate some WFOs to sites more convenient to the major centers being served. In doing so, provision would be needed to avoid single-point-of-failure configurations such as that which impacted the Huntsville area during the April 2011 tornado event (NWS, 2011a). Other potential benefits of office relocation include the opportunity to locate offices in hardened facilities[2] and to pay rent to avoid capital costs associated with maintenance.

Furthermore, regionalization of some functions might enhance the overall NWS capability to provide critically needed services to its customers. This regionalization could take any one of a myriad of different possible forms and need not be established in the same way across the entire country. Although not endorsing any particular strategy, the Committee has identified some plausible courses of action regarding the future functions and related structure of the NWS. These include business as usual, optimized collocation, and regionalization of selected NWS functions.

Business as Usual

The current post-MAR structure of the NWS could be maintained going forward. The most obvious advantage, of course, is continuity. The 122 WFOs could keep their slate of responsibilities covering many fronts. Little or no immediate cost would be involved.

However, the *Weather-Ready Nation Roadmap* as set forth by the NWS expects the local staff at each office to expand their skill set, duties, and responsibilities well beyond basic weather forecasting and warning functions (NWS, 2012). It will be challenging for forecasters and related staff to take on such varied tasks, with or without the help of the newly created emergency response specialists (ERSs) that are dispatched to areas where high-impact weather events are occurring or expected.

As it stands now, staffing at the WFOs generally maintains two meteorologists on duty for each shift. Out of the 16 man-hours, 4 to 8 hours a day are invested in generating the public or "zone" forecasts. This includes time for data and model analysis and interpretation, ingesting and modifying gridded data

[2] A "hardened facility" is one that can withstand natural or man-made disasters, including acts of terrorism.

into workstations, running the appropriate programs to produce the forecasts, and post-editing forecasts before they are issued. One forecaster is generally responsible for this process. A second forecaster is responsible for aviation, fire, and other short-term products (Molleda, R., NWS Miami WFO, personal communication to member of the Committee).

Keeping in mind that—as reported in this Committee's first report—the WFOs are "staffed for fair weather" (NRC, 2012a), any severe weather or flood threats require careful planning by local management to ensure that there is enough staff to adequately issue life-saving advisories and warnings without compromising the issuance of the routine forecast products. If a weather event "blows up" beyond expectations or occurs unexpectedly, the WFO meteorologists on shift can end up being spread too thin (Proenza, 2011). Maintaining the current functional structure of the NWS will require continued vigilance to avoid these situations. Because there is a need for field office meteorologists to invest appropriate time in analyzing local weather patterns, there needs to be flexibility in the system to enable other resources, either in the same or other offices to assist in these tasks. This will be needed to address the increasingly complex impact-weather support tasks required under *Weather-Ready Nation*.

Optimized Collocation

The post-MAR locations of WFOs are largely based on proximity to their respective NEXRAD radar. This has led to some forecast offices not being optimally located within their community. Instead of being located in a population center close to key partners such as broadcast media and emergency managers, WFOs are often located outside major population centers.

Under this scenario, the NWS could reconsider the location of its WFOs. For example, many WFOs could simply be moved closer to the primary community within their area of responsibility. Depending on the community, new locations could be chosen for their proximity to broadcast media markets or emergency management facilities. Such a restructuring would also allow the NWS to achieve the benefits of collocation. The Committee's first report (NRC, 2012a) discussed the advantages of collocating a WFO within university or research facilities, and such collocation could aid in R2O/O2R. Other options for collocation include local emergency management facilities (e.g., the Houston/Galveston WFO) or other key partners. In addition to collocation of WFOs, other parts of the NWS could benefit from collocation. For example, NOAA could consider collocating relevant ESRL research units with NCEP in the National Center for Weather and Climate Prediction to improve the transition of R2O in numerical weather prediction.

Regionalization of Selected NWS Functions

Under the recently proposed *Weather-Ready Nation* paradigm, the NWS expects its professional staff at both the local and the regional level to be able to provide critical decision support before, during, and after a wide variety of potential weather and weather-related high-impact events (NWS, 2012). Although traditionally the emergency management community and local broadcast media outlets have been the only direct beneficiaries of this office-to-office linkage or professional-to-professional contact, now the spectrum of potential partners or users of this critically important hydrometeorological support has widened. The list of field office staff duties—ranging from the lead forecasters to the supporting hydrometeorological technicians—now includes many tasks that were not considered part of the workday prior to *Weather-Ready Nation* (NWS, 2012). This is particularly true in times of impending severe weather.

Several NWS Service Assessments have described how it is often only through careful planning by local managers and the assigning of overtime shifts that the NWS can provide adequate life- and property-saving weather-warning services to their area of responsibility (NRC, 2012a). As such, unexpected but potentially dangerous weather events can suddenly arise and overwhelm the staff on duty. In addition, the skill set of the meteorologists, hydrologists, management, and supporting staff has had to expand. Incremental and continual training is required so that staff learns new techniques or augments its knowledge and skills.

A significant percentage of the man-hours on each work shift at the NWS field offices is spent by staff studying observational and remote sensing data, analyzing the synoptic weather scenario, and comparing NWP models from varied sources, all in an effort to come up with a forecast for the local area of responsibility. While in the past this forecasting task could arguably only be completed in situ, rapid technological changes—not the least of which is the expanding utility of the internet—allow for meteorologists to prepare forecasts for locations hundreds or thousands of miles away. Regardless of where a forecast is written, it is generally or greatly based on the output from NWP models. Model output serves as a basis for nearly all weather forecasts accessed by the public over the NWS web pages. As part of the forecast process, the meteorologists at the field offices use the AWIPS workstations to view a map of their area of responsibility with forecasted values derived directly from NWP output. The forecaster may or may not adjust the forecast based on his or her expertise and experience. The final product—gridded forecast data—then serves as the basis from which the public can retrieve a forecast by choosing a zip code, city name, or point on a map. Local knowledge of phenomena, terrain, and infrastructure is an important factor in forecasting, and it needs to be accounted for in any potential regionalization of functions.

An in-depth statistical analysis of the relative comparison of the local product to the NWP-produced guidance will be necessary before the NWS considers moving some or all of this public forecasting task to regional centers, freeing up the meteorologists (up to 8 man-hours a day) at the field offices to be able to focus on high-impact weather event warning, coordination, communication, and enhanced support for its core partners, the additional responsibilities proposed by the *Weather-Ready Nation Roadmap* (NWS, 2012). The responsibility for hazardous weather outlooks, advisories, and warnings would still reside at the local offices (as deployed today to coincide with NEXRAD Doppler radar coverage) in coordination with forecasters at the regional forecast centers. Field office meteorologists would still be responsible for aviation and marine weather forecasts. In evaluating its function and structure, the NWS will need to consider how much involvement in day-to-day fair weather forecasting is necessary to fulfill its mission to protect life and property during severe weather. Such a consideration would include a statistical analysis of the added value of the human element in day-to-day fair weather forecasting, as well as the value of experience in such forecasting in improving severe weather forecast skill.

The most important benefit from the regionalization of the public weather forecast task is to diminish the chances of the local staff being overwhelmed during severe weather outbreaks. The extra time at the local offices can be invested in the increasingly important role of coordinating and communicating impact-weather decision support. More time would also be available for training. Keeping in mind Lesson 4 from the Committee's first report, the NWS would need to engage the members of its workforce whose career would be affected by any change in the NWS structure and to consider the financial and social effects of relocation on personnel.

Meanwhile, the public's access to a quality forecast cannot be compromised. While there may be local weather pattern nuances for each city or county, it is reasonable to think that a team of forecasters with the tools that the NWS provides, including increased NWP accuracy and associated statistical guidance, would easily be able to produce a forecast that is just as accurate as one produced locally. This is already common practice in the private sector, which is often under pressure to produce a very exact and highly tailored forecast based on clients' requests.

The reader is reminded that these three possible modes of office realignment are advanced purely for illustrative purposes, and the Committee does not endorse any one of them. Indeed there may be other appropriate forms of restructuring.

River Forecast Center Workflow

In addition to examining its overall structure, the NWS might also do well to examine the workflow at its RFCs. As identified in this Committee's first report, one of the core services NWS hydrologists provide is the quality control and integration of critical hydrometeorological data (NRC, 2012a). RFC staff often spends an inordinate amount of time performing manual, subjective quality control of hydrometeorological data and excessive time in developing and populating relational databases to attribute such data prior to forecast activities. Although this activity can have a beneficial impact on hydrologic forecasts in some areas, it implies that major workflow issues center around the development of quantitative precipitation estimate (QPE) and quantitative precipitation forecast (QPF) products for use in streamflow forecasting activities, thus limiting time for other necessary activities. Poorly maintained precipitation and streamflow measurement stations, loss of stations, out-of-date measurement technology, and poor or untimely communication of station data all serve to increase forecast uncertainty and consume valuable RFC hydrologist labor time to either reject problem data or render such observations useful. Frequently, suspect observations are manually adjusted or "tuned" to achieve desired streamflow model results. While this approach offers some flexibility in forecasting efforts, it presents logical complexities in model performance assessment and potentially limits opportunities for sustained improvement in model prediction skill.

Furthermore, continued investment of labor to tedious and somewhat subjective quality control and attribution efforts reduces the amount of time service hydrologists can spend on forecast innovation and forecast product development efforts. More accurate, more reliable, more cost-effective technology exists for collecting and quality-controlling hydrometeorological observations but will require capital investment and training to implement as was noted in Chapter 2. As such, elements of NWS hydrologist workflow are intimately intertwined with NWS surface observing network deficiencies and these issues need to be resolved in tandem.

Generally, NWS hydrologic forecasters are characterized as being extensively "in-the-forecast-loop," (i.e., in-the-loop), meaning that numerous hands-on, subjective, often time-consuming tasks are required in order to generate basic forecast products. As discussed above, this is particularly true for data quality control and attribution tasks, but it is also true for other forecast workflows, including hydrologic prediction model state and parameter adjustment, database querying, and model execution. The problem is that many of the same issues could be addressed through the adoption of more objective, automated data assimilation and ensemble generation techniques that have been developed and validated in the hydrologic research community, including OHD, over the past 20 years. Furthermore, copious manual, subjective manipulation of forecasting workflows likely results in excessive forecaster-to-forecaster forecast quality variance either within or between RFCs. Placing the hydrologic forecaster "over-the-loop," as opposed to "in-the-loop," would shift forecaster duties to general forecast job management, model data assimilation, uncertainty quantification, forecast interpretation, product development, and forecast communication. In essence, time saved from laborious subjective data quality control and attribution tasks needs to be reallocated to continual quantitative, objective system assessment, forecast production, and communication and model R&D.

Learning from the Past

Since the April 1957 tornadoes in Dallas, Texas, the NWS has been conducting internal evaluation of its performance after significant hydrometeorological, oceanographic, or geological events that result in fatalities. The current NWS Service Assessment guidelines allow for initiation of a team of reviewers when one or more of the following criteria are met: "Major economic impact on a large area or population, multiple fatalities or numerous serious injuries, extensive national public interest or media coverage, or an unusual level of attention to NWS performance." In the 55 years since the first National Disaster Survey Report, the NWS has authored almost 150 assessments across tornado, hurricane, flood, winter storm, wildfire, and tsunami events. In each instance, the assessment is led by an internal NWS team working with other NWS employees and an occasional external scientist working as a subject matter content consultant. A thorough review of these documents and the recommendations made in them suggests that the NWS has been lax in implementing changes or unable for a variety of reasons to respond to changes that have been recommended throughout the years. In one specific example, recommendations directed at improving the communication of warnings to stakeholders (i.e., emergency managers) have been repeated in recommendations in Service Assessments for the past four decades. Increased attention and an effective management chain for implementing the recommendations and monitoring the agency's performance in responding to these Service Assessments would lead to greater agility within the NWS.

To better understand and improve the performance of forecasts and warnings, assessments of significant false alarm events, those that result in substantial public and emergency management action, also need to be carried out. The current system of assessments, which focuses only on performance after significant events, may have created a perverse incentive to over-forecast events, leading to a large and increasing number of false alarms. Indeed, for flash floods the false alarm ratio has doubled over the past ten years, while for tornadoes the false alarm ratio has failed to decline since 1985, staying constant at around 80 percent (NRC, 2012a). False alarms may result in a decrease in confidence in official warning sources (Dow and Cutter, 1998), although the likelihood of people responding to a warning is less likely to be reduced if the reasons for the false alarm are understood and explained (Atwood and Major, 1998; Sorensen, 2000).

For a better understanding of fatalities during hazardous weather events, assessments need to go beyond forecasts and warnings to also include sirens and other alerts and ultimately address decisions made by the public during warning situations. Many elements are beyond the direct control of the NWS. For example, emergency managers, broadcast media, and newer social media subscription services all create and enhance information that eventually reaches the public during a hazardous hydrometeorological, oceanographic, or geological event. Assessing the performance in the chain of events through all these elements requires a broader view of performance assessment. Composing assessment teams with memberships that include additional stakeholders beyond NOAA would bring a broader set of expertise and perspective to these reports. This, in turn, would spread understanding and insights to the wider enterprise. Moreover, having an independent entity conduct these evaluations could help to maintain the broad perspective and participation.

Recommendation II.a

The National Weather Service (NWS) should broaden the scope of the system for evaluating its forecasts and warnings to include false alarms that result in substantial public and/or emergency management response as well as significant hydrometeorological, oceanographic, or geological events. It should consider whether having an independent entity conduct all post-event evaluations of performance after false alarms and significant events would be more effective. These evaluations should address the full scope of response issues, from forecasts and warnings, to communication and public response and be conducted by an appropriate mix of individuals from within and outside the NWS. They should also include instances of relative success (minimal or no loss of life) to learn valuable lessons from these episodes as well.

WORKFORCE TRAINING

Any organization that possesses a significant service component as part of its core mission is intimately dependent on the capabilities and continued training of its workforce. This fact is particularly relevant for scientific and technical enterprises such as the NWS. A series of major workforce evolutions were undertaken as part of the MAR, and this Committee found that the process of evolving the workforce was highly successful by many measures (NRC, 2012a). To support the recommendations in this report and the objectives laid out in the *Weather-Ready Nation Roadmap* (NWS, 2012) the workforce will again require a significant upgrade in skills and training.

The proposed *Weather-Ready Nation* paradigm includes a host of new skills that will be required for proper execution of new forecaster duties, particularly with regard to interactions with key stakeholders, decision makers, and third-party service providers. The proposed emphasis in improving core capabilities of the NWS, as articulated in Chapter 2, will also place new demands on NWS staff at function levels ranging from the WFOs to the national centers and on to management. For example, there will be a growing need for scientists with multidisciplinary expertise at the national centers as environmental models are coupled and advanced.

Based on the objectives laid out in the *Weather-Ready Nation Roadmap* (NWS, 2012) and in other sections of this report, it is evident that skill requirements for NWS staff will accelerate in both breadth and depth of subject matter. The type and volume of new foundational datasets to be created by the NWS of the future will quickly overwhelm staff with only basic or "classical" meteorological training. This is particularly true with respect to the interpretation and use of probabilistic data assimilation and prediction datasets, but it also applies to basic observational data that are created from new observing platforms such as polarimetric and phased-array radar or hyper-spectral satellite imagery. The forecaster of the future will need to increasingly rely upon, but still understand, automated and objectively created data and forecast products and their error estimates and will need to largely disengage from manual, rote subjective manipulation. The forecaster will increasingly work to integrate and interpret foundational datasets in the execution of essential functions such as the issuance of watches, warnings, advisories, and guidance. Not only will the depth of knowledge required extend beyond traditional meteorological training, the breadth of skill sets required will as well. These subject matters include but are not solely exclusive to meteorology, hydrology, information technology (IT), and risk management.

The Committee notes that the *Weather-Ready Nation Roadmap* proposes to expand workforce skills primarily by selective retraining (NWS, 2012). The Committee finds that the required depth and breadth of new skills can only partially be obtained by retraining, and forecasters and other personnel with new skills will need to be hired. It is possible that a restructuring along the lines of the options discussed earlier in this chapter could open up positions for new hiring. When approaching new hiring, the NWS would be wise to consider ways in which multidisciplinary teams could achieve the required breadth of skills and expertise set out in the *Weather-Ready Nation Roadmap*. This would allow individuals on the team to possess the necessary depth of skills in their respective disciplines.

In many ways, staff at the WFO, regional center, and NCEP laboratory has already begun transitions, but it is apparent to the Committee that the pace of scientific and technological change is outpacing the evolution of the workforce. As such, the following recommendations on accelerating the breadth and depth of the workforce are offered.

Recommendation II.b

Because it is impractical to expect each individual at the Weather Forecast Office level to possess all of the requisite skills to capitalize on the quantity and quality of new foundational data being produced, the National Weather Service (NWS) management should consider expanding its vision of team structures and functions within individual offices and between local offices and regional offices and national centers.

Basic educational degree requirements are necessary but insufficient for building a highly efficient and agile workforce that can meet the requirements put forth in the *Weather-Ready Nation Roadmap*. The skill sets that will be required to accelerate foundational dataset creation as well as their effective interpretation and use at the forecast office/center level frequently exceed the basic curricula requirements of existing undergraduate programs. Many topical areas require advanced study either in graduate programs or in continuing education training modules. This is not only for meteorological disciplines but also for non-meteorological disciplines in which forecasters of the future will be required to work.

Recommendation II.c

To create a workforce that is fully able to utilize improved core capabilities and optimally serve the public, the National Weather Service (NWS) should develop performance metrics-based approaches to assessing staff skill sets to identify areas where enhanced capabilities are needed. The NWS should involve the entire enterprise in working with the academic and research communities to design new curricula to address pre-employment and during-employment education and training needs. The NWS should also work with the American Meteorological Society to update and expand the credential criteria to reflect the future educational needs of NWS personnel. The National Weather Service Employee Organization should be engaged as early as possible in the development of both performance-based metrics and improved curricula.

As discussed in Chapter 2, operationally related research is a key aspect of NWS core capabilities. A highly agile and efficient workforce requires the capability to integrate proven research findings into operations (R2O) and translate operational experience into tractable research questions and needs (O2R). Fostering this capability is difficult because it requires cultural flexibility in staff to function in both operational and research environments, and it requires staff to be literate and up to date on research issues. Similarly, it requires research entities—at national centers, in academia, or in other enterprise partners—to be literate regarding operational protocols and aware of operational demands. Such capabilities presently exist in some parts of the NWS, but those attributes are not widely distributed throughout all centers and all offices and therefore inhibit R2O and O2R activities. In addition, more generally, this reduces the overall agility of the NWS. Existing capabilities for external research collaboration need to be extended and include designated forecast staff in the WFOs and at NCEP.

The breadth and rapid acceleration of weather, water, and climate enterprise activities is resulting in the development of new weather- and water-related products and services. Although many of these products and services are developed within the NWS, many are not. At times many of these products and services may be able to contribute significant benefit to NWS services and, equivalently, many NWS products and services may be able to significantly enhance partner activities. To optimize the generation and flow of information throughout the entire enterprise, the NWS will need to develop a culture of collaboration and, where appropriate, leveraging. The Committee recognizes the complexity of this issue; thus, broader interactions between the NWS and the entire enterprise are discussed in Chapter 4.

This Committee's first report recognized that effective leadership can play an instrumental role in motivating and affecting change in the workforce (NRC, 2012a). However, the process for instituting change cannot only be top-down. Open and functional communication mechanisms are required to facilitate constructive dialogue as well as the bottom-up communication of needs and opportunities.

Hydrologic Workforce Training

An ongoing, challenging legacy of the MAR is that the qualifications for hydrologist positions were not updated to require degreed hydrologists. Negative consequences of this staffing challenge include limitations in the capability of RFCs to calibrate and improve their hydrologic models, and delays in integrating new observational or analytical technologies into the hydrologic forecasting workflow or to rapidly adopting new hydrologic modeling techniques such as ensemble prediction and data assimilation. This issue was noted in a mid-MAR review of hydrometeorologic operations (NRC, 1996) and remains an issue today. 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).

The lack of capacity to efficiently experiment with and innovate science-based hydrologic forecasting techniques, coupled with an overly regimented workflow that emphasizes hands-on, subjective processing of foundational data, suggests that NWS hydrologic prediction technology is potentially becoming out of date and, perhaps most importantly, does not possess an immediate capability to evolve.

Calibration of NWS-hydrology forecast models remains a fundamental issue in NWS hydrologic prediction services. Presently, most of these activities are largely contracted out to a long-standing private consulting firm. This is not to say that the procedures used are deficient or suboptimal from a model calibration perspective and the NWS-developed guidelines for how this work is to be executed. The trade-off is that RFC staff, particularly new staff, has fewer opportunities to develop deep expertise on model implementation, calibration, or model assessment activities. In essence, the present arrangement of having staff focus on the tedious data quality control work while contracting out core hydrologic model calibration and assessment activities has the potential to unnecessarily inhibit RFC staff from developing core model assessment and calibration skills and therefore limits its capability to innovate improvements in the modeling systems it uses.

Finally, continuous assessment of service hydrologist skill sets appears to be lacking. It is not clear that the present staff possesses the requisite mastery of modern computational model programming skills (e.g., scientific languages, parallel computing architectures), mastery of the construction and use of new "Earth System Models," a current understanding of hydrologic data assimilation methodologies, or command of the preparation and interpretation of meaningful ensemble predictions. A fundamental understanding of how current state-of-the-science hydrologic forecast models are constructed, initialized, and executed is imperative if the forecaster is to assume their position over-the-loop, as recommended earlier in this chapter. For the forecasters to have the opportunities to acquire these skills, there will need to be fundamental changes in the forecast workflow.

Staff training will play an important part in upgrading service hydrologist capacity to implement the necessary changes in prediction technologies. Existing Cooperative Program for Operational Meteorology, Education, and Training (COMET) modules for hydrology are deemed by many to be too narrow and too elementary for the envisioned staff capacity development. While COMET is good for teaching some topical fundamentals, or for some basic cross-training activities for non-subject-matter experts (e.g., teaching hydrology to degreed meteorologists), or for teaching some new standards of practice, the educational needs of service hydrologists today are far deeper. The needs of NWS hydrologists to develop a state-of-the-science evolutionary culture go far beyond those criteria. Consequently, the reeducation of service hydrologist staff, akin to the transition of the meteorological workforce under the MAR, needs to be considered. In the end, RFCs need to be staffed by degreed hydrologists and hydrometeorologists with broad and deep expertise in hydrologic modeling, hydrometeorological processes, and hydrologic data analysis.

Recommendation II.d

The National Weather Service (NWS) service-hydrologist staff requires re-education and continual re-training if NWS hydrologic prediction services are to be able to adopt current state-of-the-science prediction methodologies and instill the evolutionary culture required for optimal hydrologic services.

4

Leverage the Entire Enterprise

The weather, water, and climate enterprise within which the NWS functions is increasingly dynamic. To interact effectively and maximize public benefit from the enterprise, the NWS will need to become more agile in how it cooperates and collaborates. At the start of the MAR, the United States had a small private weather sector that was robust given the business climate and technology at the time. The private sector played an important role in delivering near-real-time data to the broadcasting sector and the portions of the aviation industry not served by the NWS or the Federal Aviation Administration (FAA). Some other private-sector firms focused on a core group of specialty, or niche, clients, such as energy companies and ski resorts. In response to society's demand for more information as well as the business world's realization of the value of tailored weather and water forecasts, warnings, and information, the American commercial weather industry[1] has broadened its spectrum of clients and its capability to provide many of the products and services that were once the exclusive domain of the federal government. The private sector today is involved in many areas, from data acquisition (e.g., National Lightning Detection Network and ground-based weather sensor mesonets) to specialized long-range forecasts for the financial sector (e.g., weather "derivatives").[2]

The overlapping roles of the public, academic, and private sectors in providing weather, water, and climate services can lead to duplication and competition (NRC, 2003a), but it can also provide opportunities for collaboration. Box 4.1 provides examples of successful enterprise partnerships that could serve as models for the future. According to the *Fair Weather* report, "the public is best served when these sectors work together to take advantage of their different capabilities or to avoid duplication of effort" (NRC, 2003a). Together, this combination of the NWS and third parties serves end users in ways that the NWS could not do on its own. So, while the NWS is only one part of the overall weather, water, and climate enterprise, the enterprise as a whole would crumble without the core infrastructure and capabilities the NWS provides.

The Committee notes that the *Weather-Ready Nation Roadmap* (NWS, 2012) reflects a desire for enhanced enterprise relationships, but it provides very few concrete steps for accomplishing that. Instead, the vast majority of the *Roadmap* reflects NWS's traditional direct-to-public perspective on how services are delivered. Indeed, the enterprise partnership efforts are focused on "communication and dissemination"

[1] This element of the enterprise is sometimes referred to as the American Weather Industry, the American Weather and Climate Industry, the commercial weather industry, the private sector, or similar terminology. Specific terminology, such as the American Weather Industry, often refers to that component of the enterprise providing weather, water, and climate services. Another key enterprise element encompasses providers of major infrastructure, such as the aerospace industry and its role in developing weather satellites. A number of companies span both areas. For the purposes of this report, the definition is purposely vague, consistent with the rapidly evolving nature of the enterprise.

[2] As noted in Footnote 7 in Chapter 1, the size of the nonfederal portion of the enterprise is difficult to estimate, but is about $4 to $5 billion and is comparable to the federal portion. NOAA accounts for perhaps two-thirds of the federal portion. The private sector accounts for the majority of the nonfederal portion.

BOX 4.1
Examples of Successful Partnerships in the Weather, Water, and Climate Enterprise

Integrated Warning Team Workshops

Since 2008 the National Weather Service has taken the lead on Integrated Warning Team Workshops to bring together emergency managers, broadcast meteorologists, and NWS forecasters to improve the coordination and effectiveness of weather information and dissemination. These regional meetings, considered a spin-off of the NWS-funded WAS*IS (Weather and Society * Integrated Studies) program, have been held in Springfield, MO; Kansas City, MO (4); Pittsburgh, PA; Cedar Rapids, IA; Indianapolis, IN; Detroit, MI; Miami, FL; Grand Forks, ND; Minneapolis, MN; and Colorado Springs, CO. These workshops have had many benefits. The partners build sustained relationships and learn about the decision-making contexts during severe weather and flood events.

The four Kansas City meetings have led to many communication and operations improvements that reflect a growing emphasis on impacts-based forecasting. Two are noted here:

- The broadcast meteorologists recognized that they were not providing a consistent message to all viewers. After the workshop and a conference call the competitors arrived at a consensus on a color scheme for representing tornado and severe thunderstorm warnings. As a result, when viewers change from one television channel to another, rather than having to interpret different colors for the same warnings from station to station, they now see consistent information across the channel spectrum.
- As a result of the first Integrated Warning Team workshop held in Kansas City, MO, in 2009, the NWS now provides hail and wind tags (special coding) showing the magnitude of the threat of strong straight-line winds and the expected hail sizes so broadcasters and others can easily tailor their own messages based on the best and most local information. This has been implemented across the Central Region forecast offices. This methodology has been expanded for use in tornado warnings with the Impact Based Warning Experiment, currently under way at 5 WFOs in Missouri and Kansas. These new tornado tags provide key partners and customers with impact magnitude and source information previously unavailable in tornado warnings. These tags had their roots in the initial Integrated Warning Team work lead by the Kansas City/Pleasant Hill WFO in Missouri.

Incident Meteorologists Help Fight Wildfires

Incident meteorologists (IMETs) are National Weather Service forecasters specially trained to work with Incident Management Teams and are deployed to severe wildfire outbreaks. They travel quickly to the incident site and set up a mobile weather center to provide continuous meteorological support for the duration of the incident. The mobile weather centers include a cell phone, a laptop computer, and a two-way portable satellite dish for gathering and displaying weather data including satellite imagery and numerical weather prediction output.

IMET duties include briefing firefighters. They have an understanding of the needs of fire managers and use their understanding of meteorology to communicate the relevant information to meet those needs. IMETs help fire control specialists from federal, state, and local agencies by interpreting weather information, assessing its impact on the fire, and helping develop strategies to best fight the fires and keep firefighters and the vulnerable public safe.

The NWS contributions to fighting Spring 2012 wildfires have been recognized by the Fish and Wildlife Service (from a letter from Troy L. Davis, District Fire Management Officer):

> "The . . . fire we just attacked this past week was burning under extreme weather conditions of very low humidity and high winds in the middle of the night and early morning. A spot forecast was requested and promptly produced by this weather office. Shortly after the spot forecast was produced a change in the jet stream caused wind gusts up to 63 mph that was heading towards the fire. The forecaster at the weather office

of NWS-generated information. As noted previously, a substantial portion of weather, water, and climate information no longer comes directly from the NWS to the public and businesses but is enhanced along the way. Moving forward, more concrete steps for directly leveraging the broader enterprise beyond "communications and dissemination" will be needed as part of explicit NWS planning, including the expected update to the *Weather-Ready Nation Roadmap* (NWS, 2012).

This chapter provides details and sub-recommendations in support of Recommendation III.

Recommendation III: Leverage the Entire Enterprise

The National Weather Service (NWS) should broaden collaboration and cooperation with other parts of the weather, water, and climate enterprise. The greatest national good is achieved when all parts of the

promptly notified me of this new development by a direct phone call so I was able to notify all fire personnel on scene in a very timely manner. All personnel was prepared and expecting this new development. Time was passing as we were attacking this fire and from when we received the original spot forecast and new development phone call. I then received a second phone call from this weather office to inform me that they had produced an updated spot forecast as conditions were changing and new developments in the storm system warranted changes to the original spot. This is twice that this weather office took the initiative to warn us of the changing conditions to keep our fire personnel safe."

NWS Chat

NWSChat has become an effective collaborative tool between the NWS and its core partners in emergency management, media, and other government agencies. The online chat rooms have opened up opportunities to coordinate and collaborate like never before. For example, an NWS forecaster can relay critically relevant information in quick and informal fashion during a severe weather threat so as to alert the partners to important changes:

[8:24 PM] <NWS> Our sounding just came in and it is eye-opening and we have high concern for tornadoes this evening. We are not in a typical South FL environment. This is more like plains type helicity/instability. Strong tornadoes could occur. Just a heads up that this is not our typical scenario and all need to pay attention to this as this unfolds.

Then as an event unfolds, the NWS can provide advance notice of upcoming warnings, and benefit from media or emergency management relaying event information as they unfold. All warnings and statements are transmitted automatically. Forecasters will not be distracted from issuing warnings and statements, but as time permits, radar trends as well as Q&A sessions may cross the chat room.

[9:27 PM] <media> Okay, will relay chaser reports if we get them, have someone on the storm.
[9:43 PM] <NWS> New tornado warning being issued for Miami-Dade & Broward counties . . . coming out shortly.
[9:59 PM] <media> Reports of multiple power flashes near Silver Lakes area about 5 minutes ago from our chaser.
[10:10 PM] <NWS> Small & tight circulation noted near Sawgrass Mills Mall . . . new TOR [tornado warning] will likely be needed.
[10:20 PM] <NWS> TOR warning will be canceled, the tight circulation once seen on the Terminal Doppler at FLL [Ft. Lauderdale International Airport] has significantly decreased—with only remnant elevated circulation.
[10:25:08] <media> Hey guys. We are getting calls into our newsroom of a house collapse in Sunrise with a man trapped inside. Has anyone else heard about this? We are sending a crew to try to confirm. The subdivision is near the mall. I am trying to get a name.
[10:26:09] <media> Silver Palms community near the mall. Multiple roofs off homes. That is the latest call.
[10:47 PM]<NWS> According to Palm Beach post report . . . Sunrise PD [police department] reported one or two homes damaged on 13300 block of NW 8 Ct in Sunrise. That's S of Sawgrass Mills Mall.

Participation by NWS employees is not guaranteed, but the chat is always available to others, and warnings and statements will be displayed automatically. During recent major weather disasters, NWS Service Assessments have cited NWSChat as having been crucial to providing valuable information that enabled timely and accurate decisions at the local level (NWS, 2011b).

All content is archived and is subject to the Federal Freedom of Information Act.

enterprise function optimally to serve the public and businesses. This process starts with the quality of core NWS capabilities but is realized through the effectiveness of NWS-enterprise relationships. A well-formulated enterprise strategy will also return direct benefit from the enterprise to the NWS, especially in areas of shared research, technology development, observational data sources, and improved end-user access to NWS-generated information.

THE OPPORTUNITY AND GOAL

Over the last two decades, the non-NWS weather, water, and climate enterprise has grown rapidly. The NWS has evolved to both promote and benefit from the rest of the enterprise. The recommendations of the *Fair Weather* report, along with a 2004 revised NWS public-partnership policy, contributed substantially to progress in this area (NRC, 2003a; NWS, 2004). Not

BOX 4.2
Chain of Events Associated with a Tornado Warning

The sequence of events associated with the public receiving and acting on an NWS tornado warning involves many elements of the enterprise interacting to minimize loss of life and property. The first steps of the sequence involve meteorology and technology. The final steps involve sociology and psychology. Key to a good outcome (in addition to luck) is a coordinated situation in which good forecasts, warnings, and response all happen together. The sequence of events includes

- The continuous acquisition of data and the production of weather analyses and forecasts on the global, hemispheric, and national scales provide a constantly evolving, general picture of the atmosphere.
- Convective outlooks a few days in advance of a tornadic storm are originated by NWS forecasters in the Storm Prediction Center and lead to tornado watches.
- WFO forecasters use radar and spotter reports to detect tornados and issue warnings that are broadcast over NOAA Weather Radio, NWSChat, and elsewhere.
- Emergency managers use warnings, their own radar displays, their spotters, and other information to issue alerts in the form of sirens, emergency broadcast systems, and teleconferences with various local officials and the NWS.
- In many cases, local television stations and other media sources, including social media sites and emergency notification phone and text message systems, pass on warnings and other information to alert the public to take cover and stay tuned to television or radio for further instructions.
- For people who do learn about the warnings, they need to believe them, personalize them, decide to take an action, and take appropriate actions in the time before the severe weather arrives. School superintendents, airlines, various types of businesses, people in cars, homes, and out in the fields all respond (or don't respond) in different ways, depending on their knowledge of what to do and their various assessments of the degree of risk to them and their ability to respond. It is worth noting that some warnings never reach some people, and that there is a public responsibility to reduce the likelihood of these failures.

only has competitive overlap been reduced[3]; the NWS now looks to the broader enterprise as a set of key partners for both creating and distributing weather and water services (Box 4.2).

NOAA's Partnership Policy is to "foster the growth of this complex and diverse enterprise as a whole to serve the public interest and the Nation's economy" (NOAA, 2007). Given the desire of the NWS to improve its effectiveness (NWS, 2012), the ability to further leverage the rest of the enterprise is very appealing. Facilitating a significantly richer and deeper engagement of the nation's broad and diverse weather, water, and climate enterprise with the NWS, its data services, and its technology development could yield a greater return on the public's investment. This reinforces, however, the need for the enterprise to support the maintenance of the collective infrastructure that all depend upon.

In the face of government budget pressures, it is conceivable that the non-NWS elements will provide most of the overall enterprise growth over the next decade. Public and private sectors will likely face different economic pressures in the near future. Non-NWS enterprise elements may have resources to expand capabilities and services when the NWS has none. One consequence of a growing enterprise external to the NWS is that the resource leverage available to the NWS will grow commensurately. This resource leverage represents critical capability that can be used by the NWS in accomplishing its mission—leverage that can allow the impact of the NWS on the nation to grow faster than its budget alone would allow. The Committee believes that a key aspect of NWS's strategy for the coming decade could well be to enhance this leverage.

Elements of this non-NWS enterprise growth are evident. The public now receives a substantial portion of their weather information through digital media channels. These include general web portals (e.g., Bing, Google, Yahoo), weather-specific portals (e.g., Accuweather.com, Weather.com, Weather Underground), mobile applications installed as defaults

[3] Competitive overlap has been reduced though not fully eliminated. One emerging area of known conflict is what role the NWS should play in developing and distributing mobile applications. As new technologies emerge, such conflicts will continue to arise and will need to be resolved.

(such as on the Android, iPhone, and Windows phone platforms), third-party weather applications (of which the iPhone App Store lists over 1,600 and the Android Market lists over 5,000 as of July 2012), Twitter feeds, social networking sites, and more. Innovation in this arena is accelerating. For example, accurate localized road weather conditions will likely be delivered in real time to automobile dashboards within the next decade. It is appropriate for the NWS to make more effective use of such channels for reaching the public directly when authoritative sources are critical to public welfare. But there is also a tremendous opportunity for the NWS to better serve the public by improving the capability of other organizations—those with expertise in use of these channels—to provide weather-based information and services to businesses and the public.

Compared to the time of the MAR, the non-NWS enterprise is more capable and diverse. Perhaps most importantly, it is increasingly robust in areas where the NWS may seek a partner. In many areas, there are now multiple suppliers having long track records of reliable performance. When the NWS chooses to place elements of its mission in the hands of partners, the NWS must have confidence that changes in a partner's financial state or business strategy can be dealt with by seeking out alternate providers of comparable quality. One consequence of an increasingly robust enterprise is the globalization of the industry and the growing complexity of business relationships. Companies based in the United States may now have international customers that influence their NWS-focused interactions. Patents and strategic business partners may constrain relationships that the NWS could build. Although such issues are routinely accommodated within many economic sectors, they are to some extent a new factor in NWS-enterprise relationships.

The benefit to the NWS in leveraging the entire enterprise is the payoff in the quality and amount of services provided to the nation. By leveraging the entire enterprise, new capabilities will arise that the NWS could not have provided on its own. Moreover, this can potentially enable the NWS both to increase the quality of its core capabilities and to provide enhanced service to its core partners (NWS, 2012).

The means by which the enterprise creates and delivers information to the public may be referred to as the information value-chain. The NWS has traditionally focused on a portion of the value-chain associated with its core partners. These partners include emergency managers, government agencies with a need for weather, water, and climate information, and electronic and broadcast media. The NWS has developed deep relationships with these partners and works closely with them during periods of severe weather. This portion of the overall information value-chain can be called the primary value-chain.

Today, a substantial amount of the weather, water, and climate information reaching the public arrives through a different part of the information value-chain associated with partners the NWS does not identify as core.[4] This can be referred to as the secondary value-chain.[5] It consists of private-sector companies as well as other governmental and nongovernmental organizations performing functions that complement the primary value-chain. Figure 4.1 illustrates the complementary roles of the primary and secondary value-chains for the specific case of a severe storm threat. The various organizations involved in the secondary value-chain will vary considerably with the particular use case, so this figure represents only a single snapshot to illustrate the concept.

The capability of the secondary value-chain to complement the primary value-chain presents an opportunity for the NWS to better serve the public. In many cases, the secondary value-chain has access to critical information not directly available to the NWS or the primary value-chain. It thus enables decisions and actions complementing those that can be made with support of the primary value-chain. It is important to recognize, however, that the primary value-chain is and should remain the main focus of the NWS. Moreover, all capabilities provided by the secondary value-chain depend on services or data originating in the NWS.

[4] As noted in Chapter 1, the majority of forecasts reaching the public arrive through the secondary value-chain, and the overall enterprise associated with this secondary value-chain is comparable to or larger than the NWS in terms of budgets.

[5] As noted in Chapter 1, the terms "primary value-chain" and "secondary value-chain" are not intended to reflect superiority or inferiority of either chain. Instead "primary" is meant to reflect the mission of the NWS to be the authoritative source of weather, water, and climate information for the nation. The capability of the NWS to reach the public through the primary chain, when an authoritative perspective is required, cannot be compromised. The term "primary" is meant to reflect this critical NWS role.

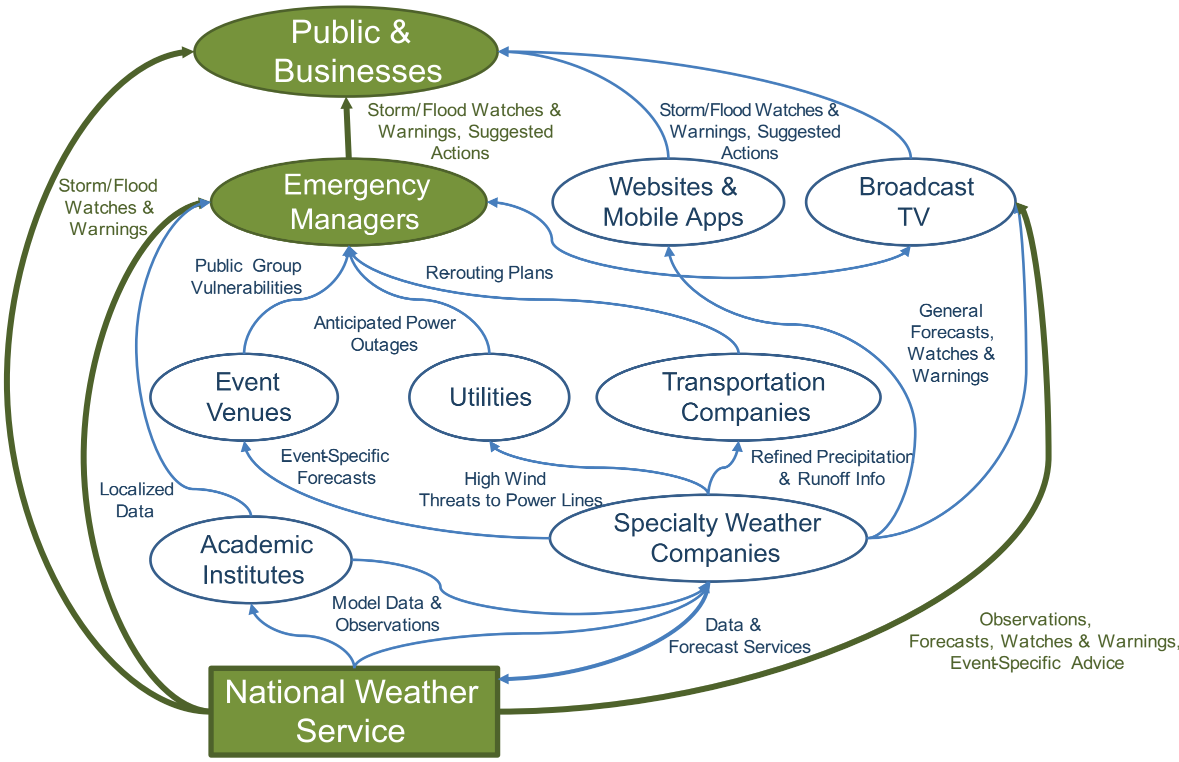

FIGURE 4.1 The hypothetical information value-chain during a period of severe storm threat accompanied by flood potential. The value-chain illustrates how various organizations may create and enhance the information that eventually reaches the public. The solid green paths represent the primary value-chain. The blue dashed-line elements represent the secondary value-chain. The figure does not present a comprehensive view of all activities but rather highlights the less-well-understood role of the secondary value-chain in serving the public. Thus only key elements of the primary value-chain have been shown, whereas the secondary value-chain is described in greater detail.

A growing overall enterprise provides opportunities for the NWS to serve the public in ways not possible on the basis of its budget alone. As stated in Recommendation III, the NWS should explore enhanced cooperation and collaboration with the enterprise. In doing so, the NWS needs to protect its direct public interaction through the primary value-chain, while improving the additional public benefit made possible by the secondary value-chain.

IMPLEMENTING A LEVERAGED ENTERPRISE

The *Fair Weather* report (NRC, 2003a) led to specific changes in NWS's interaction with the overall enterprise that have enhanced the public's access to weather, water, and climate information. This report recommends building on the success of *Fair Weather*. In general, the changes involved reflect a more direct NWS role in achieving public benefit through the secondary value-chain. Although it was beyond the Committee's charge to be prescriptive in defining how a solution should be implemented, there are many different ways change could be accomplished. The NWS will need to implement an approach that best matches its ongoing evolution. A successful approach will likely involve inclusion of the secondary value-chain in NWS planning and perhaps even involve an office designed to work with the entire enterprise. A successful approach will also reflect this report's theme of increased agility. Promising individual elements of an overall implementation approach could be examined relatively quickly as pilot projects or experiments. An effective approach will establish metrics for measuring success. Examples of key elements for successfully leveraging the enterprise include the following.

Improved Understanding of the Secondary Value-Chain and Its Role in Serving the Public

This would include better recognition of enterprise roles that go beyond "communication and dissemination" described in the *Weather-Ready Nation Roadmap* (NWS, 2012), such as how the secondary value-chain enhances information. A simple example is to include the secondary value-chain in post-event evaluations of performance (see Recommendation II.a), something that is not done with current practice. Such an assessment will allow the NWS to begin identifying actions it can take to better serve the public through the secondary value-chain, as well as how the secondary value-chain can more effectively complement the primary value-chain.

Improved Linking of NWS Capabilities to Needs of the Secondary Value-Chain

Based on the improved understanding of needs described above, NWS planning would directly guide better access to existing NWS capabilities and generation of new core capabilities so as to explicitly support the secondary value-chain. This includes foundational datasets as well as the services needed to deliver data. An example is probabilistic forecasting, as discussed in Chapter 2. Another example could be improved seasonal forecast models or integrated environmental services, a topic of high interest in the secondary value-chain and ultimately the public but of less immediate interest specifically to public safety.

Evolution of both technical and organizational capabilities, as discussed in prior sections, will need to reflect an enhanced consideration of secondary value-chain needs. The Committee suggests, however, that implementing changes to the NWS on the basis of value-chain assessment needs to proceed cautiously for the reasons cited in the following section on challenges and risks. The NOAA Science Advisory Board can provide assistance with identifying experiments, trials, testbeds, or pilot projects that accomplish this, as they have done with their *Open Weather and Climate Services* proposal (NSAB, 2011). Cost-benefit analyses will be helpful as well. This need not wait for a deeper understanding of the secondary value-chain within the NWS; the experiments themselves will help develop this understanding. New tools and processes may be needed to implement any changes, and the academic and research sectors can contribute to their development.

More Open Access to NWS Capabilities

A widely discussed means for improved linking of NWS capabilities to the secondary value-chain involves more open access to NWS data and services. The Committee notes that the NOAA Science Advisory Board has recently transmitted to NOAA management a white paper called *Towards Open Weather and Climate Services* (NSAB, 2011). There are still numerous potential issues to be resolved, including access to intellectual property (IP) generated by NWS–private sector cooperation, whether benefits from such collaboration would occur to all private-sector entities, and the joint funding of cooperative projects. However, given the potential for leveraging NWS resources to enhance the performance of its mission, the Committee supports the idea that a number of pilot or experimental projects be undertaken to explore both the benefits and the possible pitfalls. Such experiments will reveal potential conflicts of interest and IP issues, as well as resource issues involved in cooperative work and how to provide fair access to NWS data. For example, issues such as public data rights from private-sector sources represent important and only partly resolved problems. Such pilot projects will reveal how willing the private sector would be to participate equally, rather than just receiving more data. In developing these pilot projects, the NWS and its partners will need to give consideration to how progress in cooperation will be measured. If some of these experiments are successful, they will not only increase the NWS's ability to fulfill its mission but also deepen its understanding of the need for customized weather services.

Improved Value-Chain Alignment

In general, each value-chain could be better executed through improved alignment or collaboration with the other value-chain with the goal of serving national priorities. In some cases, this may involve rethinking of the relative roles of each value-chain.

Expanded IT Infrastructure

As user needs expand through the proliferation of web and mobile applications, NWS IT infrastructure will need to keep pace. This infrastructure is somewhat different when serving the public directly as opposed to serving them indirectly through the secondary value-chain. In the latter case, though transaction volume may be lower, there may be higher expectations for such things as mature interface standards, services security, backward compatibility, reliability, throughput, data archive, cloud-based services, and product validation due to the increased dependence of business revenues on the NWS.

Supportive Organizational Structure

The capability to better support the secondary value-chain and the overall enterprise needs to be included as part of any rethinking of NWS function and structure, as discussed in Chapter 3. It is expected that any expanded support to the secondary value-chain will encounter some organizational and cultural push-back in that it will change the traditional approaches to how NWS operates. Among the keys tasks of any organizational evaluation is to identify and resolve such organizational and cultural impediments.

Extension of the Weather Enterprise Interaction to Water and Climate

The successes of the weather enterprise interaction of the last decade provide a solid model for broader interaction across enterprise disciplines, with space weather and seasonal and inter-annual forecasts being particular examples for improvement. Expansion of enterprise collaboration in social science research would also bring benefit to the entire enterprise. Investigation of the impact of weather, water, and climate on economic and social systems would help prioritize investments through the evaluation of services in an economic or risk framework.

Enhanced Interaction with Professional Organizations

One successful outcome of the *Fair Weather* report has been the role of professional organizations in resolving issues impeding progress of the enterprise as a whole. The NWS has effectively supported this approach in achieving the enterprise progress of the last decade. The next step is to do more of what has worked well, perhaps expanding and extending relationships with the AMS, AWCIA, NCIM, and others.

Industry-wide Standards

The NWS can enable enterprise growth by promoting development of industry standards. Such development will need to proceed through collaboration with professional organizations.

Deeper Formal Public-Private Partnerships

Going back as far as the 1800s, public-private partnerships have been a reliable tool for creating infrastructure and providing services that reflect the public good while requiring efficient implementation. The NWS has made limited formal use of such partnerships. NESDIS has explored public-private partnerships in the form of data buys, but with generally little follow-through. The international community routinely employs such partnerships for activities such as those of the NWS. The NSAB *Open Weather and Climate Services* proposal presents a vision for how deeper public-private partnerships could enhance the NWS in a variety of areas (NSAB, 2011). They are in no way a general solution to NWS needs; done right and taken seriously, however, they can become an important part of NWS's enterprise leveraging.

Recommendation III.a

The National Weather Service (NWS) should seek to better understand the functioning of the secondary value-chain, including ways in which it complements the primary value-chain. When appropriate, it should identify new or evolved NWS data and services that can enhance public value delivered through the secondary value-chain, the benefits associated with such services, and any challenges or risks in implementing them. To the greatest extent possible, this should be accomplished through collaborative efforts with corresponding enterprise partners.

CHALLENGES AND RISKS

The Committee reaffirms the recommendations of the *Fair Weather* report regarding the enterprise partnership (NRC, 2003a). Notable among these is an understanding that the enterprise is evolving and that fixed organizational boundaries are less productive than are interactive processes (e.g., meetings and committees) that identify and evolve relationships among enterprise partners as needed. Recommendation 5 of the *Fair Weather* report, regarding availability of data and products, needs to receive increased focus (NRC, 2003a). The *Towards an Open Weather and Climate Services* white paper recently prepared by NSAB presents an excellent opportunity to further this goal (NSAB, 2011).

As an aggregation of independent entities, the enterprise cannot commit to plans or obligations. Government agencies can be obligated by their charters, with Congress holding them accountable to those charters. Private-sector "responsibilities" or "obligations" have no real meaning unless accompanied by contracts. Yet, despite this, the private sector can be a reliable partner when private incentives and values align with the NWS mission. The U.S. government does not produce many of the things it relies on, from airplanes to paper. It does not need to do so itself, and it does not need an "obligation" from the private sector—because the private-sector industries producing those things are sufficiently robust that they can be counted on. In the weather enterprise, the broadcast sector has achieved such robustness—the NWS does not need its own backup daily television broadcasts nor do they need to tell television channels what to do. The broadcast sector already does it well and reliably. Other elements of the enterprise are also beginning to achieve such robustness. Ground-based weather sensor networks are one and wind forecasting for renewable energy is another. The NWS could achieve increased leverage by encouraging the emergence of such "robust sub-enterprises."

INTERNATIONAL PARTNERS

The structure and function of the enterprise varies from country to country. Some, like the United States, have a strictly public, not-for-profit National Hydrological Meteorological Services (NHMS) and a separate private sector. Other countries have both a public component and a private component within their NHMS. Some private-sector entities offer products and services internationally. In the 1970s and 1980s, the growth of the interactions between the public and private sectors were seen to begin to impair the free and unrestricted international exchange of hydrometeorological and related data and products and led the Twelfth World Meteorological Congress (Cg-XII) in 1995 to negotiate Resolution 40.[6] The Resolution specified those data and products to be exchanged internationally without charge and with no conditions on use. The Resolution also set guidelines for relations among NHMSs regarding commercial activities, and it further proposed guidelines for relations between NHMSs and the private sector itself.

One result of the Resolution is that some data and information falling outside the designated "without charge and no conditions on use" category could be exchanged but with restrictions as to how it could be passed on to third parties in other countries, as per the dictates of the originating country's NHMS. This could, for example, increase the global coverage of weather and water observations to an NHMS but could make such an increase unavailable to private-sector entities.

Another result of the Resolution has been to provide guidelines for the expansion of, for example, U.S. weather, water, and climate enterprise companies to service the global market. At the same time, it has provided guidelines for those NHMSs that wish to offer hydrometeorological services commercially to other countries. This, then, could provide alternative weather and water information services in countries to those provided by the NHMS in that country, and it raises the fear of government decisions to reduce funding support to their NHMS, on the logic that they can get weather forecasts from international companies for less than the cost of the NHMS. The important side effect is that the capacity of the NHMSs to make and exchange the needed observations is reduced, and a lack of information on which both the NHMSs and the international enterprise base their services could result.

[6] Resolution 40 (Cg-XII) WMO Policy and Practice for the Exchange of Meteorological and Related Data and Products, including Guidelines on the Relationships in Commercial Meteorological Activities (WMO, 1995).

The Committee is not aware of any international assessment of the impact or effect of WMO Resolution 40 (Cg-XII) on the global exchange of hydrometeorological data and products or on the provision of hydrometeorological services. This is an area where private-sector interests could fail to align with NWS responsibilities to international partners. The Committee feels the tradition of "free and unrestricted" international exchange of hydrometeorological data and information is crucial to the provision of the best possible weather, water, and climate services.

ACQUISITION PARTNERS

When thinking about the role of the private sector in the context of the broader weather, water, and climate enterprise, the focus tends to be on the provision of value-added services rather than infrastructure providers. These two private-sector roles are distinct, and each has their own issues. The diversity of the private sector is reflected in a broad spectrum of commercial interests. These range from designing and building weather, water, and climate data acquisition systems and data processing systems via direct contract to a government program office to developing value-added products and services based on NWS data and directly selling these to a third-party consumer.

NOAA has well-established contract procurement processes for weather, water, and climate data acquisition and processing systems and subsystems. These systems form the core of NOAA's observation network and include elements such as satellite platforms, launch vehicles, sensors (space, air, and ground-based), command and control systems, and data processing and distribution systems. The procurement processes for elements of this core infrastructure include architecture studies at the system level (e.g., trades comparing many smaller satellites versus fewer larger satellites based on cost, risk, schedule; data product requirements such as spatial and temporal resolution), sensor design trades (cost, risk, schedule, data requirements), or segment trades (location and number of ground stations, cost, risk, schedule). Early stage studies are often only partly funded by government contracts. The competing private-sector entities frequently fund studies and early R&D largely with their own internal funds.

In line with NOAA's Partnership Policy to "foster the growth of this complex and diverse enterprise as a whole to serve the public interest and the Nation's economy" (NOAA, 2007), the Committee believes the nation needs a strong private sector capable of developing core infrastructure. The existing NOAA procurement process should be reviewed, well-functioning aspects retained, and any poorly functioning aspects improved. Per Lesson 2 presented in the Committee's first report, aspects subject to improvement may include strengthening NOAA's system architecture and system engineering processes (NRC, 2012a). It is also important that NOAA improve contract management practices where needed. Maintaining a healthy and vibrant private sector that competes to design and build traditional key infrastructure components helps to provide a best value approach for the nation. Not only do competing entities frequently develop and test some of the more innovative design ideas on their own internal, nongovernment funds; competition typically leads to important technical innovation too.

Recommendation III.b

The National Oceanic and Atmospheric Administration (NOAA) as a whole should strengthen its systems engineering and procurement processes for major systems, including ground-based sensor, gauge, and radar networks, satellites and ground processing, and major communications and processing systems so as to achieve more productive and cost-effective interactions with the enterprise partners developing and building such systems.

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A

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.

B

Acronyms and Abbreviations

3DVar	3-dimensional variational
4DVar	4-dimensional variational
ADM	Atmospheric Dynamics Mission
AHPS	Advanced Hydrologic Prediction System
AMS	American Meteorological Society
AMSU	Advanced Microwave Sounding Unit
AOML	Atlantic Oceanographic and Meteorological Laboratory
ARRC	Atmospheric Radar Research Center
ASOS	Automated Surface Observing System
AWCIA	American Weather and Climate Industry Association
AWIPS	Advanced Weather Interactive Processing System
BMA	Bayesian model averaging
C3	command, control, and communications
CAPS	Center for the Analysis and Prediction of Storms
CASA	Collaborative Adaptive Sensing of the Atmosphere
CDAS	Coordinated Data Analysis System
CFS	Climate Forecast System
CIMMS	Cooperative Institute for Mesoscale Meteorological Studies
CMC	Canadian Meteorological Center
COMET	Cooperative Program for Operational Meteorology, Education, and Training
COP	common operating picture
CWCE	Commission on the Weather and Climate Enterprise
DAR^3E	Denver AWIPS Risk Reduction and Requirements Evaluation
DMIP	Distributed Model Intercomparison Program
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DTC	Developmental Testbed Center
ECMWF	European Centre for Medium-range Weather Forecasts
EISWG	Environmental Information Services Working Group
EnKF	ensemble Kalman filter
ERS	emergency response specialist
ESPC	Earth System Prediction Capability
ESRL	Earth System Research Laboratory
FAA	Federal Aviation Administration
FACA	Federal Advisory Committee Act
FNMOC	Fleet Numerical Meteorology and Oceanography Center
GAW	Global Atmosphere Watch
GEOSS	Global Earth Observation System of Systems
GFDL	Geophysical Fluid Dynamics Laboratory
GFS	Global Forecast System
GOES	Geostationary Operational Environmental Satellite

HFIP	Hurricane Forecast Improvement Program
HS3	Hurricane and Severe Storm Sentinel (NASA program)
HWRF	Hurricane Weather Research Forecasting
HWT	Hazardous Weather Testbed
HYCOM	Hybrid Coordinate Ocean Model
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory
ICSU	International Council for Sciences
IMET	incident meteorologist
IP	intellectual property
IT	information technology
JHT	Joint Hurricane Testbed
LIDAR	LIght Detection and Ranging
MAR	Modernization and Associated Restructuring
MOS	model output statistics
MPAR	multi-function phased array radar
NAM	North American Mesoscale Model
NASA	National Aeronautics and Space Administration
NAVO	Naval Oceanography Center
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NCIM	National Council of Industrial Meteorologists
NCWCP	NOAA Center for Weather and Climate Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next Generation Weather Radar
NHC	National Hurricane Center
NMHS	National Meteorological Hydrological Service
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRC	National Research Council
NRL	Naval Research Laboratory
NSAB	NOAA Science Advisory Board
NSF	National Science Foundation
NSSL	National Severe Storms Laboratory
NWA	National Weather Association
NWC	National Weather Center
NWP	Numerical Weather Prediction
NWS	National Weather Service
NWSEO	National Weather Service Employees Organization
O2R	operations-to-research
OAR	Office of Oceanic and Atmospheric Research
OHD	Office of Hydrological Development
OSE	observing system experiment
OSIP	Operational Satellite Improvement Program
OUN	NWS Norman Weather Forecast Office
PAR	phased array radar
POES	Polar Operational Environmental Satellite
PROFS	Program for Regional Observing and Forecasting Service
QPE	quantitative precipitation estimation
QPF	quantitative precipitation forecast
R2O	research-to-operations
R&D	research and development
RFC	River Forecast Center
RFI	radio frequency interference
ROC	Radar Operations Center
RTOFS	Real Time Ocean Forecast System
SCH	Service Coordination Hydrologists
SLEP	Service Life Extension Program
SPC	Storm Prediction Center
UAS	Unmanned Aircraft Systems
UCAR	University Corporation for Atmospheric Research
UKMO	United Kingdom Meteorological Office
USGS	U.S. Geological Survey

WAS*IS	Weather and Society * Integrated Studies
WCM	Warning Coordination Meteorologist
WDTB	Warning Decision Training Branch
WFO	Weather Forecast Office
WMO	World Meteorological Organization
WSFO	Weather Service Forecast Office
WSR	Winter Storm Reconnaissance
WWW	World Weather Watch

C

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. in atmospheric science and mathematics from the University of Wisconsin at Milwaukee in 1983 and his M.S. and Ph.D. degrees 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 as a 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 Geostationary Operational Environmental Satellite (GOES)-R PDRR Program. Before working on GOES-R, Dr. Emch spent eight years on Northrop's NPOESS Program, 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, oversaw the archives for environmental multimedia data, and led environmental data-collection and application activities for hyperspectral airborne instruments. Dr. Emch holds an M.S. 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 co-chair of the Weather Coalition.

William B. Gail is cofounder and chief technology officer of Global Weather Corporation, a private-label provider of precision weather forecasts to businesses within the energy, media, and transportation sectors. He was previously 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). Prior positions include 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 (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 the 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 or has served 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 also served as associate editor for the *SPIE Journal of Applied Remote Sensing* and director of industry relations for the IEEE Geoscience and Remote Sensing Society. He has published extensively on both technical and policy issues and has been cited by American Geophysical Union for excellence in scientific journal review.

David J. 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 there he moved to NCAR to work as a postdoctoral researcher, and later he 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.

Eve Gruntfest is professor emeritus of geography and environmental studies at the University of Colorado at Colorado Springs. She has published widely and is an internationally recognized expert in the specialty areas of warning system development and flash flooding. She is writing a textbook titled *Weather and Society: Integrated Studies*. She serves on the NOAA Science Advisory Board. She cofounded the WAS*IS (Weather and Society*Integrated Studies) movement in 2005. Dr. Gruntfest received her B.A. in geography from Clark University and her M.A. and Ph.D. in geography from the University of Colorado, Boulder.

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 Semi-Arid Hydrology and Riparian Areas (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 western United States, 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. Holly 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 A. 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. He has a B.S. in engineering science from the University of Texas at Austin and an M.S. and a 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 20 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 R&D 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 director of policy studies in the Institute for Catastrophic Loss Reduction. Previously, Gordon 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, Order of Ontario, MSC Patterson Medal, and CMOS President's Prize, and he has been elected a fellow of the Royal Society of Canada, the Canadian Meteorological and Oceanographic Society, and the AMS. 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 was a counselor of the AMS (1993 to 1996). He was chair of the ICSU-ISSC-UNISDR Science Committee for Integrated Research on Disaster Risk program and is president of START International and president-elect of the International Council for Science. 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 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 NOAA's 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 eight years in this capacity. In 1982 he took the position of director of the Office of Meteorology in the NWS. 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 Global Observing System, the Global Telecommunications System, and the Global Data Processing System, as well as WMO's associated service programs. In 1994 he was appointed director of NOAA's Environmental Research Laboratories. Since retiring in 1999, he has been a consultant internationally on such topics as the Global Climate Observing System, the continued development of WWW, and the organization and management of meteorological and climate services. He has served in various capacities in the AMS (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 school's 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 Multi-function 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*, AMS (1992); the Thunderbird Award, Weather Modification Association (1995); and was named a national associate by the National Research Council (2004). He was selected as AMS'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 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 NOAA's 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. WMO-sponsored training at the National Hurricane Center and the University of Miami in 1988 garnered him several credits of master's-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 accreditations. Mr. Toohey-Morales is past president of the National Council of Industrial Meteorologists and 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 Award in 2003.