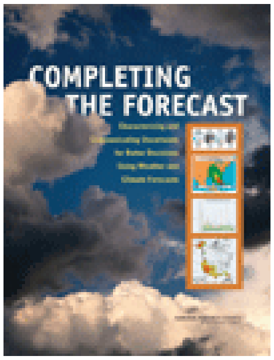

**Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts**

Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts, National Research Council

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THE NATIONAL ACADEMIES
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# COMPLETING THE FORECAST

## Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts

Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts
Board on Atmospheric Sciences and Climate
Division on Earth and Life Studies

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# Preface

Recognizing the opportunity to enhance the service it provides to the nation, the National Weather Service (NWS) commissioned the National Research Council (NRC) to form a committee to provide recommendations on how NWS can more effectively estimate and communicate uncertainty in weather and climate forecasts. This opportunity was highlighted in Recommendation 8 of the report *Fair Weather: Effective Partnerships in Weather and Climate Forecasts* (NRC, 2003a) and NWS desired more specific input in this area.

The committee was tasked with providing guidance on understanding and characterizing user needs for uncertainty information, suggesting improvements in current methods used to estimate and validate uncertainty products and recommending improvements in methods used to communicate uncertainty information. Since weather services in the United States are the result of an interdependent enterprise consisting of public, private, and academic assets, NWS also asked the committee to make recommendations consistent with an "enterprise" viewpoint.

At the very beginning of the study, the committee realized that an exhaustive look at the needs of users or user categories with regard to uncertainty information would be vastly beyond its time constraints and resources. Although several specific examples of user needs appear in the report (as requested in the charge), the overall thrust is to provide NWS with a template of how to effectively assess the unique needs of a very wide range of users. The psychology of decision-making processes is presented along with general paths that the enterprise can follow in providing useful input into decision-support systems. "Teaching how to fish versus catching a fish" is an appropriate analogy and is one that NWS used at the committee's first meeting.

The committee met a total of five times between April 2005 and February 2006 and received broad and diverse input from specialists on topics ranging from probabilistic data generation, to product development, to user decision processes. The committee would like to thank all of those who provided their time and insight. The contributors are listed in Appendix B of the report.

Finally the committee thanks NWS personnel for all of the input they provided during the course of the study, including answers to our many questions and numerous and complete product summaries. In particular we thank Ed Johnson, Lee Anderson, and John Sokich for their prompt and complete responses.

Raymond J. Ban, *Chair*
Committee on Estimating and Communicating
Uncertainty in Weather and Climate Forecasts

# 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 National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

James Block, DTN-Meteorlogix, Minneapolis, Minnesota
David Budescu, University of Illinois, Champaign
Simon Chang, Naval Research Laboratory, Monterey, California
Holly Hartmann, University of Arizona, Tucson
Kathryn Laskey, George Mason University, Fairfax, Virginia
Daniel P. Loucks, Cornell University, Ithaca, New York
Tom Skilling, WGN-TV News, Chicago, Illinois
Mort Webster, University of North Carolina at Chapel Hill
Lawrence Wilson, Meteorological Service of Canada, Dorval, Quebec

Although the reviewers listed above have provided constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by George Frederick, Vaisala, Inc., and Kuo-Nan Liou, University of California, Los Angeles. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

# Contents

APPENDIXES

# Summary

All prediction is inherently uncertain and effective communication of uncertainty information[1] in weather, seasonal climate, and hydrological forecasts benefits users' decisions (e.g., AMS, 2002; NRC, 2003b). The chaotic character of the atmosphere, coupled with inevitable inadequacies in observations and computer models, results in forecasts that always contain uncertainties. These uncertainties generally increase with forecast lead time and vary with weather situation and location. *Uncertainty is thus a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty.*

Nonetheless, for decades, users of weather, seasonal climate, and hydrological (collectively called "hydrometeorological") forecasts have been conditioned to receive incomplete information about the certainty or likelihood of a particular event. But this has not always been the case. As early as the 19th century, some predictions included qualitative probabilistic[2] expressions of uncertainty and were actually called "probabilities" rather than forecasts. By the 20th century, meteorology evolved into what was thought to be a more exact science and predictions became deterministic[3] with no expression of uncertainty. The advent of numerical weather prediction around 1950 and its early successes strengthened this deterministic viewpoint, as did improvements in satellite observations and modeling methods in the 1970s and 1980s. Users became comfortable with single-valued forecasts[4] and applied their own experience in determining how much confidence to place in the forecast. The evolution of the media as the primary vehicle for conveying weather information in the United States compounded this trend. The inclusion of uncertainty information in a forecast was viewed by some as a weakness or disadvantage instead of supporting a more scientifically sound and useful product. Most forecast products from the weather and climate enterprise (the Enterprise[5]), including those from the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), continue this deterministic legacy. Decisions by users at all levels, but perhaps most critically those associated directly with protection of life and property, are being made without the benefit of knowing the uncertainties of the forecasts upon which they rely.

Fortunately this situation can be improved. NWS and others in the Enterprise have recognized the need to view uncertainty as a fundamental part of forecasts. By partnering with other segments of the Enterprise to understand user needs, generate relevant and rich informational products, and utilize effective communication vehicles, NWS can take a leading role in the transition to widespread, effective incorporation of uncertainty information into hydrometeorological predictions.

This study explores how to improve the generation, communication, and potential use of uncertainty information for hydrometeorological forecasts and makes recommendations for improvements. The study was requested by NWS in response to ideas in *Fair Weather: Effective Partnerships in Weather and Climate Services* (NRC, 2003a). In particular,

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[1] Uncertainty is an overarching term that refers to the condition whereby the state of a system cannot be known unambiguously. Probability is one way of expressing uncertainty.

[2] A probabilistic forecast conveys uncertainty in the prediction. The converse is a deterministic forecast, which provides only one prediction of the future state of a system, with no information regarding forecast uncertainty. For example, the track forecast of a hurricane could be represented by a (deterministic) single line or by a cone that more appropriately (and probabilistically) conveys the likely range of forecast tracks.

[3] See previous footnote for definition.

[4] E.g., "the high will be 70 degrees Farenheit 9 days from now."

[5] "Enterprise" refers to all sectors and parties engaged in generating and communicating weather and climate forecasts. The Enterprise includes assets in public, private, and academic sectors, as well as user groups who add value to products such as segments of the media and risk management industry. Because the scope of the committee's task includes hydrologic prediction in addition to weather and seasonal climate prediction, the committee's use of "Enterprise" implicitly includes hydrological activities.

NWS asked the committee to (1) provide guidance on how to identify and characterize needs for uncertainty information among various users of forecasts; (2) identify limitations in current methods for estimating and validating forecast uncertainty, relating these limitations to users' needs, and recommending improvements or new methods and approaches; and (3) identify sources of misunderstanding and recommend improvements in the methods used to communicate forecast uncertainty.

Recognizing the breadth and depth of this task, NWS advised the committee at its opening meeting to "teach us how to fish as opposed to giving us a fish." The committee approached the task accordingly. Relative to the first component of the task, the report reviews how decision makers interpret and use uncertainty information with the aim of helping NWS and others in the Enterprise understand key relevant concepts in decision making under uncertainty. Building from these concepts, the committee recommends a *process* by which NWS can develop an effective system of user–provider interactions that will lead to more effective products. Relative to the second component of the task, the committee takes the view that generating comprehensive uncertainty information to support all forecasts is central to the mission of NWS and will benefit all users. Such information must be made easily accessible and include all raw and post-processed products as well as verification and measurement information.[6] The committee addresses the third component of the task by exploring the roles of graphics and language, dissemination technologies, and the media in communication of uncertainty information. In addition, the committee proposes refinements to NWS's product development processes and highlights the need for education and research to support Enterprise-wide progress on communication of uncertainty information.

NWS asked the committee to recognize the diverse roles of participants in the Enterprise and the varied needs of forecast users. In addition, NWS requested that the committee's recommendations focus primarily on the NWS mission, but may also address other components of NOAA or seek to guide other relevant government agencies and nongovernmental entities. In cases where a recommendation states that "NWS should . . ." it is the committee's intention that the recommendation also applies to any relevant group or activity within NOAA, such as the Office of Oceanic and Atmospheric Research (OAR). The committee met five times between April 2005 and February 2006. One of its meetings was held in parallel with the annual American Meteorological Society Numerical Weather Forecasting and Broadcast Meteorology Conference, and another was held at the National Center for Atmospheric Research. NWS provided significant informational input to the process, both at meetings and in responses to questions posed by the committee.

## OVERARCHING FINDINGS AND RECOMMENDATIONS

Moving toward effective estimation and communication of uncertainty information has broad and deep implications for the Enterprise and the community it serves. Because of the immense breadth and depth of this challenge, detailed solutions are beyond the reach of a single committee. Consequently, this report provides general ideas for consideration by NWS and the entire Enterprise.

The committee presents nine overarching recommendations all with equal priority. In addition, detailed recommendations appear in Chapters 2, 3, and 4 that add further specificity and breadth. All recommendations should be considered in the context of NOAA's Policy on Partnerships in the Provision of Environmental Information.[7]

### Enterprise-wide Involvement

**Finding 1:**[8] Hydrometeorological services in the United States are an Enterprise effort. Therefore, effective incorporation of uncertainty information will require a fundamental and coordinated shift by all sectors of the Enterprise. Furthermore, it will take time and perseverance to successfully make this shift. As the nation's public weather service, NWS has the responsibility to take a leading role in the transition to widespread, effective incorporation of uncertainty information into hydrometeorological prediction.

**Recommendation 1: The entire Enterprise should take responsibility for providing products that effectively communicate forecast uncertainty information. NWS should take a leadership role in this effort.**

### Product Development Incorporating Broad Expertise and Knowledge from the Outset

**Finding 2:**[9] Understanding user needs and effectively communicating the value of uncertainty information for addressing those needs are perhaps the largest and most important tasks for the Enterprise. Yet, forecast information is often provided without full understanding of user needs or how to develop products that best support user decisions. Parts of the Enterprise (e.g., within the private sector and academia) have developed a sophisticated understanding of user needs. In addition, there is a wealth of relevant knowledge in the social and behavioral sciences that could be more effectively incorporated into product research and development. Currently, this variety of resources is not being fully tapped by

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[6] Forecast verification is the means by which the quality of forecasts is assessed. Forecast post-processing converts model output into human-comprehensible information and corrects for model biases.

[7] See http://www.nws.noaa.gov/partnershippolicy/ and also Box 1.2.

[8] See Section 1.5 for further discussion on this topic.

[9] See Sections 2.4, 4.2.6, and 4.2.7.

NOAA,[10] and user perspectives are not incorporated from the outset of the product development process.

**Recommendation 2: NOAA should improve its product development process by collaborating with users and partners in the Enterprise from the outset and engaging and using social and behavioral science expertise.**

### Education on Uncertainty and Risk Communication

**Finding 3:**[11] Enhanced Enterprise-wide educational initiatives will underpin efforts to improve communication and use of uncertainty information. There are three critical areas of focus: (1) undergraduate and graduate education, (2) recurrent forecaster training, and (3) user outreach and education.

**Recommendation 3: All sectors and professional organizations of the Enterprise should cooperate in educational initiatives that will improve communication and use of uncertainty information. In particular, (1) hydrometeorological curricula should include understanding and communication of risk and uncertainty; (2) ongoing training of forecasters should expose them to the latest tools in these areas; and (3) forecast providers should help users, especially members of the public, understand the value of uncertainty information and work with users to help them effectively incorporate this information into their decisions.**

### Ensembles

**Finding 4:**[12] The ability of NOAA to distribute and communicate uncertainty information is predicated on the capacity to produce post-processed probabilistic model guidance on a variety of spatial scales. Currently, NOAA maintains long-range (global) and short-range ensemble[13] prediction systems. However, the short-range system undergoes no post-processing and uses an ensemble generation method (breeding) that may not be appropriate for short-range prediction. In addition, the short-range model has insufficient resolution to generate useful uncertainty information at the regional level. For forecasts at all scales, comprehensive post-processing is needed to produce reliable (or calibrated) uncertainty information.

**Recommendation 4: NOAA should develop and maintain the ability to produce objective uncertainty information from the global to the regional scale.**

### Ensuring Widespread Availability of Uncertainty Information

**Finding 5:**[14] NWS, through the National Centers for Environmental Prediction (NCEP), produces a large amount of model output from its deterministic and ensemble numerical weather prediction models. The ensemble forecasts and output from statistical post-processing (i.e., Model Output Statistics) already produce a wide variety of uncertainty information. However, both the model output and statistical information regarding its skill[15] are difficult to access from outside NCEP. Thus, NWS is missing an opportunity to provide the underlying datasets that can drive improved uncertainty estimation and communication across the Enterprise.

**Recommendation 5: To ensure widespread use of uncertainty information, NWS should make all raw and post-processed probabilistic products easily accessible to the Enterprise at full spatial and temporal resolution. Sufficient computer and communications resources should be acquired to ensure effective access by external users and NWS personnel.**

### Broad Access to Comprehensive Verification Information

**Finding 6:**[16] To make effective use of uncertainty products, users need complete forecast verification information that measures all relevant aspects of forecast performance. In addition, comprehensive verification information is needed to improve forecasting systems. Such information includes previous numerical forecasts, observations, post-processed uncertainty information, and detailed verification statistics (for raw and post-processed probabilistic forecasts).

**Recommendation 6: NWS should expand verification of its uncertainty products and make this information easily available to all users in near real time. A variety of verification measures and approaches (measuring multiple aspects of forecast quality that are relevant for users) should be used to appropriately represent the complexity and dimensionality of the verification problem. Verification statistics should be computed for meaningful subsets of the forecasts (e.g., by season, region) and should be presented in formats that are understandable by forecast users. Archival verification information on probabilistic forecasts, including model-generated and objectively**

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[10] Recognizing that private-sector entities gain a competitive advantage through knowledge of user needs, there is, nonetheless, some opportunity for information sharing that could significantly improve the effectiveness and efficiency of product development.

[11] See Section 4.2.8.

[12] See Chapter 3. Production of objective uncertainty information is covered in Sections 3.1 through 3.3.

[13] An ensemble is a collection of forecasts, each starting from a different initial state. The variations in the resulting forecasts can be used to estimate the uncertainty of the prediction.

[14] See Sections 3.1.4, 3.1.5, and 3.3.1.

[15] Skill measures how well a forecast performs relative to a naïve standard of comparison, such as climatology or persistence.

[16] See Section 3.5.

**generated forecasts and verifying observations, should be accessible so users can produce their own evaluation of the forecasts.**

### Effective Use of Testbeds[17]

**Finding 7:**[18] Testbeds are emerging as a useful mechanism for developing and testing new approaches and methodologies in estimating, communicating, and using uncertainty information.[19] The effectiveness of testbeds is limited when all appropriate sectors of the Enterprise are not included.

**Recommendation 7: To enhance development of new methods in estimation, communication, and use of forecast uncertainty information throughout the Enterprise, and to foster and maintain collaboration, confidence, and goodwill with Enterprise partners, NOAA should more effectively use testbeds by involving all sectors of the Enterprise.**

### Enterprise Advisory Committee

**Finding 8:**[20] Only through comprehensive interaction with the Enterprise will NWS be able to move toward effective and widespread estimation and communication of uncertainty information. One mechanism for engaging the entire Enterprise on this and related topics is an independent NWS advisory committee with broad representation. Such a committee is under consideration by NOAA in response to a recommendation in the *Fair Weather* report (NRC, 2003a).

**Recommendation 8: The committee endorses the recommendation by the National Research Council *Fair Weather* report to establish an independent advisory committee and encourages NOAA to bring its evaluation of the recommendation to a speedy and positive conclusion.**

### Uncertainty Champion

**Finding 9:**[21] Incorporating uncertainty in forecasts will require not only the attention but also the advocacy of NWS management. Given the scope of this challenge, the level of effort involved will demand a "champion" within the NWS leadership—an individual who can effectively organize and motivate NWS resources and engage the resources and expertise of the entire Enterprise.

**Recommendation 9: NWS should dedicate executive attention to coordinating the estimation and communication of uncertainty information within NWS and with Enterprise partners.**

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[17] Testbeds are multipartner collaborations that create prototypical environments where innovative approaches can be tested before being applied more generally. They allow the community to evaluate new modes of cooperative research, development, training, and operations.

[18] See Sections 3.1.1, 3.1.6, 3.2.4, and 3.3.2.

[19] For example, Joint Hurricane Testbed (http://www.nhc.noaa.gov/jht/), WRF Developmental Testbed Center (http://www.dtcenter.org/index.php), NOAA Climate Testbed (http://www.cpc.ncep.noaa.gov/products/ctb/), NOAA Hydrometeorology Testbed Program (http://hmt.noaa.gov/).

[20] See Section 4.2.6, overarching recommendation 2, and Chapter 5.

[21] See Section 1.5 and Chapter 5.

# 1

# Introduction

All prediction, including weather, hydrologic, and climate forecasting, is uncertain. Although information about this uncertainty[1] is potentially of great value to society, many users neither have access to it nor apply it. Such shortcomings will decrease as methods for estimating uncertainty are improved, as knowledge of the best approaches for communicating uncertainty is enhanced, as the user and forecasting community becomes better informed regarding the advantages of uncertainty information, and as means for disseminating uncertainty information are refined.

This study summarizes the current situation regarding the generation, communication, and use of uncertainty information in weather, seasonal climate, and hydrological forecasts (collectively, hydrometeorological[2] forecasts) and makes recommendations for improvements. Specifically, the charge to the committee from the National Weather Service (NWS), which is part of the National Oceanic and Atmospheric Administration (NOAA), is to

1. Provide guidance on how to identify and characterize, and examples of, needs for uncertainty information among various users of forecasts, including the public, emergency managers and other government decision makers, and private-sector entities, both direct users and intermediaries.
2. Identify limitations in current methods for estimating and validating forecast uncertainty, relating these limitations to users' needs and recommending improvements or new methods and approaches (with the goal of finding ways to better couple methods of estimating uncertainty to users' needs).
3. Identify sources of misunderstanding in communicating forecast uncertainty, including vulnerabilities dependent on the means of communication used, and to recommend improvements in the ways used to communicate forecast uncertainty.

With respect to the general approach of this study, NWS asked the committee to recognize the diverse roles of participants in the weather and climate enterprise (Enterprise)[3] and the diverse needs of forecast users. The Enterprise encompasses all sectors and parties engaged in generating and communicating hydrometeorological forecasts. It includes the public, private, and academic sectors, as well as user groups, such as segments of the media and risk management industry, who add value to products.[4]

The report addresses the first task in Chapter 2, the second task in Chapter 3, and the third task in Chapter 4. Each of these chapters includes detailed recommendations. In addition, a set of overarching recommendations is presented in Chapter 5. NWS requested that the committee's recommendations focus primarily on the NWS mission, but it was agreed that this study could also address other components of NOAA or guide other relevant government agencies and sectors within the Enterprise. In cases where a recommendation states that "NWS should . . ." it is the committee's

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[1] Uncertainty is an overarching term that refers to the condition whereby the state of a system cannot be known unambiguously. Probability is one way of expressing uncertainty. A probabilistic forecast conveys uncertainty in the prediction. The converse is a deterministic forecast, which provides only one prediction of the future state of a system, with no information regarding forecast uncertainty. For example, the track forecast of a hurricane could be represented by a (deterministic) single line or by a cone that more appropriately (and probabilistically) conveys the likely range of forecast tracks.

[2] For the purposes of this report, "hydrometeorology" will refer to the combined fields of meteorology and hydrology from the short time scales of weather prediction to inter-seasonal climate forecasting.

[3] The Weather Enterprise is described in *Fair Weather: Effective Partnerships in Weather and Climate Services* (NRC, 2003a). Because the scope of the committee's task includes hydrologic prediction in addition to weather and seasonal climate prediction, the committee's use of "Enterprise" implicitly includes hydrological activities in addition to weather and climate activities.

[4] The concept of the Enterprise is now sufficiently widely accepted that the American Meteorological Society has formed a Commission on the Weather and Climate Enterprise to facilitate dialog among Enterprise participants.

intention that the recommendation also applies to any relevant group or activity within NOAA, such as the Office of Oceanic and Atmospheric Research (OAR). Recognizing the breadth and depth of the task presented to the committee, NWS urged the committee to think in terms of "teaching us how to fish as opposed to giving us a fish." The committee approached the task accordingly, and explains its approach to each task at the beginning of each chapter. The remainder of this first chapter summarizes the issues that are central to the committee's charge, most of which are examined in more detail in subsequent chapters.

## 1.1 THE UNCERTAIN ATMOSPHERE AND HYDROSPHERE

Uncertainty in hydrometeorological predictions, often described in terms of probability (Box 1.1), varies by weather/climate situation, location, and length of forecast. As demonstrated in the seminal work of Lorenz (1963, 1965, 1968, 1969), the origins of this uncertainty include (1) lack of an accurate, complete description of the initial three-dimensional state of the atmosphere; (2) incomplete and inaccurate descriptions of physical processes and other inadequacies in the modeling systems; and (3) the *chaotic* character of the atmosphere, in which small uncertainties in the starting point of a forecast or in the forecasting system can result in large differences as the prediction unfolds. In addition to the inherent sources of uncertainty in the atmosphere, there are also uncertainties in Earth surface characteristics and fluxes that contribute to the overall uncertainty in hydrometeorological prediction (e.g., Beven, 1989).

Numerical prediction is the basis for most hydrometeorological forecasts beyond several hours. All numerical weather forecasts begin with a three-dimensional description of the atmosphere, known as an *initialization*. Such initializations have improved during the past several decades as more observing systems have become available and as data assimilation systems, which combine observations with previous forecasts to provide a coherent, three-dimensional description of the atmosphere, have improved. Nevertheless, all observations have errors, data assimilation systems have inadequacies, and even the improved observational networks have substantial gaps on all scales. The result is that the three-dimensional descriptions of the atmosphere, even from large centers such as NWS's National Centers for Environmental Prediction (NCEP), are inevitably imperfect. Such imperfect initializations lead to errors and therefore uncertainty in the forecasts that increases with forecast projection forward in time.

Computer forecast models also possess other sources of error that result in degraded prediction. Some errors result from inadequacies in the model descriptions of the physics of the atmosphere, such as radiation, cloud physics, and surface drag. Other errors result from lack of sufficient horizontal and vertical *resolution*, the scales at which the numerical simulation can accurately forecast the evolving atmosphere and hydrosphere. Because computer resources are finite, there are always small scales that are not properly described. Additional errors accrue due to approximations in *numerics*, how the forecast models are integrated into the future. Still other errors arise because of fundamental uncertainties in boundary fluxes, especially surface fluxes such as latent and sensible heat fluxes, and surface properties. The results of model inadequacies are often apparent early in forecasts and generally increase in time, resulting in increasing uncertainty as the forecasts progress.

In summary, the chaotic character of the atmosphere, coupled with inevitable inadequacies in observation quality and data assimilation, model physics and numerics, boundary conditions, and model resolution, result in forecasts that always contain uncertainties that generally increase with forecast lead time and vary by the type of weather situation and location. *Uncertainty is thus a fundamental characteristic of hydrometeorological prediction, and no forecast is complete without a description of its uncertainty.*

## 1.2 THE EVOLUTION OF HYDROMETEOROLOGICAL UNCERTAINTY PREDICTION

Early forecasters, faced with large gaps in their nascent science, understood the uncertain nature of the hydrometeorological prediction process and were comfortable with expressing uncertainties in their forecasts. Cleveland Abbe (Figure 1.2), who organized the first American forecast group as part of the U.S. Army Signal Corps, did not use the term "forecast" for his first prediction in 1871, but rather employed the term "probabilities," resulting in him being known as "Old Probabilities" or "Old Probs" (Box 1.2). A few years later, the term ‘‘indications’’ was substituted for probabilities and by 1889 the term ‘‘forecasts’’ received official sanction (Murphy, 1977).

As meteorology evolved during the late 19th and early 20th centuries into a more exact science based on explicit physical laws, the weather forecasting community increasingly presented deterministic[5] predictions, with the uncertainties eventually succumbing to improving knowledge, technology, and observations (Murphy, 1977). The advent of numerical weather prediction around 1950 and its early successes strengthened this deterministic viewpoint. Forecast skill[6] rapidly improved in the 1950s and 1960s as faster computers allowed higher spatial resolution and increasing sophistication in the numerical prediction models. But also during this period, the research of Lorenz (1963, 1965, 1968) and others demonstrated that forecast skill was inherently limited in a chaotic atmosphere in which small initialization

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[5] A deterministic forecast provides only one prediction of the future state of a system, with no information regarding forecast uncertainty.

[6] Forecast skill is a statistical measure of the relative accuracy of forecasts compared to an alternative forecast such as climatology or persistence.

## BOX 1.1
## Interpretation of Probability

This report has many references to the notion of probability. While often treated as a synonym for uncertainty, it is better described as one of many ways in which uncertainty can be expressed. The meaning of probability is an active area of debate. In spite of differences in its interpretation, probability thrives as a useful measure of uncertainty because the same calculus of probability—the ways in which probability distributions can be manipulated—applies to all of the definitions.

De Elia and Laprise (2005a,b) describe different interpretations of probability and their implications in the context of hydrometeorological forecasting. These are the *frequentist, subjective, and propensity* interpretations of probability.

In the *frequentist* interpretation, probability is defined as the limit, as the number of trials becomes arbitrarily large, of the number of times an event occurs divided by the number of opportunities for the event to occur. In frequentist theory, probability theory is legitimately applied only to phenomena for which such limiting frequencies are expected to exist. Frequentists use observed empirical frequencies from finite sequences to estimate the inherently unknowable limiting frequency. Such estimates are expected to become more accurate with larger numbers of trials. For example, consider the gambler who only trusts that a die is honest after counting the number of times the number two is rolled and dividing by the total number of rolls of the die. Another example is given by observational climatologies: the probability of exceeding a certain temperature threshold on a certain day can be obtained by counting the number of times that threshold was exceeded over the observational record for that day and dividing by the number of years of the observational record. In both cases, the probability calculated from past events is projected into the future and assumed to be valid.

A strength of the frequentist approach is that it is unambiguous; two people analyzing the same dataset would produce the same estimates of probability values, but critics would claim that probabilities estimated in this way confuse the *definition* of probability with the *measurement* of probability. Another shortcoming of the frequentist approach is that it is not well suited for short records or extreme events (unless there is a large enough observational record). The notion of conditional probabilities (e.g., probability of temperatures in excess of 90°F in the second week of May in El Niño years) effectively reduces the observational record, and indicates that there are many “types” of 90-degree days, each of which might have different probabilities. This is often called the reference class problem.

The *subjective* interpretation of probability is an expression of the degree of belief that an event is going to occur. While useful for expressing uncertainty, the production of subjective estimates of probability is difficult, or impossible, to quantify. If a forecaster issues a subjective probability of a 30 percent chance of rain, how was 30 percent chosen over 25 or 35 percent? Subjective probability has been found to be a useful means of expressing uncertainty in a wide variety of applications, so regardless of issues associated with the *production* of subjective probabilities there are well-established methodologies for their assessment. A particular benefit of the subjective interpretation of probability is its ability to assign probability values to extreme events.

An advocate of the *propensity* interpretation of probability would argue that the true probability density function (PDF; Figure 1.1) is available for any event, and forecasters and ensemble forecasting systems are striving to produce estimates of that PDF. In the context of hydrometeorological prediction, the argument would be that physical laws place constraints on the states that the weather, climate, and hydrosphere can realize, and a

*continued*

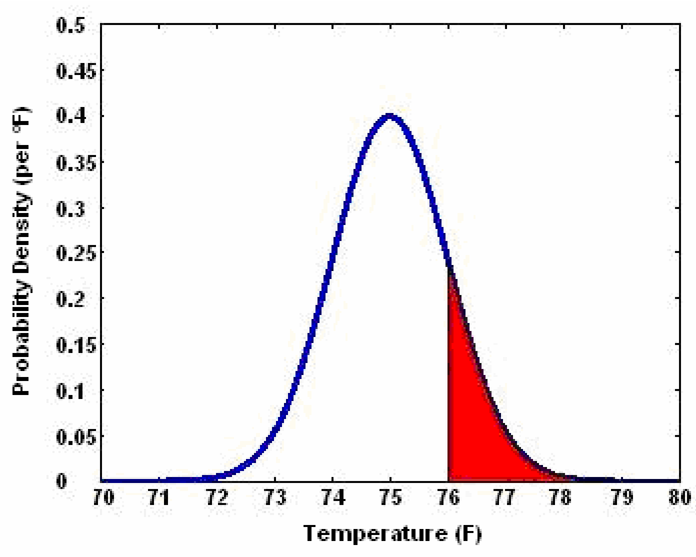


FIGURE 1.1 Example of a PDF (curve) that describes how the probability of some event varies as a function of some variable. In this case, the x-axis represents temperature at a location, and the y-axis the associated probability density. The probability of a particular range of temperatures is obtained by computing the area under the curve (the integral) for that range of temperatures. For example, the filled area indicates the probability of a temperature exceeding 76°F. SOURCE: Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts.

### BOX 1-1 Continued

complete knowledge of those laws would ultimately enable correct probability forecasts. This is analogous to the concept of attractors in nonlinear dynamical systems theory where the attracting set reflects an underlying PDF that describes the probability of finding the system state in a particular region of state space. A practical argument against the propensity interpretation in hydrometeorological forecasting is that the "true" probability is conditioned on the exact initial state of the atmosphere, ocean, land surface, sun, and all associated physical processes. It is effectively a function of the state of the universe and is therefore unknowable. A related argument would be that, in the same way that initial condition uncertainty renders the future deterministic state of the system unknowable, an imperfect knowledge or representation of the model that governs the hydrometeorological system renders the future PDF of the system unknowable, even if the initial PDF is correct.

Effectively estimating and communicating uncertainty in hydrometeorological forecasts is not dependent on which of these interpretations of probability is used, and it is likely that all three can be applied to provide users with valuable information. For example, ensemble forecasting can be motivated by propensity ideas where scientists strive to make improvements to models and forecasting system components that drive objectively produced, ensemble-based forecast PDFs closer and closer to "true" PDFs. A measure of the quality of the ensemble forecasts is given by their comparison to frequentist climatological PDFs, and human forecasters use these objective PDFs as guidance for their own subjective estimates of probability. Users can also utilize the different forms as well as combinations of uncertainty information to aid in their own decision making.

FIGURE 1.2 Professor Cleveland Abbe, who issued the first official "Weather Synopsis and Probabilities" on February 19, 1871. SOURCE: NOAA Photo Library, http://www.photolib.noaa.gov/people/images/big/pers0074.jpg.

or model errors would inevitably grow large. To deal with forecast uncertainty, Epstein (1969) suggested stochastic-dynamic forecasting, in which forecast errors are explicitly considered during model integration, but computer processing power was not sufficient to support this method at that time. Another approach, *ensemble prediction*, was proposed by Leith (1974), who suggested that prediction centers run a collection (ensemble) of forecasts, each starting from a different initial state. The variations in the resulting forecasts could be used to estimate the uncertainty of the prediction or produce probabilistic guidance. But even the ensemble approach was not tractable at that time due to limited computer resources. The 1970s and 1980s brought rapid improvement in deterministic forecasts due to satellite observations, better numerical models, and rapidly increasing model resolution, further enhancing the dominance of a single-solution, deterministic approach to forecasting.

The first operational probabilistic forecasts in the United States were produced in 1965. These forecasts, for the probability of precipitation (PoP), were produced by human weather forecasters and thus were *subjective* predictions. The first objective probabilistic forecasts were produced as part of the Model Output Statistics (MOS) system that began in 1969. MOS made use of the historical performance of deterministic predictions to provide probabilistic predictions for parameters such as precipitation, precipitation type, and

## BOX 1.2
## Early History of Forecast Uncertainty

Cleveland Abbe ("Old Probabilities"), who led the establishment of a weather forecasting division within the U.S. Army Signal Corps, produced the first known communication of a weather probability to users and the public. On May 7, 1869, Abbe proposed to the Cincinnati Chamber of Commerce that they "inaugurate such a system, by publishing in the daily papers, a weather bulletin, which shall give the probable state of the weather and river for Cincinnati and vicinity one or two days in advance."

Cleveland Abbe released the first public weather forecast on September 1, 1869. With a sense of history, he wrote to his father: "I have started that which the country will not willingly let die." Following the signing by President Ulysses S. Grant of an authorization to establish a system of weather observations and warnings of approaching storms, on February 19, 1871, Abbe issued the first "official" public Weather Synopsis and Probabilities. An early example reports

> "Synopsis for past twenty-four hours; the barometric pressure had diminished in the southern and Gulf states this morning; it has remained nearly stationary on the Lakes. A decided diminution has appeared unannounced in Missouri accompanied with a rapid rise in the thermometer which is felt as far east as Cincinnati; the barometer in Missouri is about four-tenths of an inch lower than on Erie and on the Gulf. Fresh north and west winds are prevailing in the north; southerly winds in the south. *Probabilities* [emphasis added]; it is probable that the low pressure in Missouri will make itself felt decidedly tomorrow with northerly winds and clouds on the Lakes, and brisk southerly winds on the Gulf."

W. E. Cooke, a government meteorologist in Australia in the early part of the 20th century, was one of the first forecasters to advocate a numerical form for uncertainty information in weather forecasts. Cooke developed a numerical scale for presenting forecaster confidence that would "indicate, approximately, the weight or degree of probability which the forecaster himself attaches to that particular prediction" (Cooke, 1906). C. Hallenbeck of the U.S. Weather Bureau was the first to suggest the possibility of probabilistic forecasts of precipitation using a true numeric probability scale (Hallenbeck, 1920). Others in this period also experimented with objective methods for producing probability forecasts, such as through the use of scatterplots showing relationships between previous forecasts and observations (an earlier form of forecast verification).

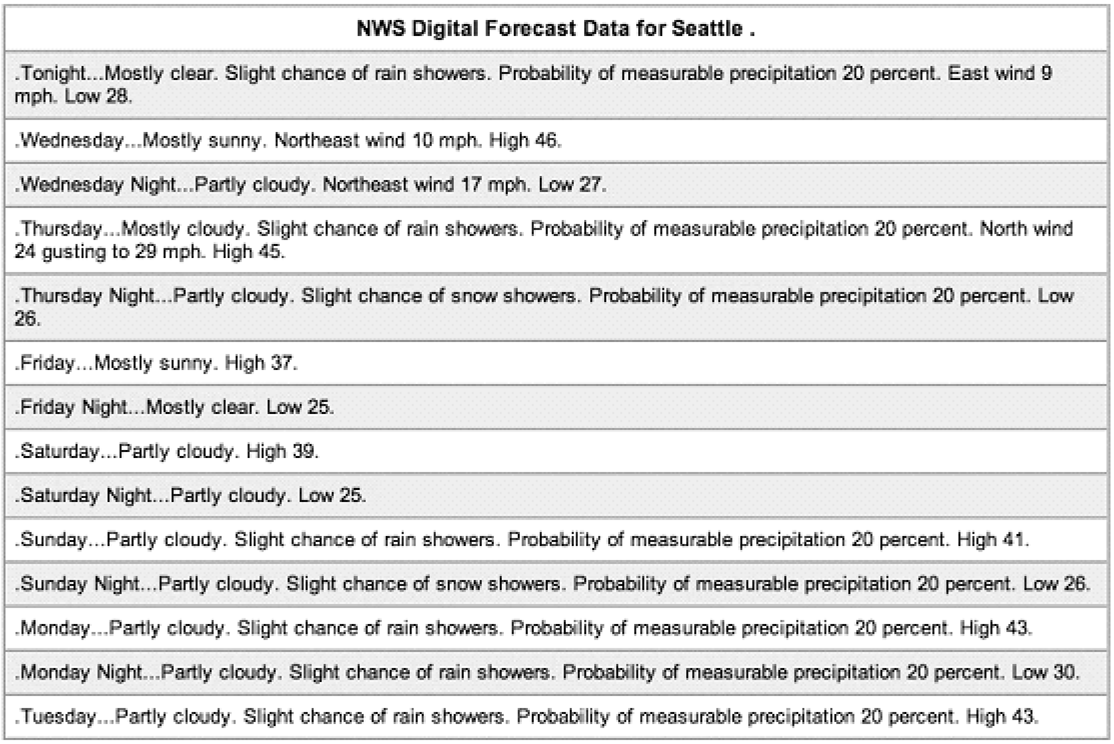
A. Ångström, who focused most of his career on studies of atmospheric radiation, also considered uncertainty in weather forecasting in papers published in 1919 and 1922. In particular Ångström identified sources of uncertainty in weather forecasts (e.g., incomplete observations) and advocated the combination of statistical methods and physics in producing forecasts. Angstrom was apparently the first to suggest the economic value of probabilistic forecasting, long before others made this connection (Liljas and Murphy, 1994). In 1944, G. Brier summarized the rationale for providing forecast uncertainty information to decision makers rather than implicitly making decisions for them by providing deterministic forecasts. This rationale was expounded by other researchers (e.g., Thompson, 1962) and proven analytically by Murphy (1977).

thunderstorms. MOS predictions for most parameters (e.g., wind and temperature) have only provided single-value deterministic forecasts, even though the method is capable of providing uncertainty information.

By the early 1990s, ensemble forecasting became a practical approach to objective estimation of weather forecast uncertainty. Faster computers allowed the initiation of global ensemble prediction at major operational prediction centers such as NCEP, the European Centre for Medium-Range Weather Forecasts, and the Canadian Meteorological Centre. During the past decade the size and sophistication of the global ensemble systems have grown considerably, with medium-range, global ensemble prediction becoming an integral tool for many forecasters. Also during this period, NCEP constructed a higher resolution, short-range ensemble forecast system. High-resolution ensemble systems have also been tested at several universities and government laboratories (Grimit and Mass, 2002; Colle et al., 2003a,b).

NWS began issuing seasonal (30- and 90-day) temperature and precipitation forecasts each month in the late 1950s. These forecasts were developed using historical analogs. They identified areas with a greater chance of experiencing above- and below-average conditions. In the mid-1990s, NWS's Climate Prediction Center (CPC) began issuing overlapping temperature and precipitation "outlooks" for each month up to a year ahead. Several different methods (e.g., dynamical models, analogs, cannonical correlations with El Niño/Southern Oscillation) are used to determine the probability of experiencing above-, below-, and near-average conditions. CPC continues to adjust the outlook product and has developed additional products thought to be useful to weather-sensitive decision makers.

The generation of uncertainty measures for hydrologic forecasts has also long been recognized as an important component in weather-sensitive decision making (in particular, for those associated with water resources). An



| NWS Digital Forecast Data for Seattle . |
|---|
| .Tonight...Mostly clear. Slight chance of rain showers. Probability of measurable precipitation 20 percent. East wind 9 mph. Low 28. |
| .Wednesday...Mostly sunny. Northeast wind 10 mph. High 46. |
| .Wednesday Night...Partly cloudy. Northeast wind 17 mph. Low 27. |
| .Thursday...Mostly cloudy. Slight chance of rain showers. Probability of measurable precipitation 20 percent. North wind 24 gusting to 29 mph. High 45. |
| .Thursday Night...Partly cloudy. Slight chance of snow showers. Probability of measurable precipitation 20 percent. Low 26. |
| .Friday...Mostly sunny. High 37. |
| .Friday Night...Mostly clear. Low 25. |
| .Saturday...Partly cloudy. High 39. |
| .Saturday Night...Partly cloudy. Low 25. |
| .Sunday...Partly cloudy. Slight chance of rain showers. Probability of measurable precipitation 20 percent. High 41. |
| .Sunday Night...Partly cloudy. Slight chance of snow showers. Probability of measurable precipitation 20 percent. Low 26. |
| .Monday...Partly cloudy. Slight chance of rain showers. Probability of measurable precipitation 20 percent. High 43. |
| .Monday Night...Partly cloudy. Slight chance of rain showers. Probability of measurable precipitation 20 percent. Low 30. |
| .Tuesday...Partly cloudy. Slight chance of rain showers. Probability of measurable precipitation 20 percent. High 43. |

FIGURE 1.3 An example (for Seattle, Washington) of a forecast produced by the IFPS, NWS's digital forecasting system, which provides deterministic predictions for temperature and other variables out seven days. SOURCE: NWS Seattle Forecast Office Web site.

ensemble-based technique was developed and operationalized during the late 1970s and early 1980s. This technique produced an ensemble of likely future flows on the basis of historical records of precipitation and temperature and current estimates of soil moisture and snow pack (Day, 1985). This approach only accounted for uncertainty in the meteorological input to hydrological models. Since the mid-1970s, hydrologists have used formal estimation theory to account for input, model, and observation errors to produce short-term flow forecast means and variances, and at the same time to assimilate observations of streamflow by the operational models for short-term forecasts (Kitanidis and Bras, 1980).

## 1.3 COMMUNICATION OF UNCERTAINTY INFORMATION

Hydrometeorological prediction is inherently uncertain and information about such uncertainty should be helpful to users in their decisions. Although some products contain uncertainty information (e.g., in those produced by the private sector for specialized users, and by the NWS in its Area Forecast Discussion and Probability of Precipitation predictions), relatively little headway has been made in supplying actionable uncertainty information to most of the user community.

As an example, the NWS meteorological preparation and communication system (the Interactive Forecast Preparation System, or IFPS) is inherently deterministic. Forecasters prepare graphical descriptions of the state of the atmosphere out as far as seven days into the future, with no uncertainty information or probabilities except for precipitation. The output from the IFPS system (known as the National Digital Forecast Database) is used to provide site-specific forecasts out seven days in graphical and text formats that are single-valued for nearly all parameters (see Figure 1.3).

NWS is not alone in providing such single-valued forecasts, both in the short and extended (3- to 10-day) ranges. Many private-sector firms follow a similar deterministic approach, and their forecasts are provided to the public through new and traditional media outlets. For example, local television news broadcasts, in which the weather is often the lead story, compete to provide single-valued projections as far out as two weeks (Figure 1.4) even though uncertainties typically increase with time and are large beyond a few days. Such single-valued forecasts are a mainstay of the international media and many users have adjusted their decision processes to accommodate these simplified predictions. Even though such deterministic forecasts are without scientific basis and suggest a level of forecasting skill that does not

FIGURE 1.4 A 10-day deterministic forecast from a local television station. The forecast implies certainty in long-range predictions. The length of the forecast is dictated by the station's channel number (an initial five-day deterministic forecast, "Plus 5 More"), as a promotional tactic. SOURCE: KING5-TV, http://www.king5.com/weather/.

FIGURE 1.5 Inconsistent use of NWS icons used to communicate PoP. Note that the same symbol is used for probabilities ranging from 20 to 100 percent. SOURCE: NWS Web sites.

exist, media presentation of these forecasts has multiple drivers in addition to the science.[7]

Problems with the dominance of deterministic forecasting information are compounded by the poor communication of the limited uncertainty information that does exist. For example, PoP is communicated through icons that are unclear and sometimes inconsistent with their supporting text (e.g., Figure 1.5). Furthermore, a portion of the public is uncertain regarding the interpretation of precipitation probabilities (see Section 2.2.2.1). Does a 50 percent probability mean half the area will get wet, or it will rain for half of the day, or there is a 50 percent chance it will rain at any single location within the forecast area during some period (the correct choice)?

One of the few attempts at communicating uncertainty for an important parameter other than precipitation has been the recent introduction of the "cone of uncertainty" diagram used for hurricane track prediction, with the width of the path representing the uncertainty in the track forecast (Figure 1.6). However, the existence of a central line in some of these forecast products, indicating the most probable path, may detract from the effectiveness of the graphic, because many users think that the forecast has failed whenever the observed track deviates from the central line. Such a situation occurred in 2004 when Hurricane Charley, for which the central line crossed the coast near Tampa, Florida, made landfall to the south at Punta Gorda, Florida, which was approximately 40 miles east of the centerline track. Both locations were within the forecast track and were under a hurricane warning. Underlying these and other communication problems is that the Enterprise has conducted little formal research on how to effectively communicate uncertainty information to its users.

## 1.4 REASONS FOR SUPPLYING UNCERTAINTY INFORMATION

The American Meteorological Society's "Statement on Enhancing Weather Information with Probability Forecasts" (AMS, 2002) noted that the current deterministic approach to weather prediction and communication has resulted in "much of the informational content of meteorological data, models, techniques and forecaster thought processes not being conveyed to the users of weather forecasts. Making and disseminating forecasts in probabilistic terms would

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[7] See Chapter 4.

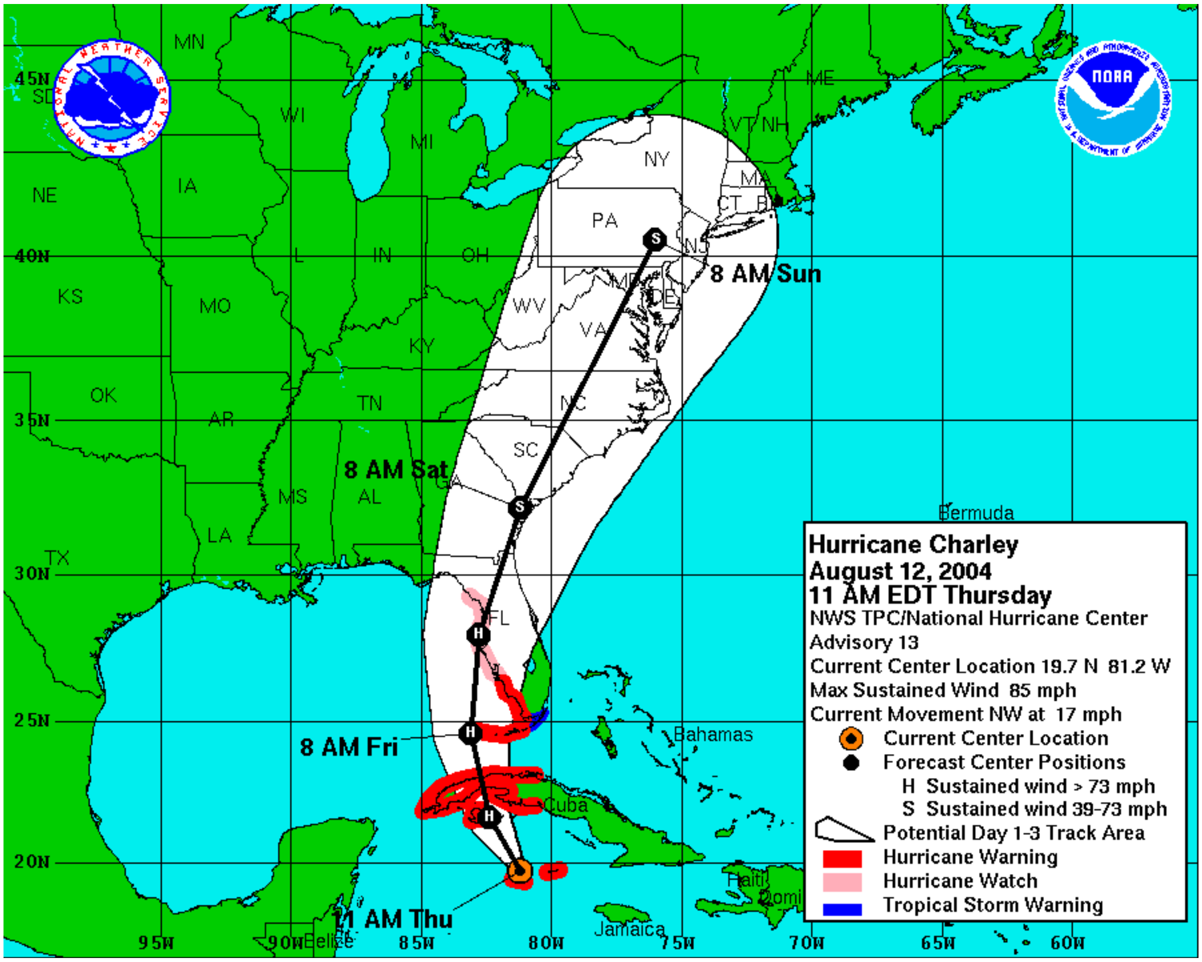

FIGURE 1.6 The three-day forecast of the track of Hurricane Charley about 28 hours prior to landfall near Punta Gorda, Florida. The cone of uncertainty is represented by the white shading, with the most probable track indicated by the black line. This product consistently showed that the ultimate landfall area was within the forecast cone of uncertainty. SOURCE: National Hurricane Center.

correct a major portion of this shortcoming." By providing mainly single-valued categorical information, the hydrometeorological prediction community denies its users much of the value of the information it produces—information that could impart economic benefits and lead to greater safety and convenience for the nation.

There is an extensive literature documenting the potential socioeconomic value of uncertainty information over traditional deterministic forecasts (e.g., Katz and Murphy, 1997). Many of these studies consider simplified forecast-related decisions with a certain cost for protection and a specified loss if the event occurs without mitigation. For example, Murphy (1977) demonstrated that for such predictions reliable probabilistic forecasts always had a higher economic value than categorical forecasts or those based on climate averages, and that even unreliable uncertainty predictions reduce costs over categorical forecasts for most cost/loss ratios.[8] Other studies have examined specific users' decisions in greater detail. In aviation, for example, Keith (2003) demonstrated that the use of probabilistic predictions of visibility and cloud base afforded considerable economic benefit over the usual deterministic Terminal Aerodrome Forecasts. A retrospective study of management strategies for large reservoirs in California (WSAT, 2000) showed that using uncertainty information from a seasonal ensemble resulted in a 9.5 percent increase in annual hydroelectric revenue with a 40 percent reduction in wasteful spillage compared to using deterministic predictions.

The failure to provide forecast uncertainty information can contribute to damage and loss of life. For example, Pielke (1999) discussed how the lack of uncertainty information

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[8] A low cost/loss ratio means a large loss or very expensive loss relative to the cost.

in NWS forecasts dealing with the potential rise of the Red River in 1997 contributed to insufficient preparation by the population and public agencies. This catastrophic flooding event, which caused over a billion dollars of damage, was well within the typical error of the forecast river level. But such uncertainty information was not provided to the public or even other federal agencies.

With the availability of uncertainty information, users—each with their own sensitivity to costs and losses and with varying thresholds for taking protective action—could better decide for themselves whether to take action and the appropriate level of response to hydrometeorological situations. For example, current NWS wind predictions provide limited uncertainty information; consequently, for users who experience damage at 30 mph or more, a single-valued prediction of 25 mph or even a range of say 23 to 27 mph might not prompt any protective action. A probabilistic wind prediction, however, would likely indicate a modest probability that wind speeds could exceed 30 mph. Thus, the user with a low cost/loss ratio (low cost to protect or very expensive loss) might choose to use resources for protection in such a circumstance, whereas users with a high cost/loss ratio would likely do the opposite. In this way, probabilistic information can improve use of resources and enhance protection of life and property. More complex situations arise in the case of water resources facilities that serve many users and multiple objectives (e.g., water supply, ecosystem health, hydroelectric power production, flood control). In such cases, more elaborate decision-support systems may be necessary to guide decisions that result in substantially increased benefits for all stakeholders (Loucks, 1989).

In addition to socioeconomic value and scientific validity, a third reason for provision of uncertainty information is to retain user confidence. Forecasting a single atmospheric or hydrologic evolution when considerable uncertainty exists, without effectively communicating that uncertainty, inevitably undermines user confidence since there will always be significant and unavoidable forecast errors. If users knew that a range of occurrences was possible, the credibility of the forecasting community could be maintained since a probabilistic prediction system may have indicated a significant probability for the actual occurrence.

Finally, there is also an ethical dimension to the lack of uncertainty information in most hydrometeorological predictions. The Enterprise is providing many users with deterministic forecasts for a week and beyond, implying a level of forecast accuracy and skill that does not exist. Providing such single-value forecasts at any time range is deceptive and incompatible with the well-known state of the science, which acknowledges the inherent uncertainty in prediction. By comparison, in the medical arena probabilistic prognoses are commonplace as are the probabilities of cure with various therapies. As noted in recommendation 8 of the *Fair Weather* report (NRC, 2003a), NWS, as "the organization responsible for setting the scientific standard for operational meteorology" should "adopt and improve probabilistic methods for communicating uncertainties in the data and forecasts where such methods are accepted as scientifically valid."

## 1.5 THE NEED FOR AN ENTERPRISE-WIDE RESPONSE

The shift of hydrometeorological prediction to a scientifically valid approach that fully considers, communicates, validates, and appropriately applies forecast uncertainty will demand the cooperation of the entire Enterprise. For NWS, this cooperation occurs in the context of NOAA's partnership policy, which guides the agency in interactions with others in the Enterprise (Box 1.3).

Treating uncertainty as a fundamental characteristic of hydrometeorological predictions will require new links and feedbacks among the various sectors of the Enterprise. The academic, public, and private sectors will need to cooperate in estimating and studying uncertainty, understanding user needs and capabilities, generating new products that effectively communicate uncertainty, and developing new types of public outreach and educational and training programs to promote appropriate interpretation and use of these new forecasts. In addition, uncertainty-explicit forecasts will likely foster the emergence of new intermediaries from academia and the private sector to develop decision-support systems

### BOX 1.3
### NOAA Partnership Policy

NOAA's Policy on Partnerships in the Provision of Environmental Information (updated January 2006) states that "[t]he nation benefits from government information disseminated both by Federal agencies and by diverse nonfederal parties, including commercial and not-for-profit entities. NOAA recognizes cooperation, not competition, with private sector and academic and research entities best serves the public interest and best meets the varied needs of specific individuals, organizations, and economic entities. NOAA will take advantage of existing capabilities and services of commercial and academic sectors to support efficient performance of NOAA's mission and avoid duplication and competition in areas not related to the NOAA mission. NOAA will give due consideration to these abilities and consider the effects of its decisions on the activities of these entities, in accordance with its responsibilities as an agency of the U.S. Government, to serve the public interest and advance the nation's environmental information enterprise as a whole."

SOURCE: http://www.nws.noaa.gov/partnershippolicy/.

to enhance the utility of such forecasts. Such intermediaries would encourage new links and feedbacks between forecast producers and forecast users within the Enterprise. Last, the introduction of new uncertainty-explicit forecasts will generate the need for continuing validation, producing feedbacks from the forecast users to the forecast producers that may affect the manner of product generation and form of communication.

Although cooperation among sectors of the Enterprise would require some additional effort from all participants, several benefits are envisioned for each sector. NWS, through cooperation with academia and the research sector, gains access to state-of-the-science models, methods, and approaches, whereas through cooperation with the private sector and users it enhances the utility of forecast products, gains an understanding of the economic or market-driven forces of effective communication of uncertainty information, and receives feedback on forecast validation and user needs. The academic and research sectors gain access to NWS data and model resources for advancing research goals, receive feedback from NWS and the private sector for improving educational objectives, and develop new interdisciplinary areas of inquiry at the interface of physical, social, and behavioral sciences. For the private sector, close cooperation would facilitate the transfer of academic research to societal use and would ensure educator/researcher knowledge of the requirements of the workplace. Furthermore, the private sector gains access to validated operational predictions and data that may be used to generate value-added products tailored to user needs.

## 1.6 EDUCATION AS A CORNERSTONE OF THE TRANSITION TO A PROBABILISTIC VIEWPOINT

If the Enterprise is to make a successful transition from a predominantly deterministic mode of forecast generation and communication to one in which uncertainty information is an integral part of all products, substantial education and retraining of both users and providers of hydrometeorological predictions will be required. The university community will need to support changes in courses and curricula to ensure its graduates possess necessary knowledge of forecast uncertainty, methods for its generation, and the potential value of uncertainty information for meeting societal needs. NWS forecasters will need to master the underlying ideas of ensemble prediction and forecast uncertainty and will require retraining to deal with the new probabilistic forecast communication systems of the future. To facilitate such a transition NWS will need to establish new training materials, drawing on outside expertise in areas including the social sciences to create new tools such as educational modules for the Cooperative Program for Operational Meteorology, Education and Training dealing with forecast uncertainty. Similarly, the private sector will need to retrain its forecast personnel, both in the production and communication of uncertainty information. Reaching out to expertise beyond the traditional hydrometeorological community will increase the probabilities of success. Finally, the Enterprise will need to facilitate substantial outreach to the public and other users to acquaint them with the limitations of traditional single-value predictions and the considerable value of uncertainty information.

## 1.7 THE UNCERTAINTY IMPERATIVE

There is a confluence of compelling reasons for the Enterprise to transition to a new paradigm for hydrometeorological prediction, one in which uncertainty information is considered an integral and essential component of all forecasts. Prediction is inherently uncertain, and only by having access to actionable uncertainty information can users consider and apply the complete information required to make the best decision for their needs and situation. Fortunately, the demand for a transition to uncertainty communication is concurrent with an increasing ability to generate reliable uncertainty guidance.

The remainder of this report examines the psychological elements underlying use of uncertainty information (Chapter 2), reviews the strengths and weaknesses of the current operational systems for producing and verifying such forecasts (Chapter 3), and then evaluates current modes for communicating uncertainty information (Chapter 4). Based on this analysis, a series of overarching recommendations is presented in the final chapter. Actions in response to these recommendations will enable the transition to a new era in hydrometeorological prediction.

# 2

# Uncertainty in Decision Making

This chapter provides guidance on how to identify and characterize the needs for uncertainty information among various users of forecasts, including members of the public, emergency managers, other government decision makers, and private-sector entities, both direct users and intermediaries.

To do so, it is first necessary to understand how decision makers interpret and use uncertainty information. Following a general overview of user types and needs for uncertainty information, Sections 2.2 and 2.3 summarize, respectively, how two streams of research have addressed the question of how decision makers interpret and use uncertain information—one from a descriptive perspective (how decisions under uncertainty *are* made), the other from a prescriptive perspective (how decisions under uncertainty *should* be made).

The descriptive perspective identifies *psychological* factors that influence how users perceive risk and uncertainty and process uncertainty information. These factors can lead to decisions that are quite different from those suggested by traditional "rational" decision models and, in the case of weather and climate forecasts, different from those expected by forecast communicators. The prescriptive perspective, *statistical decision theory*, considers how the major factors (inputs, preferences or goals, outputs, etc.) affecting a decision can be developed into a model that relates inputs to outputs and expected performance. Quantifying these factors and analyzing the results makes it possible to identify "superior" choices, conditional on the data used and the model's assumptions. While the psychological perspective suggests that the statistical decision theory does not fully describe real-world decision making, such a process may aid decisions and improve understanding of decision making by reducing complexity and focusing the analysis.

Following the sections on prescriptive and descriptive approaches, Section 2.4 discusses how National Weather Service (NWS) and the Enterprise might apply this knowledge to better understand users' needs for uncertainty information. There is a vast and growing literature on psychological issues associated with processing of uncertainty information and different methods of communicating user-specific probability and other uncertainty information. The committee did not review and digest this literature and parallel literatures (e.g., on the communication of risk information in health and medicine) to the point of making recommendations for the design of specific forecast products. Instead, and given that the need for probabilistic forecast products will grow, the committee recommends a *process* by which NWS can develop an effective system of provider-user interactions that will lead to the design and testing of effective forecast formats. Detailed recommendations about the specifics of the process are distributed throughout the chapter. Some of the recommendations are further developed in Chapter 4.

## 2.1 USER TYPES AND NEEDS FOR UNCERTAINTY INFORMATION

### 2.1.1 General User Types and Needs for Uncertainty Information

As forecast skill has increased in recent years, forecasts have become an important component of everyday and hazardous-weather decision making for many segments of society and the U.S. economy. Users of forecasts generated by the Enterprise range from members of the public to those with significant training in statistics and risk management. These different groups of users are diverse in both information desires and needs and their ability to process uncertainty information. NWS, in support of its mission to protect life and property and enhance the national economy, provides forecast information to some users directly, and to some users indirectly through intermediaries such as the media and other private-sector entities.

There are two broad categories of NWS forecast users (Figure 2.1): individuals or organizations who use the forecast directly in their operational decisions or their strategic planning, and organizations or institutions that act as inter-

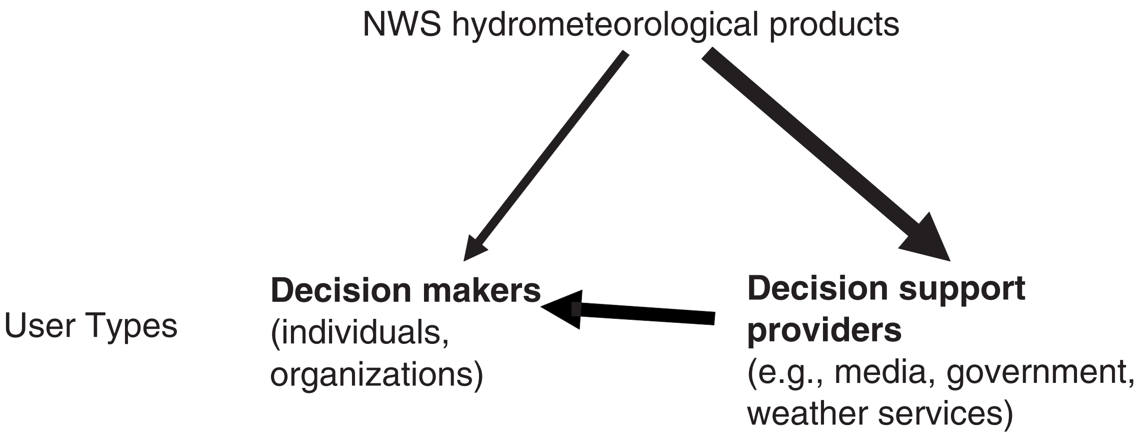

FIGURE 2.1 User categories for NWS products and the flow of forecast information and products among them. Line thickness qualitatively illustrates the relative magnitude of flow. SOURCE: Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts.

mediaries between NWS and the public. Those include the media, government organizations, and weather services. The psychological factors in interpretation and use of uncertainty information apply mostly to individual end users. However, some intermediaries (such as the media) can exhibit similar understanding of probabilistic information. In addition, forecast products and formats that work for the NWS scientists who develop them may not be understandable to and usable by less specialized information processors.

The decision-support systems and analytic decision methods discussed in Section 2.3 are found to a far greater extent among users who get their information from the intermediaries listed on the right-hand side of Figure 2.1. Whether the decision processes that utilize hydrometeorological forecasts are informal and intuitive or formal and analytic, forecast producers need to be cognizant of how forecast information gets used to decide on how to optimally present its uncertainty.

Weather and climate affect nearly all segments of society, and there is a multitude of weather- and climate-related decisions and decision makers. More specifically, decision processes and their consequences vary on at least the following dimensions:

- *Forecast user*: for example, individual, institution, or Enterprise member/intermediary;
- *Sector:* for example, travel, tourism, energy, water, agriculture, insurance;
- *Type of decision*: for example, emergency response, routine/recurrent operation, or adaptive long-term management plan;
- *Time or space scale*: for example, imminent flood management at a location, or prediction of global market prices for commodities in a future season, or long-term corporate or national investments in infrastructure;
- *Problem complexity*: for example, single objective with a few known inputs, or multiple objectives with many inputs/outputs and sources of uncertainty;
- *Decision processes*: for example, analytic versus intuitive; exhaustive analysis of response options versus semiautomatic decision rules or response triggers, and framing of outcomes as gains or losses; and
- *Consequence of decision*: for example, carrying an umbrella unnecessarily; saving lives and property.

In general, users want forecasts to help them make a decision: What clothes do I wear? Do we send out snowplows, and if so, when? Do we purchase additional fuel supplies for the coming months, and if so, how much? Do we order mandatory evacuations?[1] The decisions made with hydrometeorological forecasts are so numerous and variable that this report cannot identify and specify the information needs of each individual user or user community. Thus, this section explores user needs for uncertainty information by discussing broad user communities and presenting examples. Guidance to NWS on how to build capacity to identify its users' needs in greater detail is presented in Section 2.4

### 2.1.2. Specific User Types and Needs for Uncertainty Information

Although NWS has not established a comprehensive formal method for incorporating uncertainty information into its services and products based on user needs,[2] it does have

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[1] As these examples illustrate, many (but not all) user decisions are binary (yes or no), often with some threshold for action. Within this binary decision, however, there can still be a range of alternatives related to type of action (e.g., take a raincoat or an umbrella), timing of action, and other factors.

[2] As noted in written responses from NWS to the committee and in a presentation by Ed Johnson at the committee's first meeting.

snapshots of those needs. For example, according to a recent customer satisfaction survey commissioned by NWS, most NWS customers surveyed want uncertainty information, but they are significantly less interested in probability information. With regard to the Advanced Hydrologic Prediction Service, NWS reports that although the available probabilistic information is utilized by specialized users, it has yet to be widely utilized by members of the public or even emergency managers. Nonetheless, these same users do understand and use qualitative uncertainty information.

Hydrometeorological forecasts are used in multiple ways that include variations in the time horizon of the forecast, the type(s) of variables being predicted, their geographic specificity, and other factors. This section discusses the different uses to which hydrometeorological forecasts can be put from a more abstract decision-making perspective. The examples provided differ on three continua. The first is along the dimension from simple, binary or go/no-go decisions that rely on some criterion cutoff to more complex, continuous decisions, such as deciding on the planting density of a crop as a function of a seasonal precipitation forecast. The second continuum ranges from little or no lead time to make a decision to decisions with longer lead time that often allow for adjustments along the way. The third continuum ranges from decisions of little consequence to decisions with severe consequences. Whereas decisions with low stakes occur very frequently (e.g., should I carry an umbrella today?), the consequences of the rare decisions with high stakes and thus the importance of transmitting forecasts in those situations in the most effective and socially beneficial way are many orders of magnitude greater.

One of the three examples in this discussion depicts short-term warning of an approaching hurricane (Box 2.1), and forecasts and warnings are directed at intermediaries but also at end users. This example involves high stakes, the loss of human life, and major physical destruction. The second and third examples (Boxes 2.2 and 2.3) involve the communication of a seasonal climate forecast to analytically more specialized users and intermediaries in different sectors. In these cases, the time urgency and the targeting of the message at analytically less well trained recipients make it less desirable to transmit the probabilistic nature of the forecast and more important to hit the right emotional tone and level of the message conveyed by the forecast.[3]

Much can be learned about users' needs for forecast uncertainty information from the experience of the private meteorological sector.[4] For example, according to one major private weather forecasting company, although its clients differ widely in their uses of forecasts, there are common themes in their needs for uncertainty information. Many of the company's customers want to know the "worst case" and the forecaster's "best guess" (i.e., most likely outcome), as well as the level of confidence the forecaster has in their own forecast (often phrased as "What would the forecaster do in their situation?"). Their users frequently assess uncertainty by seeking multiple sources of information, given its relatively easy availability on the Internet. Rather than a continuous probability distribution function (see Box 1.1), many of their users also prefer a presentation of high-, medium-, and low-likelihood events (expressed quantitatively, a 10/80/10 percent distribution in which the middle 80 percent corresponds to the medium likelihood). Many of their customers also want decision-support tools that translate uncertainty forecasts into risk analysis.

Finally, much can also be learned from the experience of the international community in understanding user needs. Some of these international experiences may not be directly applicable to NWS, since hydrometeorological services operate differently and have different missions in different countries (particularly with respect to roles of public and private sector), but it still can be informative.

### 2.1.3 Constraints and Limitations on Use of Uncertainty Information

While users may seek uncertainty information, they may not always need it or be able to use or to act upon it. For instance, state departments of transportation reportedly want probability information on road weather, but researchers find that they may not actually know what they are really asking for.[5] As discussed in more detail in Section 2.2.1.4, users have a range of numeracy and analytical skills, and many users, even sophisticated ones, may not be able to process and manage uncertainty information, either manually or by computer. Emergency managers in Los Angeles, for instance, report that they are grappling with more mundane data problems such as accessing, exchanging, and verifying data, not to mention reviewing, understanding, and interpreting such data.[6] Users also require time to incorporate new information into their decisions; for example, tactical decision making in the aviation industry involves extremely short timescales, which can complicate the use of uncertainty information. Moreover, the information provided must also be compatible with the capabilities of the science. In the long term, providing information that is scientifically indefensible will not benefit users' decisions and thus will not satisfy their wants and needs.

The provision of more information is also not always desirable because additional information can delay or complicate action, with great costs in situations of time pressure and high stakes, especially when information besides hydrometeorological forecast information plays an important role.[7]

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[3] See related material in Box 4.3.

[4] Presentation by Jim Block, September 2005.

[5] Presentation by Bill Mahoney, September 2005.

[6] Presentation by Ellis Stanley, August 2005.

[7] The *provision* of uncertainty information is different from the *production* of such information. As noted in Chapter 3 in particular, the capability to

## BOX 2.1
## Hurricane Katrina

Forecasts of extreme weather events such as tornadoes and hurricanes that are associated with large socioeconomic impacts must communicate important information to many types of users ranging from members of the public to decision makers in industry and government. Such forecasts generally provide a small lead time (e.g., up to 3 days in the case of hurricanes; see Figure 2.2) for decision makers. In the case of Hurricane Katrina, which hit the Gulf Coast in late August 2005, everyone in the affected region had to make weather-related decisions, many of them with life-death consequences.

The consequences or outcomes related to decisions varied widely among users. Many decided to stay and either lost their lives (nearly 1,500 individuals died) or were stranded in the flooded areas in and around New Orleans. Nearly everyone in the region experienced some unavoidable economic loss. However, some organizations (e.g., regional railroads) used the forecasts of the projected hurricane path to make critical decisions (e.g., remove trains from the city prior to landfall) to minimize losses. Although the hurricane track forecasts were provided with uncertainty information (e.g., the cone of uncertainty) the short decision period of less than 48 hours forced a relatively limited decision in most situations (e.g., evacuation of at-risk locations and oil and natural gas platforms). Decision-support systems that highlight the likelihood of potential consequences, and provide

*continued*

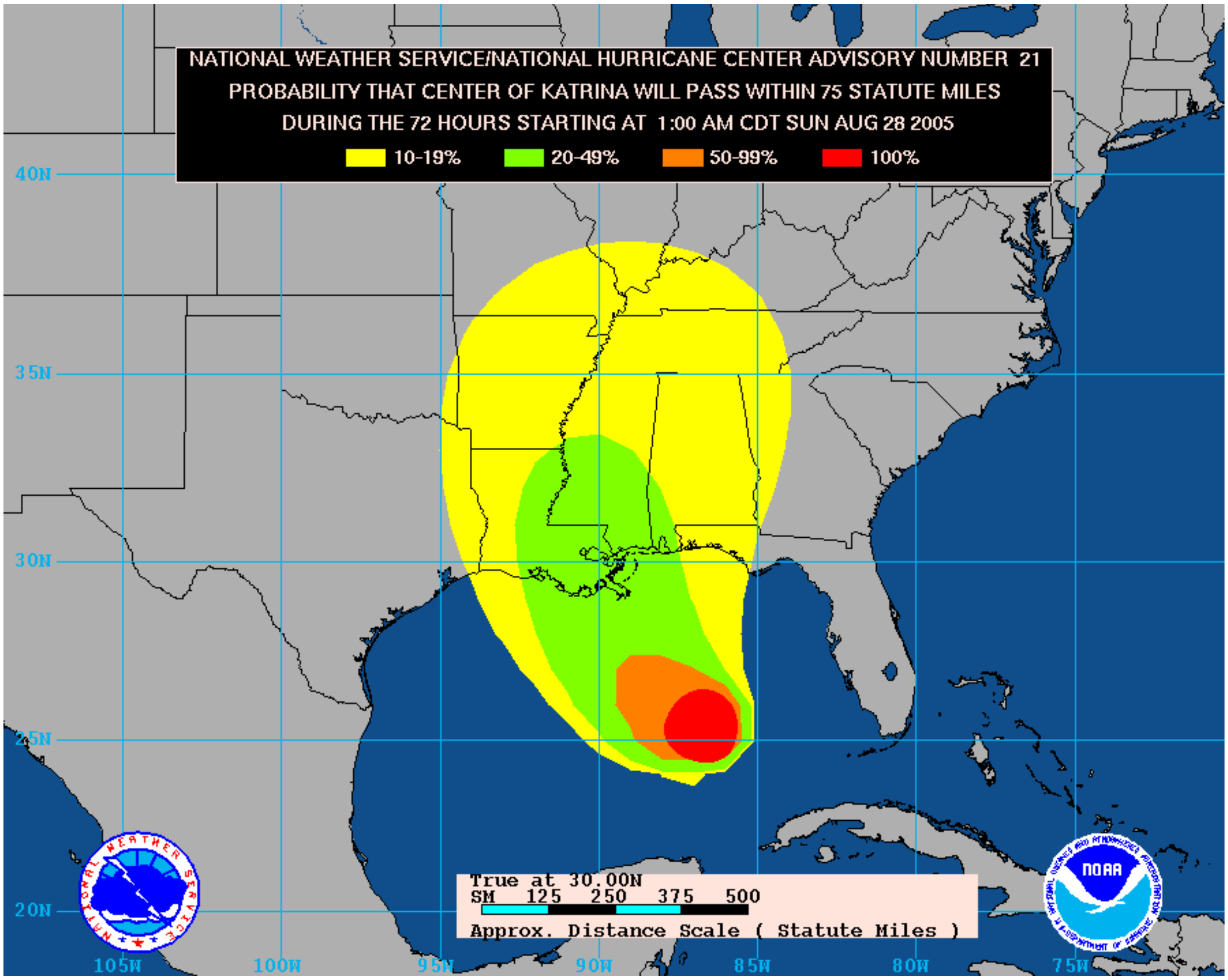

FIGURE 2.2 72-hour NOAA hurricane strike probability forecast from August 28, 2005, preceding Katrina's landfall. SOURCE: National Hurricane Center.

### BOX 2.1 Continued

information on the continuously changing evacuation times and conditions, could be of great value to a number of key groups, such as emergency managers, in these high-pressure decision situations. However, it is not yet clear to what degree such tools were used during Hurricane Katrina.

A key approach in catastrophic events is to communicate information in a clear, consistent manner. In addition, those disseminating information must understand and communicate the accuracy of the forecast and the potential consequences. For an emergency manager it may be critical to receive forecast uncertainty information to decide whether or not (and where) to order an evacuation and to put in the necessary support services (e.g., national guard, evacuation vehicles, communication methods, financial support services). The affected public needs to decide whether and how to act based on an evaluation of their situation, the emergency manager directive, and their access to the services. As to the communication aspect, care is needed when comparing an ongoing event to one that occurred earlier. For example, comparisons of Hurricane Katrina with Hurricane Camille, which occurred in 1969, might have triggered an undesirable response by some (based on their memory). Showing worst-case scenarios, such as the levees failing and the entire Ninth Ward of New Orleans under water, might have created a different response. However, someone would still have to decide to show such scenarios and how to present them. That decision would need to be informed by prior analyses of potential consequences and of what to do as a function of the assessed uncertainty of the forecast, and of the consequences. Hurricane wind and rain forecasts are but one part of the uncertainty associated with levee failure.

### BOX 2.2
### Seasonal Energy Decisions

Deregulation of the energy markets in the 1990s and the success of recent long-lead winter seasonal temperature forecasts (e.g., in 1997-98) have altered how power-utility decision makers view the use of climate information and seasonal forecasts (Changnon et al., 1995). Lead times associated with weather-sensitive utility decisions vary from a week to months. Primary applications of seasonal forecasts within utilities include power trading, load forecasting, fuel acquisition, and systems planning. Energy companies consider factors that often change, including those that are not weather-related. This creates complex decision schemes and the need for decision-support systems. For example, use of the winter temperature forecast depends not only on the accuracy or confidence in the forecast, but on whether other factors such as current natural gas supplies dominate over the forecast information.

The consequences of weather-related decisions can be extremely large for a utility. Prior to the El Niño winter of 1997-98, many Midwestern power traders used the forecasted warm, dry winter conditions to alter their purchasing decisions, thus saving consumers millions of dollars (Changnon, 2000). The development and use of “weather derivatives” during the 1990s provided a means for power traders to insure against weather and climate risks (Dutton, 2002; Changnon, 2005). On average approximately $4 billion worth of weather contracts are sold in the United States each year. Other utility users of seasonal forecasts, including those in fuel acquisition and system management also must make economically important decisions that are based on a full understanding of the potential benefits and losses of such decisions.

Utility companies are generally comfortable with probability-based forecasts but are often interested in obtaining climatological information and explanations of the forecasts (Changnon et al., 1995). In addition, utility officials have identified a number of hindrances to the use of forecasts including forecasters not communicating the level of accuracy of winter forecasts, forecast information that is difficult to understand and integrate into existing decision-support systems, and lack of access to forecast experts who could enhance use of information by providing a level of confidence in a given forecast (Changnon et al., 1995).

As discussed in more detail in Chapter 4, when developing products to communicate forecast uncertainty (and deciding where to expend resources in doing so), it is necessary to consider user needs and capabilities rather than simply providing a large amount of information and expecting it to be useful or used. For example, many road weather decisions are primarily driven by budgets.[8] Some transportation agencies also prefer a deterministic rather than probabilistic forecast because the weather of interest has such severe consequences that they will treat the roads in the event of any chance of precipitation (and would also prefer not to have field staff, aided

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produce uncertainty information for users, in and of itself, is valuable and indeed critical for creating forecast products tailored for a specific use.

[8] Presentation by Steve Zubrick, August 2005.

### BOX 2.3
### Sacramento Floods and Folsom Reservoir Operation

Like New Orleans, Sacramento, which lies in the flood plain of the American and Sacramento rivers, is one of the U.S. cities most vulnerable to flooding (NRC, 1995, 1999a, 2000). Major floods in the years immediately following the Gold Rush of 1849, in particular the flood of 1861-62, highlighted Sacramento's vulnerability. Initial efforts to control floods purely by levees were shown to be ineffective by the 1907 flood, and by 1956 a comprehensive system of levees, bypasses, channel improvements, and dams, including Folsom Dam on the American River, was largely implemented.

The development of design criteria for Folsom Dam entailed the use of the historical hydrometeorological data to provide the city with protection from a 500-year flood event. Folsom Reservoir was developed as a multipurpose reservoir for hydropower, flood control, recreation, and water supply. Operating rules were developed for the reservoir using historical data, as well as synthetic flows generated from time-series analysis—but not hydrometeorological forecasts. These rules specify upper and lower limits on storage volumes retained for future flood control, water supply, and energy production as a function of calendar date. The rules are derived from long simulations of system operation to meet target demands under acceptable levels of reliability for each aspect of operation. Thus, the physical infrastructure and its operation rules are developed in the context of statistical decision theory (Section 2.3) using probabilistic information on supply and flood volume and timing derived from the historical record.

A major flood not included in the design studies for the Folsom Dam occurred in 1997. As was the case with a record flood in 1986, the 1997 flood brought the system to the brink of failure—levees were nearly overtopped. With the new flood taken into consideration, the estimate of the degree of flood protection may be revised to be as low as the 80-year flood level (NRC, 1999a). It is unclear whether the occurrence of two very significant floods in the past two decades is due to sampling variability (i.e., uncertainty in the estimation of the flood occurrence probabilities) or climate change (i.e., a lack of representativeness of the historical record used for system design). The inability to resolve the nature of this uncertainty, combined with other scientific, economic, and political issues, has led to inaction regarding construction of new infrastructure to adequately protect Sacramento from flooding. Consequently, adaptive system management using probabilistic inflow forecasts and improvements to the release structures have emerged as the primary approaches to manage the reservoir operations against hydroclimatic risk. Along these lines, the U.S. Army Corps of Engineers (USACE) is studying alternatives to a pre-release scenario on the basis of hydrometeorological forecasts (USACE, 2002).

Development of adaptive system management under inflow forecast uncertainty is a challenging problem for the multipurpose Folsom Reservoir. Multiple time scales need to be considered for the operation of the system. Probabilistic weather forecasts at 0- to 7-day lead times would be needed in conjunction with monitored watershed hydrology to estimate flood volume probabilities to aid decisions on advanced releases of water in anticipation of a flood. Probabilistic forecasts of monthly and seasonal rainfall would be needed to generate probabilistic inflow forecasts to assess reservoir refill probabilities by the end of the wet season. The consequences of excess advanced release could be the inability to fill the reservoir by the end of the wet season and, consequently, an inability to meet future energy and water demands. Multidecadal scenarios of forecasts would be needed to assess whether modifications in operating rules to take advantage of probabilistic forecasts would indeed translate into risk reduction and benefits relative to the existing default policies in the long run. Implementation of modified rules by the managers in the absence of long-term performance simulations is unlikely. Initial work in these directions has started as a collaborative effort of researchers, forecasters, and managers (Georgakakos et al., 2005).

This is an example of a system vulnerable to hydroclimatic variability for which there is the technical ability to use probabilistic hydrometeorological forecasts in an analytic framework for risk reduction. It also represents a good opportunity for the development of a testbed (see Section 3.1.6).

with uncertainty information, second-guessing management decisions). In agriculture, many users' decisions are affected more by economic factors such as export market conditions, than by hydrometeorological forecasts.[9] Water resources managers' decisions are dominated not by hydrometeorological forecasts but instead by regulations, costs, power markets, politics, and, of late, terrorism threats.[10] Organizations often also establish standard operating procedures (e.g., with specific roles and responsibilities for each position) that have developed over many years and may not easily adapt to inputs of new information (e.g., Box 2.4). And some users do not even utilize *existing* forecast products and tools. For example, by law, the USACE cannot make reservoir management decisions based on forecasts.[11] When they do use forecast information, many water resources and agricultural users prefer scenarios and collections of past observed events that "look like" what they expect to see in the future (analogs), instead of simply probability information.

Users process information both emotionally and rationally. The next two sections discuss ways in which users might deal with probabilistic forecasts from the perspective of the recent descriptive and psychological literature on decision making under uncertainty. The elements of statistical decision theory

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[9] Presentation by David Changnon, September 2005.

[10] Presentation by Kathy Jacobs, September 2005.

[11] Presentation by Beth Faber, September 2005.

### BOX 2.4
### Example of the Complex Ways that Uncertain Hydrometeorological Information Can Interact with User Decision Making

Flood managers often make high-stakes decisions based on complicated and usually incomplete data and information amidst not only much uncertainty but also constant change. The interaction between hydrometeorological uncertainty and flood management decision making was explored in a study by Morss et al. (2005). Like many groups of users, flood managers are not a homogeneous group; rather, the group includes decision makers from a variety of disciplines who operate under the priorities and values of their respective constituencies and communities. Their decisions must often be made quickly, using whatever information is available at the time, and the options available to them frequently must be taken in untidy, discrete chunks and not continuously along an elegant distribution of probabilities. And in many cases, flood management decisions are, in essence, already made for them, determined well in advance by land-use patterns, existing infrastructure, and rigid operating rules.

In such an environment, these resource constraints—in addition to technical capacity, familiar and comfortable routines, and even personal relationships with trusted advisers—triumph over scientific information, especially when different sources of hydrometeorological information and guidance conflict. Flood managers thus often retreat to simple analyses and actions that, while perhaps not fully incorporating the best science and uncertainty information available, are nonetheless logical and defensible. Based on their findings and the experience of others, Morss et al. (2005) recommend that to provide usable scientific information, scientists must invest time and effort to develop long-term relationships with flood managers, providing a two-way street for ongoing interaction and feedback. For information to be used, scientists must also make hydrometeorological information directly applicable and practical for a flood manager's situation and environment. Such an approach should eventually lead to the familiarity with, trust in, and credibility of scientists that flood management practitioners seek when making critical decisions and thereby allow them to better incorporate hydrometeorological information into those decisions. As noted earlier, for some users a key component of this information is detailed forecast and historical information for user-based verification.

that may constitute an input into such processes are then discussed in the subsequent section. The formal analyses of the statistical decision analysis approach may be internalized in many businesses (e.g., for decisions on maintenance, inventory and supply chain management, infrastructure and strategic planning, and insurance). The opportunity for the use of probabilistic forecasts by different users may vary dramatically, and different types of efforts (e.g., modification of an existing decision-support system, or a detailed analysis of factors that determine decisions and the "safe" introduction of probabilistic information into that process) may need to be stimulated by the Enterprise to make forecasts useful to these groups.

## 2.2 PSYCHOLOGICAL FACTORS IN INTERPRETING AND USING UNCERTAIN INFORMATION

This section reviews some established results from the psychology of risk and uncertainty; that is, what is known about the way in which people deal with risk and uncertainty and how they understand and utilize uncertainty information? It begins by describing several psychological dimensions relevant to the communication of uncertainty information on which potential users of weather and climate forecasts are known to differ. Most of these differences derive from the fact that people process uncertainty information with the help of two systems, an experiential/emotional system and an analytic system. These two processing systems operate for everyone, but the degree of sophistication of the analytic processing system and the attention paid to it by the decision maker strongly differ as a function of education and training, and by the current rules of practice in an organization. This section discusses the implications that this and other individual differences might have for the design of forecast uncertainty products. Section 2.2.2 describes three complications in the communication of uncertainty information that lie at the root of possible user misinterpretations or rejections of probabilistic forecasts and point the way to user needs.

### 2.2.1 Psychological Heterogeneity in Users

The psychological heterogeneity of users makes it impossible for any single forecast product to satisfy the needs and constraints of all users. Factors that influence the way in which users perceive uncertainty and make decisions include the operation of different information-processing systems, how information about possible events and their likelihood is obtained, the different emotional impact of gains versus losses, and the degree of numeracy and personality of a particular user.

#### *2.2.1.1 Two Processing Systems*

Research from cognitive, social, and clinical psychology suggests that people process information in two distinct ways when making judgments or arriving at decisions (Epstein,

TABLE 2.1 Two Human Information-Processing Systems

| Emotionally Driven Experiential System | Analytic System |
|---|---|
| Encodes reality in concrete images, metaphors, narratives linked in associative networks | Encodes reality in abstract symbols, words, numbers |
| - Experiential<br>- Intuitive<br>- Vivid<br>- Affective | - Analytic<br>- Logical<br>- Abstract<br>- Deliberative |

SOURCE: Marx et al. (2006).

1994; Chaiken and Trope, 1999; Sloman, 1996; Table 2.1). The first, evolutionarily older system works on the basis of affective associations and similarity; it teaches us, for example, to avoid the hot stovetop that caused us pain when touched, and to avoid similar stovetops in the future. This associative system is intuitive, automatic, and fast. It maps uncertain and adverse aspects of the environment into affective responses (e.g., fear, dread, anxiety) and thus represents *risk* as a *feeling* (Loewenstein et al., 2001). It requires real-world experience as input (and more experienced decision makers make better decisions using it than novices), but its basic mechanisms are present in every healthy infant and do not need to be learned.

The second processing system works by analytic algorithms and rules, including those specified by formal models of judgment and decision making (Section 2.3), but also less formal rules like those embodied in customs or proverbs. It translates experience into symbolic representations (words, symbols, or numbers) that can be manipulated by rules and algorithms. These rules need to be learned and are taught both formally (e.g., college courses on probability theory) and informally (e.g., culture-specific rights and obligations that are transmitted in the form of proverbs or professional codices). Unlike the associative system, the analytic processing system does not operate automatically, and its operation requires effortful conscious awareness and control.

The two processing systems typically operate in parallel and interact with each other. Analytic reasoning cannot be effective unless it is guided by emotion and effect (Damasio, 1994). In many if not most instances, the two processing systems arrive at similar decisions or conclusions. In those cases where the decisions or conclusions disagree, however, the affective system usually prevails, as in the case of phobic reactions, where people know that their avoidance behavior is at best ineffective and possibly harmful to them but cannot suspend it. Even in seemingly objective contexts such as financial investment decisions, emotional reactions (e.g., worry or dread) to investment opportunities are just as important as statistical variables (e.g., outcomes and their probabilities) to predict perceptions of risk (Holtgrave and Weber, 1993). If perceptions and reactions to risk were driven mostly or exclusively by statistical probability distributions, they would not be influenced by the way a particular hazard is labeled. Yet, reports about incidences of "mad cow disease" elicit greater fear than reports about incidences of bovine spongiform encephalitis or Creutzfeld-Jacob disease, a more abstract, scientific label for the same disorder (Sinaceur and Heath, 2005).

In another example, different labels for the same NWS forecast product have been found to evoke different associations and feelings. Broad et al. (2006) examined media interpretations from local Florida newspapers of the National Hurricane Center (NHC) hurricane forecast product, referred to by NHC as the cone of uncertainty (Figure 1.6). A search of Lexis/Nexis and the Miami-Dade Public Library System Databases identified 101 articles in 14 daily papers for the period of January 1, 2004 to August 16, 2005. As shown in Figure 2.3, "cone of uncertainty" and "cone of probability" were the most common terms used by the newspapers to refer to the forecast product. Jardine and Hrudey (1997) suggested that people interpret the word "probability" (the chance that a given event will occur) incorrectly as "probable" (likely to happen), implying that the product label "cone of probability" may lead some to conclude that the depicted hurricane track forecasts are more certain than they in fact are. NHC wisely does not use the term "cone of probability," preferring instead "cone of uncertainty." Other labels generated by the media for this forecast product can be expected to lead to different misinterpretations on the part of the public; for example, the term "cone of error" may be expected to reduce confidence in the product (see below), and other observed labels like "cone of death" or "cone of terror" may engage the emotional processing system and may induce fear or panic, rather than analytic evacuation contingency planning.

There is not a sharp separation between experiential and analytic processing. Decisions typically integrate both types of processing. The role of analytic processes in the understanding of hydrometeorological uncertainty and in decisions involving such information has, however, often been overestimated and the role of experiential processes has been ignored (Marx et al., 2006). A better appreciation of experiential processing may point the Enterprise toward improved risk communication strategies.

#### *2.2.1.2 Decisions from Personal Experience versus Decisions from Description*

Personal experience is a great, albeit painful way to learn. The single painful touch of a hot stove produces substantial learning. The ability to understand and utilize the cautionary tales and anecdotes of others extends the range of personal experience. The ability to combine the personal experiences of many into statistical summaries or to derive forecasts of probabilities from theoretical or statistical models is an additional powerful evolutionary accomplishment that

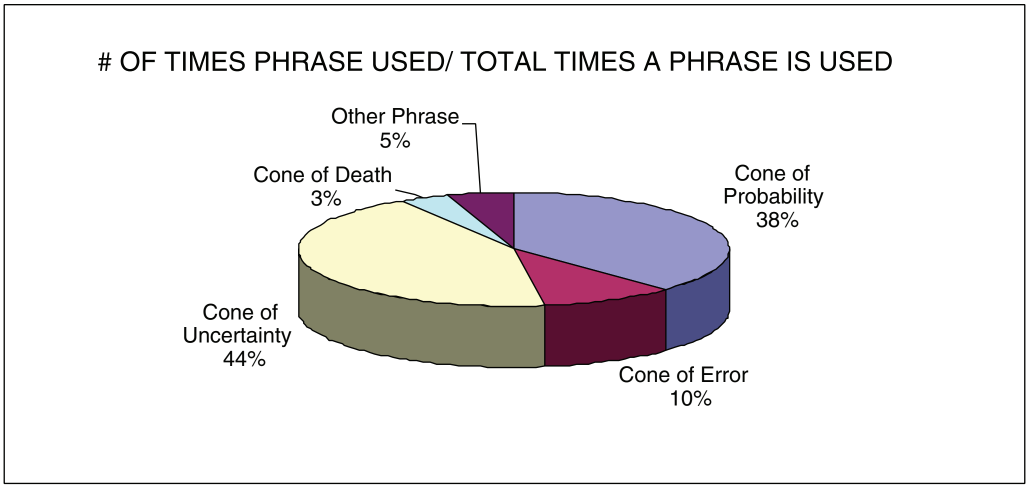

FIGURE 2.3 Percent time that different phrases were used to describe the cone of uncertainty. SOURCE: Broad et al. (2006).

dramatically increases the ability to learn in less costly ways. Recent work has compared the two ways of learning about the possible outcomes of decisions and actions (Hertwig et al., 2004; Weber et al., 2004; Hertwig et al., 2006). Formal models of decision making under risk and uncertainty (such as statistical decision theory, discussed in Section 2.3) have predominantly focused on analytic decision making, even though researchers have long been aware that abstract statistical evidence is typically at a disadvantage when people have a choice between it and concrete personal experience.

Concrete, personal, or vicariously related experience is processed by the experiential system and the generated effect is an effective motivator of action. More pallid statistical information is processed by the analytic system, whose output tends to have less weight in actions or decisions, unless decision makers have been trained to pay conscious attention to statistical information and its implications. In daily life, decision makers often learn about outcomes and their probabilities as a function of their profession or role. Doctors, for example, learn about health outcomes of treatment decisions in a different way than the public. Consider the decision whether to vaccinate a child against diphtheria, tetanus, and pertussis (DTaP). Parents who research the side effects of the DTaP vaccine on the National Immunization Program Web site will find that up to 1 child out of 1,000 will suffer from high fever and about 1 child out of 14,000 will suffer from seizures as a result of immunization. Although doctors have these same statistics at their disposal, they also have access to other information not easily available to parents—namely, the personal experience, gathered across many patients, that vaccination rarely results in side effects. Few doctors have encountered one of the unusual cases in which high fever or seizures follow vaccination. If the importance assigned to rare events differs as a function of how one learns about their likelihood, then doctors and patients might well disagree about whether vaccination is advised.

Related to the distinction between analytic and experiential processing is the distinction between decisions made from description versus decisions made from experience. An example of a description-based decision is a choice between two lottery tickets, where each ticket is described by a probability distribution of possible outcomes (i.e., statistical summary information). In contrast, when people decide whether to back up their computer's hard drive, cross a busy street, or invest in a new water system to irrigate their crops, they often do not know the complete range of possible outcomes, let alone their probabilities. Instead people typically decide based on past personal experience. Research has shown that the weight given to small-probability events differs dramatically between the two processing systems (with much greater weight given to small-probability events when small probabilities are provided as a statistic than in decisions from experience), demonstrating that the way in which information is acquired is an important determinant in the outcome of decisions that involve small-probability events (Hertwig et al., 2004, 2006; Weber et al., 2004). Decisions from personal experience put a large premium on recent events. By definition, rare events have not occurred very often in recent experience and their possible consequences thus get discounted more than they should. On those rare occasions where the rare event did occur in recent history, people will overreact to it, making decisions from experience also more volatile than decisions from statistical description.

These results have important consequences for the management of small-probability risky events. If people base their preparations for a rare event like a tornado or hurricane on their past personal experience with such events, they will most likely underprepare for them. Marx et al. (2006) discuss ways in which experiential and analytic processes might better be jointly utilized and combined in risk communications, though research in this area is still in its infancy.

### 2.2.1.3 Different Risk Attitudes for Gains and for Losses

The most successful behavioral model of risky decision making is prospect theory, first formulated by Kahneman and Tversky (1979) and later refined by Tversky and Kahneman (1992). The theory deviates from its economic competitor, expected utility theory, in a small number of important ways. Expected utility theory assumes that people evaluate the outcome of a decision in terms of its *absolute* effect on their wealth or well-being. Most applications of expected utility theory find people to be risk-averse. Risk aversion is a label that describes a concave utility function that predicts a decision maker will prefer receiving $10 for certain to a 50 percent chance of receiving $20. Prospect theory, on the other hand, assumes that people evaluate the outcome of a decision in a relative fashion (i.e., as a relative gain or relative loss from a reference point). The reference point is typically the status quo but can also be the outcome the decision maker expected to achieve. When expecting a price of $50 per ton of wheat, a farmer will experience an obtained price of $45 not as a gain, but as a relative loss. The reason that the relative evaluation of an outcome (as a gain or as a loss) matters is that people have been shown to be risk-averse primarily when they perceive themselves to be in the domain of gains. Most people would prefer to be certain of receiving $100, rather than taking their chances at a 50:50 gamble of getting $200 or nothing. In the domain of losses, on the other hand, people tend to be risk-seeking. Most would prefer to take their chances at a 50/50 gamble of losing $200 or nothing, rather than being certain of losing $100. Risk seeking is a label that describes the convex loss part of the utility function which predicts that a decision maker will prefer a 50/50 gamble of losing $20 or nothing to losing $10 for sure. In addition, losing $20 feels a lot worse than winning $20 feels good (Figure 2.4), a widely observed phenomenon that has been called loss aversion. The existence of loss aversion and of different risk attitudes for perceived gains versus perceived losses mean that one can influence which option a decision maker selects by modifying the reference point used to evaluate the outcomes of the decision.

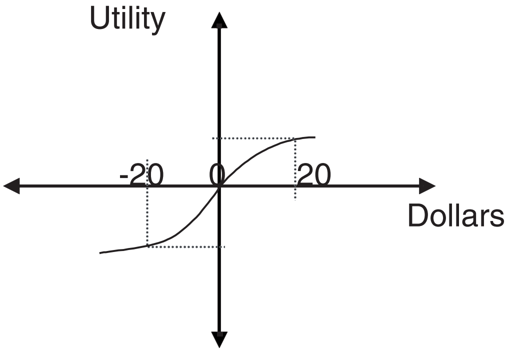

FIGURE 2.4 Different risk attitudes for perceived gains and losses. Losing $20 feels a lot worse than winning $20 feels good. SOURCE: Committee on Estimating and Communicating Uncertainty in Weather and Climate Forecasts.

### 2.2.1.4 Numeracy

A challenge to risk communication is the difficulty of expressing quantitative risk information in an easily comprehensible form. Cognitive limitations cause biases in the human ability to interpret numerical probabilities; particularly small probabilities are especially difficult to interpret. Under some conditions, people overestimate them, and under others, they round down to zero (Tversky and Kahneman, 1974; Nicholls, 1999). These difficulties in interpreting probabilities and other quantitative and analytic information are compounded by the limited instruction and training of their analytic processing system received by a large proportion of the U.S. population. The "numeracy" scale that assesses basic quantitative processing skills and that is used extensively in the medical risk communication community to assess the quantitative sophistication of users of medical risk information has been administered to large samples of the U.S. population, with discouraging results (Lipkus et al., 2001). Yet, numeracy and the related ability to follow printed guidelines on how to interpret graphs (e.g., the cone of uncertainty of a hurricane track forecast) are crucial if users are to correctly understand and utilize probabilistic forecast products that are typically designed for processing by the analytic processing system.

The failure of both end users and even the (presumably more sophisticated) media to correctly interpret the cone of uncertainty resulted, in the aftermath of Hurricane Charley (Figure 1.6), in such frustrated statements by members of NHC as "if anything needs improvement, it is the interpretation skills of the local weather media" (Broad et al., 2006). More important perhaps is the realization that forecast products, provided either to end users or intermediaries, need to be designed with full defensive awareness of the limitations in numeracy and analytic processing skills that they may encounter.

### 2.2.1.5 Personality Characteristics

Personality characteristics have been shown to influence how people make decisions under uncertainty (Hansen et al., 2004). Self-regulation theory (Higgins, 1999) distinguishes between two systems, the promotion and the prevention systems, with distinct survival functions. The promotion system is concerned with obtaining nurturance (e.g., nourishing food) and underlies higher-level concerns with accomplishment and advancement. In contrast, the prevention system is concerned with obtaining security and underlies higher-level concerns with safety and fulfillment of responsibilities. The two systems have been shown to employ qualitatively distinct means to achieve desired end states. Promotion-focused individuals are inclined to utilize "approach means" to attain their goals. For instance, a promotion-focused student seeking a high exam score might study extra material or organize a study group with fellow classmates. Conversely, individuals with a prevention focus tend to use "avoidance means" to attain their goals. For example, a prevention-focused student seeking a high exam score (or rather, trying to avoid a low exam score) might ensure that they know the required material and will avoid distractions prior to the exam. Hansen et al. (2004) found that *prevention-focused* farmers were more likely to seek to minimize post-decisional regret than *promotion-focused* farmers. They also remembered a greater number of flooding events and were more likely to purchase crop insurance.

Promotion uses hope to motivate action, whereas prevention uses fear to do the same. Promotion-focused decision makers can be expected to pay greater attention to the upside of possible outcomes. Prevention-focused decision makers, on the other hand, will pay greater attention to the downside or worst cases. Many forecast products have the potential to either promote opportunity or to prevent loss or calamity. Seasonal climate forecasts, for example, allow farmers to maximize economic gain by selecting seasonally appropriate seed corn. They also allow emergency managers to prevent mass starvation in the case of a drought, by planning the timely purchase of feed corn. The Internet has made the customization of information a lot easier. It is not inconceivable that future Web users of NWS forecasts could first answer two or three simple questions about the purpose to which they plan to put the requested forecast, based on which they would receive the forecast in an appropriately tailored version.

### 2. 2. 2 Misinterpretations of Uncertainty and Probabilistic Forecasts

There is a danger that users will misinterpret the very meaning of the forecast variable and/or the uncertainty associated with that variable. Users also have a distinct psychological reaction to the notion of uncertainty in estimates of uncertainty, or ambiguity.

#### *2.2.2.1 Interpretation of a Weather or Climate Event*

Forecast providers may not be aware that the definition of the event they are forecasting may not be obvious to the users. Following up on an earlier study by Murphy et al. (1980), Gigerenzer et al. (2005) asked a small sample of respondents in five cities with different degrees of exposure to probabilistic forecasts—Amsterdam, Athens, Berlin, Milan, and New York—what was meant by the probability of precipitation (PoP) forecast of a "30 percent chance of rain tomorrow," in both a free-response and a multiple-choice format. Only in New York did a majority of respondents supply the standard meteorological interpretation, namely, that when the weather conditions are like today, in 3 out of 10 cases there will be (at least a trace of) rain the next day. In each European city, this alternative was judged to be the least likely one. The preferred interpretation in Europe was that it will rain tomorrow "30 percent of the time," followed by "in 30 percent of the area." The authors of the study concluded that the forecast providers ought to explicitly specify the situation, or reference class, to which the single-event probability refers.

The more general point of this example is that perceptions and interpretations of NWS technical staff may not be universally shared by members of the public and that the heterogeneity in reactions and interpretations might be wider than NWS appreciates.

#### *2.2.2.2 Interpretations of Probabilities (Words, Numbers, Frequencies)*

A common and seemingly simple way of communicating the uncertainty of an event is by providing a probability estimate of its occurrence, as for example the PoP forecast. This is also a common format in other areas, for example, the communication of health risks, where drug package inserts provide information about the probability of a series of side effects, conditional on taking the medication.

Concerns about people's ability to process numerical probability information (i.e., their low numeracy levels; Section 2.2.2.4) have given rise to the suggestion to replace the numeric communication of probability information with verbal expressions, which may be less intimidating or taxing to nonspecialist recipients of uncertainty information. There are, however, a host of reasons for why this idea may not be practical. Wallsten et al. (1986) collected information about the numeric equivalents that members of the public would assign to common probability words such as "probable," "possible," and "unlikely." The likelihood ranges people assign to many common probability words is very wide (Figure 2.5), meaning that their use in communicating probability levels may not be very precise or diagnostic. Furthermore, the numeric interpretation of probability words depends on a host of other factors, including the base rate of the event that it describes (Wallsten et al., 1986) and the severity of the consequences of the event (Weber and Hilton, 1990; Weber, 1994). Thus, people will assign a higher numeric interpretation to "good chance" when it describes the probability of rain in London rather than rain in Cairo, and when it describes the probability of cancer rather than a sprained ankle.

Similar issues have been raised for the communication of climate change uncertainty. For the IPCC's Third Assessment

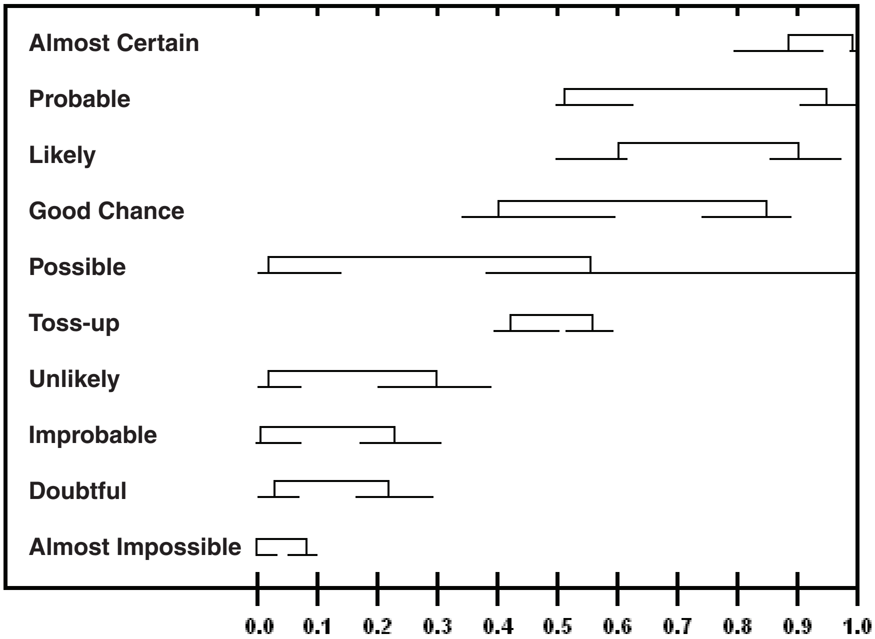

FIGURE 2.5 Range of interpretations of different verbal uncertainty terms. SOURCE: Wallsten et al. (1986).

Report (TAR), Moss and Schneider (2000) assessed several means for characterizing climate change uncertainties and prepared a guidance paper for use by all TAR authors. Noting the need for a consistent approach, Moss and Schneider (2000) proposed not only a general process for assessing uncertainties but also several specific tools that could be used to communicate them. They decided to deal with the problem that words used as descriptors of probability can hold very different meanings to different stakeholders, with the recommendation that verbal descriptions of scientific information must be calibrated consistently. For the purpose of communicating uncertainties in the TAR report, they mandated that verbal confidence descriptors—probability expressions of a specific type—should be used in accordance with the numeric equivalents shown in Table 2.2.

TABLE 2.2 Quantification of Verbal Confidence Descriptions in IPCC's Third Assessment Report

| | Likelihood Ranges | |
|---|---|---|
| Verbal Descriptor | From | To |
| Very High Confidence | 0.95 | 1.00 |
| High Confidence | 0.67 | 0.95 |
| Medium Confidence | 0.33 | 0.67 |
| Low Confidence | 0.05 | 0.33 |
| Very Low Confidence | 0.00 | 0.05 |

SOURCE: Moss and Schneider (2000).

Given the lack of precision of probability words and possible confusion in their interpretation, the routine use of verbal probability expressions in the communication of uncertainty has its dangers. People seem to be aware of the ambiguity inherent in the verbal communication of uncertainty. When asked whether they preferred to receive uncertainty information either verbally or numerically, most people preferred the greater precision of the numerical format. When asked about their preference in communicating uncertainty information, on the other hand, people preferred to provide verbal forecasts, because their greater ambiguity made it less likely that they would turn out to be wrong (Wallsten et al., 1993).

Gigerenzer and Hoffrage (1995) showed that many misinterpretations of numeric probabilities are improved when such information is communicated in the form of a relative frequency. Thus, people may not pay sufficient attention to the fact that a disease has a base rate of 0.005 of occurring in a population, but are much more likely to use this information accurately when they are told that it has a 1-in-200 chance of occurrence (see also the discussion of frequentist interpretation of probabilities—Box 1.1). While the use of relative frequencies is no panacea (Mellers et al., 2001), it seems to be a more effective communication format because it allows people to connect probabilistic information to their personal experience base, where information is typically stored in the form of event counts. In addition, use of relative frequencies can help clarify the nature of the target event and reduce the possibility of misunderstanding it.

**Finding:** The use of verbal probability expressions does not appear to be an effective way to communicate uncertainty information to less analytic users, suggesting that better ways should be found to communicate such information numerically. Errors in the interpretation of numeric probability information are often reduced when probabilities are described in terms of relative frequencies

**Recommendation 2.1: For users who have difficulty with numeric probabilities and prefer a less analytic approach, forecast uncertainty should be expressed using relative frequencies rather than probabilities.**

### 2.2.2.3 Reactions to Uncertainty in Estimates of Uncertainty

People react in different ways to the different sources of uncertainty in forecasts. Decisions whose outcomes are known only probabilistically are referred to as decisions under *risk* when the likelihood of different events is known precisely (e.g., the probability of getting a "head" when tossing a fair coin) and as decisions under *uncertainty* when the likelihoods themselves are uncertain (e.g., the probability of precipitation tomorrow). The past half-century has seen a lot of theoretical and empirical work that provides further distinctions between different types of uncertainty as well as sources of uncertainty. Uncertainty about probability has been called *ambiguity* (Ellsberg, 1961) or *vagueness* (Wallsten, 1990). Whereas ambiguity is sometimes expressed and modeled as second-order uncertainty (uncertainty about the degree of uncertainty), Camerer and Weber (1992) endorse the more general definition of ambiguity as uncertainty about probability, created by missing information that is relevant and could be known.

It has long been known that people are risk-averse; that is, they do not like uncertainty and will settle for certainty equivalents that are smaller than the expected value of risky choice options (Bernoulli, 1738), at least in the domain of gains (Section 2.2.1.3). A more recent discovery is the fact that people and organizations are also ambiguity-averse (Ellsberg, 1961). People prefer to bet on a lottery where they know the precise odds of winning over a lottery that has the same expected probability of winning, but less well specified probability levels or more second-order uncertainty. Not knowing important information is aversive and makes people shy away from making any decision at all in such a situation (Heath and Tversky, 1991). Similarly, insurance companies are often unwilling to insure ambiguous risks (i.e., new risks with no record of losses on which actuarial estimates of the probability of a loss can be placed). Just as risk aversion is typically mediated by an emotional rather than cognitive response, so is ambiguity aversion. Not knowing the precise probability level makes us feel uncomfortable, and feelings of worry or discomfort translate into avoidance. When other factors, such as familiarity with the domain of the decision problem reduce the feelings of worry or discomfort, ambiguity aversion disappears or turns into ambiguity seeking. For example, when people with expertise in a sport like college basketball are given the choice between betting on a risky lottery (i.e., on a lottery with well-specified probability levels) or on a college basketball game where the probability of winning is more ambiguous, they tend to prefer betting on the ambiguous basketball game (Fox and Tversky, 1995). People have also been found to react differently to uncertainty from different sources. Uncertainty arising from a stochastic environment (called aleatory uncertainty) is seen as less aversive than uncertainty arising from incomplete and/or unreliable observations (called epistemic uncertainty), presumably because the latter can be reduced, at least in principle (Heath and Tversky, 1991; Wallsten et al., 1997).

Confidence in a probabilistic forecast is a way of expressing second-order uncertainty and often reflects the internal or external conflict experienced in making the forecast (Weber et al., 2000). While confidence could just be seen as an expression of subjective probability, the confidence information that people provide about a judgment they made tends to reflect their internal conflict in arriving at that judgment rather than to reflect the probability of being correct. Forecasters' Area Forecast Discussions have been reported to be one of the most accessed pieces of information on the NWS Web site, probably in part because these discussions convey forecasters' confidence and their reasoning behind it. Using another example from the climate-change arena, Moss and Schneider (2000) in their recommendation for the communication of uncertainty in the third assessment report of the IPCC, also suggest that level of agreement or consensus (the complement of degree of conflict) is qualitatively different from other sources of uncertainty. They propose to communicate both sources of uncertainty separately (in this case, qualitatively and verbally; Table 2.3), rather than to incorporate or compound the two into an overall probability level or confidence interval for the target event. Although this distinction between two (or more) different contributors to forecast uncertainty may not apply to all forecasts, the distinction is important both for general users of uncertainty information and for forecasters, who may feel some responsibility to reduce uncertainty due to differences in agreement

TABLE 2.3 Suggestion to Conceptually Separate Level of Agreement and Amount of Evidence as Sources of Uncertainty

| | | AMOUNT OF EVIDENCE | |
|---|---|---|---|
| | | Low | High |
| LEVEL OF AGREEMENT AND/ OR CONSENSUS | Low | Speculative | Competing explanations |
| | High | Established but Incomplete | Well established |

SOURCE: Moss and Schneider (2000).

about forecasts but no responsibility for uncertainty due to insufficient evidence.

**Finding:** Different types and sources of uncertainty in hydrometeorological forecasts are processed by the transmitters and recipients of uncertainty information in different ways.

**Recommendation 2.2: The Enterprise should signal to users the different sources of uncertainty in their probabilistic forecasts and risk communication products.**

## 2.3 STATISTICAL APPROACHES TO DECISION MAKING UNDER UNCERTAINTY

This section explores objective, statistical approaches to decision making under uncertainty as opposed to the psychological factors covered in the preceding section. In statistical decision theory all sources of uncertainty are assessed and their impact on a process of interest is quantified so that a "best" decision can be made. For decisions that use weather or seasonal climate forecasts, the sources of uncertainty include not just atmospheric processes but also any other processes that influence the consequence of the event. For instance, agricultural outcomes may be influenced by uncertainty in the market price of the product, as well as by the local weather forecast. These objective approaches provide a user with a decision, but in a practical sense individual users are not bound by these objectively produced decisions, and the psychological factors discussed in Section 2.2 will still be in play. A key advantage of analytical approaches such as statistical decision theory is that, if properly developed, they provide a formal structure for eliciting and integrating all information relevant to a particular decision process. Thus, the context for the use of hydrometeorological forecasts, as well as the sensitivity of the decisions to these forecasts, can be made clear.

The following section begins with a brief historical context and then discusses the basic concepts associated with statistical decision theory, linking to a series of examples that seek to convey some of the issues that emerge in considering decision making under uncertainty and risk in the hydrometeorological context. The section closes by outlining findings in the application of statistical decision theory, with an eye toward implications for NWS.

### 2.3.1 Historical Context

There is a long history of the use of concepts from statistical decision theory[12] for the management of risk in the agriculture, water, energy, insurance, emergency planning, and business communities. The hydrometeorological community, as a provider of probabilistic information, participated in the evolution of this literature as well (e.g., Thompson and Brier, 1955; Epstein, 1962; Glahn, 1964; Murphy, 1976; Katz et al., 1982; Brown et al., 1986; Murphy and Ye, 1990; Wilks and Hamill, 1995).

The statistical decision theory framework has addressed both the derivation of "optimal" decisions in the presence of uncertainty and the associated value of information (e.g., improved forecasts or more data). The literature on statistical decision theory is quite mature with respect to both theory and to the development of case studies and examples. However, the frequency of applications for real-world decisions varies widely depending on the sector, the setting, and the dimension of the problem. Typically, decision-support systems that use statistical decision theory are developed on a case-by-case basis for a particular application, and generalized applications that facilitate their broader use are not readily available. Even if generalized applications were available, the data requirements and peculiarities of each problem might necessitate significant modifications. Where decision-support systems are used most routinely, they are embedded in either legal guidelines (e.g., federal water project design guidelines), are part of a specific corporate culture, or are developed as part of a customized software package for a production scheduling, inventory management, or protective response.

NOAA/NWS has historically supported decision-support systems in water resources management (Fread et al., 1995; Changnon, 2002; Georgakakos and Carpenter, 2005; Power et al., 2005). For example, streamflow observations and forecasts are considered in the operation of some large reservoir facilities that have competing objectives such as flood control, hydroelectric power production, ecosystem health, recreation, river transportation, and others. Disaster management agencies also routinely use flood forecasts. The decision-support systems in these cases may use simulation models for scenario analysis, or linked simulation and optimization tools.

### 2.3.2 Illustration of Seasonal Climate-related Use Scenarios

Analytic processing, of which statistical decision theory is a common example, can serve to summarize and focus the available information. A starting premise of statistical decision theory is that the key elements that characterize the decision problem can be and have been identified. This entails the identification of

- the decision maker's *objectives*, formalized by a numerical utility function that measures preferences with respect to different consequences;
- all *actions* available to the decision maker;
- the *possible consequences* of these actions; and
- the *conditional probability distribution* of each consequence given each action.

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[12] Also known as Bayesian decision analysis.

The conditional probability distribution may be derived from models of system dynamics or specified subjectively. In addition, it should include consideration of the underlying sources of uncertainty, whether they relate to information or to model/knowledge attributes. Once these four elements have been defined, the expected utility or the average utility associated with each action can be computed and the different actions can be ranked as to their expected utility given information about the current or projected state of the world.

Consider three situations for decision making using hydrometeorological information: determinism, uncertainty, and ambiguity. *Determinism* is a situation where the system dynamics and the available amounts of each input are known (including all model parameters), consequences (outputs) can be predicted perfectly, and the utility of each level of output is known. The resulting optimization problem is well defined and one can mathematically determine the decisions that maximize utility. *Uncertainty* is a situation where one or more of the inputs or model parameters are not known with certainty but its probability distribution is known precisely. In this case, the probability of each outcome must be evaluated, and the average expected utility[13] is calculated as a function of decision choices. The decisions that maximize expected utility are considered optimal. *Ambiguity* exists when the probability distributions of interest, in addition to one or more of the model parameters, are not known precisely and must be estimated (see also Section 2.2.4). In this case, a two-step process is used. The probability of each outcome for each decision is estimated by considering each possible probability distribution of each input, weighted according to its probability of occurrence. These probability distributions may be estimated objectively or subjectively. Expected utility is then computed and maximized. A condition of decision making under uncertainty is approached as the precision of information about the underlying probability distributions (forecasts) increases. Conversely, with less precise information as to the underlying probability distributions, the decision maker is exposed to a higher degree of variability in potential outcomes and hence in expected utility.

These three situations (determinism, uncertainty, and ambiguity) are demonstrated in the hydrometeorological context in Boxes 2.5 through 2.7. The boxes should be read sequentially as they build upon one another. The examples provide an insight into the kinds of considerations that may influence the use or applicability of forecast information. They strive to make clear the danger of a forecast agency supplying probabilistic forecast information without the supporting guidance that went into the forecast (see Chapters 3 and 5).

## BOX 2.5
## Determinism

Many retail goods are sensitive to seasonal factors (e.g., snowblowers, seasonal clothing, umbrellas). Consider the example of a retailer located in New York purchasing a stock of winter coats. The retailer has information on how demand for coats has historically varied with the seasonal temperature. He has a fixed budget, and plans to stock two types of coats. The first is a fashion brand whose demand is relatively insensitive to climate, and the second one is a generic brand whose demand is quite responsive to temperature early in the season. Any stock left over at the end of the season is usually liquidated with a higher markdown on the fashion brand than on the generic brand. The storage and hanger space that can be devoted to the coats is also limited.

The *inputs* into the retailer's decision are budget, storage space, hanger space, unit costs, selling and liquidation prices of each coat, and the equation for the demand for each coat at a specified price as a function of seasonal temperature. The *decisions* are the number of each type of coat to order, and a *system mechanics model* is specified by the demand equations and the capacity and budget constraints. The *outputs* are the numbers of each coat sold during the season and the number liquidated at the end of the season. The *utility* is the profit derived from the operation as the difference between the total revenue and the total cost (when the potential for catastrophic loss can be ignored, and when factors other than profit are negligible components of value). The decision problem is readily solved mathematically given this information, provided all parameters are known precisely and the forecast temperature for the season is known perfectly.

Often competing goals lead to the need for weather and climate forecasts that are compatible across different space and time scales. To emphasize this point, Box 2.8 revisits the Folsom Dam example (Box 2.3) and highlights the need for multiscale consistency in seasonal climate forecasts from a user perspective. In addition, this example shows that even when the complexity of the decision process increases dramatically, formal analysis and quantification of forecast probabilities and their uncertainty may be helpful to evaluate competing proposals from multiple agencies and stakeholders, each of whom may have different utilities and catastrophic risk thresholds.

### 2.3.3 Statistical Decision Theory in Decision-Support Systems: Findings on Uses in Relation to Hydrometeorological Forecasts

Decision-support systems based on statistical decision theory have an analytic basis, are informed by user needs,

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[13] This is the hypothesis that the utility of an agent facing uncertainty is calculated by considering utility in each possible state and constructing a weighted average. The weights are the agent's estimate of the probability of each state. The expected utility is thus an expectation in terms of probability theory (see Keeney and Raiffa, 1976).

## BOX 2.6
## Uncertainty

Now consider that the temperature for the upcoming season (as discussed in Box 2.5) is not known with certainty. Rather, its probability distribution is known quite reliably because the temperature records in New York extend back nearly 200 years (and long-term variations are not considered). Since the demand for the fashion brand is not expected to be climate sensitive, the retailer considers his key decision to be the number of utility coats to order given the probability distribution of temperature. Since the demand for coats as a function of temperature is known precisely, the number of coats sold during the season and the number liquidated at the end of the season for each possible value of temperature can be computed.

Given the probability of experiencing each temperature, one can also compute the contribution to the expected utility as the product of the probability of that temperature and the net profit from the sale of the corresponding number of coats at the regular and liquidation prices. This process is repeated for each candidate decision level (i.e., number of coats to buy). In other words, the retailer computes the expected utility through an evaluation of the potential profits for each possible temperature weighted by the probability of that temperature. The optimal coat order is the one that maximizes expected utility. Consistent with the discussion in the beginning of this chapter, this is a strategy for long-term or static risk management. If the coat costs and other market conditions do not change from year to year and the probability distribution of temperature is invariant, then under this criterion the retailer would make the same decision each year. The profits realized would vary from year to year but would average to those indicated by his optimal solution based on expected utility. Indeed, the success of the plan is predicated on long-term performance and the ability to average over good and bad years.

The last observation points to an apparent flaw in the approach in that the expected utility approach as presented above does not consider the potential of catastrophic loss. Suppose, for instance, that in a given year the temperature is anomalously warm and very few coats are sold, leading to a large loss for the retailer. If the loss is large enough, the retailer may not be able to stay in business. If this low-probability event were to occur early in the sequence of years, the opportunity to achieve maximum expected utility is lost since the retailer is not in business long enough to average across bad and good years.

This situation can be addressed in several ways. First, the utility function could be modified to recognize this situation and heavily penalize outcomes that translate into the catastrophic failure of the business. This will lead to a different optimal solution for the coat order but may expose the retailer to lower average profit and may still lead to catastrophic failure with some probability. The severity of the penalty on catastrophic failure reflects the retailer's risk aversion, which may or may not be easily revealed in practice. Another approach is to add a second decision. This may be a decision to purchase index insurance on temperature. The insurance would require a premium and would pay off a known multiple of the premium if the temperature were to exceed a prescribed value. The *decisions* now are the number of coats to order and the size of the insurance premium to purchase. Given the probability distribution of temperature, the economic information and the new utility function that includes the profits and the insurance payoffs, the retailer can now determine the optimal decisions as before by maximizing his expected utility over both choices. This approach decomposes the management of catastrophic risk from routine risk and is becoming increasingly popular as a way to manage static risk.

## BOX 2.7
## Ambiguity

Now consider a final modification of this example in which the retailer uses NWS seasonal temperature forecasts. These forecasts are available as tercile probabilities for the region; that is, a probability is attached to each of three possible states of the forecast temperature: above normal, normal, or below normal. When the skill of the forecast is not significant, NWS instead releases the long-term probability distribution of temperature (i.e., the climatological average distribution) in which there is a 0.33 (33 percent) probability for each temperature tercile category.

When considering how he might use these forecasts, the retailer has two related questions. First, should he start using the forecast to modify his decision each year instead of using the same decision each year based on the long-term risk analysis using a well-established temperature probability distribution? Second, how does he evaluate the decision for the coming year?

At first glance the second decision problem seems straightforward. Instead of using the probability of 0.33 for each category to define the long-term risk, use the published NWS probabilities (e.g., 0.5, 0.3, 0.2) as the characterization of the *dynamic* temperature risk for the coming season and repeat the analysis of maximum expected utility as in Box 2.6 to determine the optimal coat order for the upcoming season. However, in light of the discussion in Box 2.6, the retailer is quite concerned with catastrophic failure. Unfortunately, the NWS tercile forecast provides no information on low-probability events and cannot address that question. Further, the tercile forecast imposes an arbitrary discretization of the temperature data (i.e., above normal, normal, below normal) that may not match the ranges of temperature over which coat demand is most sensitive.

In public meetings organized by NWS to publicize its forecast products, the retailer asks for temperature forecasts with higher temperature resolution (i.e., more categories, or a fitted probability distribution). An NWS scientist comments that, given the number of ensembles it is able to run, NWS does

*continued*

## BOX 2.7 Continued

not believe it can reliably offer information on low-probability events or the full distribution. A private-sector intermediary in the audience mentions that she has come up with an algorithm that takes the NWS tercile forecast and can generate a full temperature probability distribution for it. The retailer wonders whether it would also be possible to estimate the reliability of the forecast probability distribution. The intermediary answers that she could do this if NWS provided estimates of the uncertainty in its forecast tercile probabilities. Indeed, she would like the tercile forecast and its estimated uncertainty for each year instead of average climatology in some years and forecasts in others. She says it would be even better if the raw ensemble data used to compose tercile forecasts were available for all years for which forecasts were made—including retrospective forecasts (hindcasts). With such information she could select the best probability distribution to fit and assess the uncertainty in its parameters.

The NWS scientist wonders how the retailer would use this information. Consider its application to the coming season and assume that the forecast probability distribution is now available at the desired temperature resolution, and with minimal uncertainty. The analysis in Box 2.6 can now be repeated under the new (dynamic) risk setting, and the optimal amount of insurance and coats to buy can be evaluated. The retailer's insurance provider may of course be using the same or other forecast source and could change the premium associated with a particular temperature threshold. Even if the NWS probabilistic temperature forecasts have very low uncertainty, the retailer may wish to evaluate whether a long-term strategy of using the historical temperature probability distribution (i.e. the *static* risk management strategy) with a fixed order size (assuming nonchanging economics) is inferior to a strategy of using the forecast (*dynamic* risk management) where the order size could potentially change dramatically from year to year. In addition to the variability in annual profits and cash flow, there may be relationships with the supply chain vendors to consider any transaction costs involved in changing the order size.

To address this question, the retailer could apply both strategies over a number of years and evaluate whether, on average, the long-term use of the forecast probabilities and dynamic risk management overcomes the increased transaction costs. Thus, the first assessment the retailer might make is whether a dynamic risk management strategy would actually be superior to a static risk management strategy, assuming that the NWS probability forecasts accurately capture the probability distribution of temperature on a season-by-season basis. This is the approach implied by various documents publicized by NWS and other forecast providers who show seasonal climate forecast probability distributions as a "shift" in the climatological or historical probability distribution. *But this approach still does not address the issue of uncertainty in the estimated forecast probability distribution.*

The uncertainty in the probability distribution of historical temperature in New York is closely related to the length of record used for its estimation. In contrast, the uncertainty in the seasonal forecast may depend on a variety of factors, including the number of ensemble members in each forecast model; the number of models whose forecasts are combined; the number of years over which the model results were tested and the model parameters recalibrated; and how representative the equations, resolution, and numerical accuracy are for the underlying processes modeled. For the sake of illustration, assume that the needed estimate of uncertainty in the probability distribution in the retailer's decision process is available. The retailer can now revisit the problem as described in Box 2.6 in the following way. The uncertainty in forecast probabilities is represented as the probability of the parameters taking specific values. For example, consider two forecasts—A and B—where both forecasts have the same average but forecast B has higher uncertainty (i.e., it has a higher spread in the tercile probabilities):

Forecast A: Published tercile probability forecast is (0.5, 0.3, 0.2)
Associated uncertainty distribution:
A.1 Probability =1/3 that the forecast is (0.5, 0.3, 0.2)
A.2 Probability =1/3 that the forecast is (0.45, 0.33, 0.22)
A.3 Probability =1/3 that the forecast is (0.55, 0.27, 0.18)

Forecast B: Published tercile probability forecast (0.5, 0.3, 0.2)
Associated uncertainty distribution:
B.1 Probability =1/3 that the forecast is (0.5, 0.3, 0.2)
B.2 Probability =1/3 that the forecast is (0.4, 0.36, 0.24)
B.3 Probability =1/3 that the forecast is (0.6, 0.24, 0.16)

Using this information about the uncertainty in the forecast, the retailer can now reevaluate the decisions that maximize his expected utility. The uncertainty distribution for forecast A suggests that there is equal likelihood that the temperature probability distribution could be A.1, A.2, or A.3. The retailer could compute the expected utility for a particular number of coats to order using the three category probabilities given for each of A.1, A.2, and A.3 and then calculate the overall average expected utility using the estimated probability (1/3) for each forecast. The process would be repeated for forecast B. If the utility function is nonlinear, the expected utility from forecast A will not equal the expected utility from forecast B even though the published tercile forecasts are the same (i.e., the uncertainty information as to the probabilities matters).

Since most utility functions are asymmetric and nonlinear (i.e., the unit profit realized from liquidation sales and regular sales is quite different), and the uncertainty distribution for the probability forecast is not symmetric (whereas it is symmetric in the example above), the optimal solution considering uncertainty is usually not the same as when only the risk (i.e., the average or "known" probability distribution as in Box 2.6) is considered. This highlights the need for NWS to provide not just the forecast probability distribution but also the background information that allows the uncertainty distribution to be computed by each user in the context of their decision problem and its associated utility functions.

### BOX 2.8
### Further Analysis of the Folsom Dam Example (Box 2.3): The Need for Multiscale Consistency

Consider the decisions to be made by stakeholders in Folsom Dam given a rainfall forecast for Folsom Dam for the next three days (January 31 to February 2) and one for the balance of the wet season from January to May. The *outcomes* of interest could be (1) whether Sacramento floods, (2) whether the reservoir fails to fill by the end of the May and hence there is a deficit in both energy production and water supply, and (3) how much revenue is generated by water and energy releases between now and May.

The *inputs* could include the rainfall forecast for the two time periods, the watershed conditions over the next three days and the season so that rainfall could be converted to streamflow coming into Folsom Lake, the water and energy demands between January and May, the unit prices of water and energy, the relationships between volume of water in the dam and the rate of outflow during flood conditions, the volume and the surface area, and the surface area and evaporation among other things.

The *system dynamics model* would convert rainfall over the watershed to inflow into the reservoir, water volume in the reservoir and releases to energy and keep track of the mass balance in the reservoir from day to day until May. The *decisions* to be made are the volume of water to release now in advance in anticipation of a flood in the next three days, the amount of water to release for water supply and energy between now and May. The *utility* derived from the outcomes may be given by the revenues generated from water and energy supply, less the damages caused by a flood. Generally, additional factors beyond the direct economics of the outcomes may be considered in defining the utility. For instance, there may be specific targets for energy production and if these are missed institutional credibility may be at stake. Similarly, there may be a value assigned to ensuring that flooding is avoided altogether since a variety of emergency preparedness activities that may result in social and individual costs are then avoided. Other goals may pertain to the maintenance of a downstream fishery and ecological habitat through environmental releases from the dam that maintain adequate water quantity and quality downstream, and recreation and fisheries benefits that may be derived from keeping the reservoir at certain target levels.

Typically, the decision process might require proposals for the modification of system operation by the reservoir operator, an interest group, or both followed by the evaluation of each proposal through a long-term simulation of the system mechanics model. Such a modification might be a specific formula for advance release that is tied to a weather forecast, or for retaining a prescribed amount of water in storage given current storage and a seasonal climate forecast. The evaluation of each proposal would entail assessing each outcome and the expected utility of interest to each stakeholder group. As in Boxes 2.5 through 2.7, these assessments would need the historical climate probabilities and the probabilistic weather and climate forecasts (and their associated uncertainty distributions). The weather and climate forecasts would need to be compatible in the sense that the conditional forecast probability of January through May seasonal rainfall is correct given the three-day forecast.

The forecast compatibility issue is critical for successful application of probabilistic forecasts in these complex decision processes. For example, the historical data for the American River above Sacramento show that if major floods occur in January, there is a high probability that the subsequent wet season will be anomalously dry. This creates a potential double-jeopardy situation for managing the dual objectives of flood control and water/energy production using probabilistic forecasts. If the operator lowers the reservoir storage using an advance release in anticipation of a flood given the three-day rainfall forecast and the rainfall does not materialize in this period because the storm tracked just north or south of the basin, then whether or not the subsequent season is wet or dry becomes critical for meeting the target water demands. The decision to make the advance release would be questioned by the other stakeholders. Indeed, the entire advance release proposal could be abandoned if the simulations over a historical period demonstrated adverse outcomes by using a probabilistic forecast process in which the three-day and seasonal rainfall forecasts individually or collectively led to misinformation.

and are readily updated and a key building block that will underpin the systematic use of probabilistic hydrometeorological forecasts. This section lists eight findings[14] on areas that could profit from further development of such systems and provide NWS with a framework to identify opportunities for action—in partnership with others in the Enterprise as appropriate.

#### *2.3.3.1 A Formal, Analytic Approach Such as Statistical Decision Theory Has Value*

Section 2.2 established that many cognitive and emotional factors are involved in decisions and many decisions do not reflect the "rational" outcome of utility maximization. However, a formal, statistical decision theory approach still has value for several reasons. First, in many situations the metrics may be clearly defined, and a corporate structure may decree such analyses as part of a systematized risk management system. In these cases, a decision maker may choose to conform to the decisions indicated by the mandated analytic process and reduce the personal risk involved in

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[14] Expressed as the title of each subsection, and supported by information within that subsection. These subsections summarize (and point to) experiences discussed earlier in the chapter and/or the experience of the committee.

varying from the system. Second, even where the decision process is marked by higher complexity as in the Folsom Dam example (Boxes 2.3 and 2.8), using an analytic process can be useful in making the diverse sources of information, their uncertainty, and the potential outcomes tractable for cognitive processing, particularly if the process leads to an iterative sequence of analysis and discussion. Third, since each user's utility function and risk preferences are different, it would be more effective to provide (1) a probability forecast, (2) the means to assess the time variation of the forecast's uncertainty distribution, and (3) the historical forecast data and corresponding observations so that the user can verify the performance in the context of their utility function. The user could then either modify the decision process to include a decision on whether to use the forecast system or, alternatively, use it at times when the indicated uncertainty leads to a superior result.

#### *2.3.3.2 The Decision Problem Is Typically Cast as a Risk Management Problem*

Two types of risk are usually considered: (1) the management of the variability of outcomes due to the random nature of process inputs and (2) the management of catastrophic risk. The decision structures to manage these two types of risk are not necessarily the same.

For weather and climate forecast-related risk management, it is important to consider the traditional context of risk management that existed in the absence of formal forecasts. Where physically or economically feasible, users may seek to reduce their exposure to risk in the long run (i.e., *static risk*). The residual *dynamic risk* may still be managed using time-varying forecasts, suggesting the need to examine the integrated management of risk across events over multiyear time scales. The examples in Boxes 2.5 to 2.8 highlight that static risk management is used in many cases and provides the context in which available actions and options enabled by information as to dynamic risk have to be evaluated. At longer time scales, uncertainty about climate change as well as uncertainties in physical and socioeconomic factors become large and need to be considered as part of a predictive and monitoring strategy in the context of infrastructural, financial, or other structural decisions made to reduce exposure to long-term risk. Similarly, event or weather predictions require both monitoring and forecast information to be effectively communicated for risk characterization and mitigation. Finally, consistency in forecasts across multiple time scales (weather to seasonal climate) is often needed for dynamic risk management, since many decision problems have multiple targets and time lines.

#### *2.3.3.3 Knowing the Level of Uncertainty in the Available Information Allows the Decision Maker to Assess the Value of Reducing the Uncertainty*

There is a cost associated with the generation or acquisition of information to reduce uncertainties. Nonetheless, uncertainty reduction can translate into increased utility for a decision maker through a reduction in the variance (and bias) of realized utility. Thus, if the uncertainty in a particular source of information (e.g., a probabilistic forecast) can be quantified, the decision maker can evaluate the value of additional information in reducing the uncertainty and hence of enhancing the aggregate utility or reducing the risk of exposure to catastrophe. The value of forecasts and the associated uncertainty reduction will vary by user since utilities of outcomes vary by user. In the absence of information about decision consequences and their utilities, a formal quantification of the value of the forecast is not possible.

#### *2.3.3.4 Expected Utility Frameworks Require the Ability to Spread Risk Exposure*

The idea of expected utility (and its variants) implies that the user is able to average their exposure to risk in some way, either over time with repeated applications of a forecast or over different operations (e.g., multiple stores, across unrelated assets and operations, or by insuring a wide variety of users who have uncorrelated risk factors). If this is not possible, for instance for a homeowner in the event of an impending hurricane, then the framework is not easy to apply, and the utility of the probabilistic forecast information may be difficult to assess for the homeowner. However, since emergency managers average over the potential outcomes for many homeowners, they could use such a framework with probabilistic content, provided that the necessary information on potential consequences was also available. Indeed, this is one reason why many users may first seek to manage long-term or static risk (e.g., through hurricane insurance in this case) and then manage the residual dynamic risk. The situation is complicated by the presence of multiple actors with varied goals and potentially incommensurate utilities and roles in the decision and implementation process. This also suggests that NWS cooperation with "large users," who are capable of averaging risk across enterprises, locations, and time, would be beneficial for the development of decision-support systems that can use probabilistic forecasts and readily demonstrate economic and social value from such use. These sectors include water supply, flood and drought hazard management, energy production and management, insurance, environmental regulation and management, transportation, aviation and the travel industry, retail and seasonal goods manufacturing, and construction industries. Collectively, these sectors are a significant contributor to the national economy.

#### *2.3.3.5 Outcomes Depend on Many Factors in Addition to the Hydrometeorological Conditions*

Even if the uncertainty in hydrometeorological forecasts is low, the value of such forecasts may also be low if another factor critical to the decision is highly uncertain. A variety of factors will introduce a variety of uncertainties, and not all of these uncertainties will be objectively quantifiable. Consequently, all analyses are conditional upon the vagaries of specific choices of uncertainty quantification, be they objective or subjective.

#### *2.3.3.6 Decision Support Has Value at All Scales of User*

Decision-support systems can be valuable for situations where the scale of the user or the application is very small[15] or very large and complex.[16] Although the production of customized decision-support systems is necessary, either some potential users may be unable to pay to develop or support such systems, or this development may require commitments by many partners to fund and maintain. In the latter case, and given the multiple users and goals in such a coalition of partners, additional processing of the information may be needed to reveal the outcomes, their differential utilities, and the dependence of these outcomes on intermediate variables and various sources of uncertainty in the analysis.

In the context of applying probabilistic hydrometeorological forecasts into decision-support systems, retail, tourism, travel, agricultural supply chain management, insurance, and energy are obvious areas of application. Customized decision-support systems are used for risk management in industries in each of these areas, as are private-sector-generated hydrometeorological forecasts with associated uncertainty information.

The specialized users most likely to adopt decision-support frameworks, and the intermediaries that work with them, are likely to require more detailed information than is currently provided by NWS hydrometeorological forecast products—both in terms of spatial and temporal detail and in terms of the resolution of the probability distributions and their uncertainty. Other public-sector agencies (e.g., the Federal Emergency Management Agency) would need to support such an effort by developing databases on consequences (e.g., assets at risk, costs of relocation, costs of false alert) and committing to the use of the hydrometeorological forecast information with a decision-support system. This mismatch could be reduced if action is taken on the recommendations in Chapters 3 and 5.

#### *2.3.3.7 There Has Been Limited Penetration of Probabilistic Information to User Communities Through Decision-Support Systems*

Despite the likely benefits of the use of probabilistic, hydrometeorologically influenced decision-support systems, such systems have achieved limited penetration into user communities. Reasons for this may include the following:

- a lack of awareness of products that could be available and how to acquire them;
- the limited format of the forecasts that are issued, including the lack of information as to the uncertainties associated with extreme (catastrophic) events, and to the multiple time scales of interest to the decision maker;
- the perception of poor skill in forecasts, or the inability to verify the uncertainty (ambiguity) in the forecasts and assess it relative to a baseline;
- an inability to access historical error/verification information or estimated forecast uncertainty;
- an assessment that the uncertainty associated with the forecasts is not low enough to justify their use over using climatological probabilities;
- a formal assessment that the sensitivity of the decisions to weather/seasonal climate is too low to use the information;
- an assessment that transaction costs or organizational factors outweigh the benefits of managing dynamic risk using forecasts versus maintaining a steady operational policy; and
- an assessment that the measures taken to reduce long-term climate-related risk have effectively eliminated the need to use routine forecasts (and if so, perhaps there is interest in extreme forecast for event management).

In addition to developing a greater understanding of the relative importance of these factors in limiting the use of probabilistic hydrometeorological forecasts in decision-support systems, the Enterprise will be better positioned to generate and communicate uncertainty information that meets users' needs through such tools if NWS and its partners explore

- whether the spatial or temporal resolution of the products leads to a mismatch with NWS products, and if the users have access to intermediaries who can provide bridging products;
- whether there are vendors who can provide decision-support systems that integrate access to and analysis of NWS products and that satisfy user needs for bundling such products; and
- whether users perceive potential financial gains through reduced insurance costs or other ways if they implement decision-support systems that promote adaptive short- and long-term management of routine and catastrophic hydrometeorological risk.

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[15] For example, an individual farmer, for whom managing catastrophe may be as important as income, and who may have limited resources for information acquisition or evaluating outcomes.

[16] For example, for water systems, disaster planning and relief, or public health.

#### *2.3.3.8 Public Agencies Tend Not to Consider Hydrometeorological Uncertainty in Their Models Despite Most Environmental Risk Management Being Inherently Multiscale*

Public agencies involved in environmental, water, and energy resource management have a variety of modeling and information management tools that use climate information. For example, USACE, Bureau of Reclamation, Departments of Energy and Agriculture, Environmental Protection Agency, Forest Service, and Geological Survey all have freely available models that have climate as a primary driver. For the most part, these models have been developed as simulation tools with the intention of managing long-term climate risk. Consequently, their management applications relate to infrastructure sizing and design for mitigating long-term risk, planning, regulatory and operation rule evaluation and formulation, and assessment of impacts of specific practices on environmental attributes. Some of these models have explicit probabilistic inputs and outputs, whereas others are simulation models whose outputs and inputs could be treated as probabilistic. Most have very limited, if any consideration of probabilistic hydrometeorological forecasts, given that their legacy goes back to the 1950s or 1960s in some cases. In what represents a fundamental shift in management thinking and an opportunity for stronger links between forecast producers and manager-users of forecasts, however, the USACE, the main policy-establishing agency for water resources management through large reservoir facilities in the United States, will now consider reservoir operations based on forecasts.[17]

Almost all of these agencies recognize the need for characterizing and managing uncertainty as part of their mission. However, often due to legal strictures and sometimes due to inertia, there is limited consideration of factors other than long-term risk because it matches a regulatory purpose. Nonetheless, most environmental risk management problems are inherently multiscale (both temporally and spatially). While most of these agencies have operational responsibilities to ensure long-term performance, they are also responsible for responding to events or operational exigencies that result from the residual dynamic risk. If NWS seeks to enhance applications of its probabilistic products within the public sector, launching joint initiatives to consider a comprehensive approach to environmental risk management driven by probabilistic hydrometeorological products and also by changing landscape and social settings would be an important goal. The second point of NWS engagement with the other federal agencies could be to participate with them in addressing one or two high-profile environmental or agricultural projects where probabilistic seasonal forecasts could have a significant impact. This would provide a concrete example of multiagency proactive efforts to bring science forward to address emerging problems. It would also bring engagement from the academic and other communities interested in tackling complex decision problems through innovation in the decision sciences. In addition, NWS would learn more about what probabilistic products to provide.

In general, as NWS moves forward in its interaction with and support of users of sophisticated decision-support systems, it will need to be cognizant that the use of new forecasts in old decision-support systems tailored for deterministic forecasts may actually degrade the system performance (e.g., Yao and Georgakakos, 2001), unless the underlying decision rules are also modified to account for the uncertainty information and updated.

## 2.4 GUIDANCE ON IDENTIFYING AND CHARACTERIZING USER NEEDS

This section provides general guidance on how to identify and characterize user needs. It builds on material from the preceding two sections that describes how decision makers interpret and use uncertain information. The complexity of this task—with a large number of interacting factors influencing the effectiveness of different communication formats and their use in forecast-related decisions—puts any precise specification of user needs far beyond the ability of a single committee. (The private sector, for example, spends millions of dollars each year on customer research.) Instead, the committee recommends a *process* by which NWS can develop an effective system of provider-user interactions that will lead to identification of user needs and the design and testing of effective probabilistic forecast formats.

### 2.4.1 Problems with Existing Assessments of User Needs

As mentioned previously, NHC collected user data about their cone of uncertainty format of hurricane track forecasts in the aftermath of Hurricane Charley. It requested public comments on the original graphic and two new alternatives on its Web site and asked respondents to vote for their preferred graphic from among the three options. This was not a representative survey of the general population. Because it was conducted online, participation was strongly biased toward those with Internet access and, perhaps more importantly, a preexisting interest in NHC and its Web site. The call for comments was advertised by issuing a Public Information Statement to the media, emergency managers, the private sector, and on the Tropical Prediction Center Web site. Thus, the survey was based entirely on individuals self-motivated to take the survey. This almost certainly produced a highly skewed sample. In addition, no demographic information was collected, making it impossible to determine the representativeness of the sample on even demographic characteristics. These are problems that could have been easily avoided had NWS consulted expertise on survey design and sampling.

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[17] Beth Faber, Presentation to the Committee, September 2005.

TABLE 2.4 Preferences of Respondents as Determined by NHC Reviewers

| Preference | Number of Respondents |
|---|---|
| Option 1 | 540 |
| Option 2 | 121 |
| Option 3 | 201 |
| No preference | 33 |
| Cannot determine | 67 |
| Total | 962 |

SOURCE: Broad et al. (2006).

Another problem with the NWS survey is its choice of metric by which the appropriateness of a forecast format is being evaluated. Asking people for their preference among alternative displays, especially when one of them is the well-publicized status quo alternative, turns out to be a bad choice. The fact that the majority of respondents (540 out of 962; see Table 2.4) indicated that they preferred the status quo option is not surprising to behavioral scientists.

There are at least two well-established psychological mechanisms that would give rise to this result. The first is the effect of familiarity, and in particular the emotional comfort derived from familiarity, which has been shown to lead to irrational perceptions of lower risk in the context of financial investment decisions that lie at the root of such problematic investment behavior as insufficient diversification (Huberman, 2001; Weber et al., 2005). Another mechanism is loss aversion (i.e., the fact that people's disutility when giving things up is greater than their utility when acquiring the same things) and the status quo bias it has been demonstrated to lead to (Samuelson and Zeckhauser, 1988; Johnson and Goldstein, 2003). Anecdotal evidence for the operation of the familiarity and status quo bias comes from the open-ended responses to the NHC question: "Those of us that have lived in the path of these storms are familiar with, and used to, the way you have been clearly warning us and informing us. Please do not let a few people, who may not have been paying attention, cause you to change your system unless you believe . . . know . . . that you have a better system."

### 2.4.2 One Size Does Not Fit All

The population of NWS forecast product users is diverse. One cannot talk to just a subset of users and assume knowledge gained accurately represents the range of user needs. Even within a class of user (e.g., "emergency manager," "public"), there is a lot of diversity in capacity, constraints, and information needs and desires. A specific user's needs may also change across situations (e.g., emergency managers may need different information about future rainfall when there has recently been flooding than when it has been dry, and they may need different information during the day than at night). Furthermore, the situation is also not static: users' needs evolve as their decision context, level of knowledge, or information capabilities change. So one size certainly does not fit all, and even well-characterized user needs will need to be revisited. This suggests that understanding user needs is a large and evolving task, but one that is critical to successful provision of uncertainty information for the nation's benefit. Fortunately, entities within the private sector and academia have experience in characterizing user needs and would be valuable partners in this Enterprise-wide endeavor.

Information about the wide variety of user needs for uncertainty information is also available in previous NRC reports, which find that the value or usefulness of forecast uncertainty information depends on users' capacity to take action to help them change, or at least cope with, the future. For example, NRC noted in *A Vision for the National Weather Service: Road Map for the Future* (1999b) that the Enterprise must think less about information "in terms of what it is about" and more in terms of "how it will be used." In *Making Climate Forecasts Matter* (1999c), NRC also noted the importance of user informational needs, situational factors (e.g., social, economic, environmental), and coping strategies. For instance, does a user have alternatives or contingency plans that can be implemented? In other words, it is important not simply to provide uncertainty information, but to communicate uncertainty information in a way that can actually help users solve a problem or improve their situation.

It is tempting to think that one way of dealing with heterogeneous user needs is to provide everyone with all available information, with the assumption that unnecessary information will simply be ignored. Unfortunately this is not a viable strategy. Unnecessary information can delay or complicate action, with great costs in situations of time pressure and high stakes. Such information can also be misinterpreted, as in the case of the "skinny black middle line" in the cone of uncertainty (Figure 1.6). When people misunderstand the information, they tend to make worse decisions. Finally, too much information packed into a graphic is often confusing (Tufte, 2001) and poorly designed or produced visuals are worse than no visual at all (Hager and Scheiber, 1997). There is a difference between the *provision* of too much information to users and the *generation* of information that could be provided to users. The potential availability of a wide range of different forecast information helps to ensure that the best information for a particular user group is available.

**Finding:** The utility of a forecast has many user-specific and contextual constraints. Consequently, it is valuable to approach questions of forecast utility in a structured manner. Basic principles of relevance will need to be applied, such as disclosure of all the information available, disclosure of sources, and truthfulness in reporting. In the spirit of openness, transparency, and disclosure, it will also be useful to consider ways to make multiple forms of presentation available to all, and to accompany them with a menu of recommendations for use by different user groups and situations.

**Recommendation 2.3: The utility of any forecast uncertainty product should be evaluated within the individual, social, and institutional contexts of the recipient. What to include and not include should in part be a function of the intended user and their ability to handle different sorts of information. Those developing risk communication products should consider a set of basic questions:**

- Who, specifically, are your intended users? Are they other scientists and meteorologists? The public? Particularly vulnerable populations? Particular economic sectors? Local, state, or national officials? Each user may need a specifically tailored product.
- What information does the user *want*? This may be quite different from the information currently provided. Not giving the user the information they want can be dangerous. If people do not find the information they are looking for in a graph or in some risk communication, they might misinterpret other information for what they are looking for.
- What information do the users *need* to make informed decisions, whether they realize it or not? Do they really, for example, need to understand the uncertainty in hurricane track forecasts? Is this more important than other information (e.g., projected wind speeds, storm surge, flooding risks)?
- Does the information provide enough detail for its intended users to assess their risk exposure and plan action (Fischhoff, 1994)? In the case of hurricanes, for example, some individuals and areas are more vulnerable to storm surge (e.g., coastlines), others to wind speed (e.g., trailer parks), while others are more vulnerable to the loss of electricity (e.g., elderly who rely on refrigerated medication). Merely knowing the likelihood that a hurricane might strike a particular area does not provide the more specific information people need to consider when assessing the risks and choosing a course of action.
- What other information is the intended user currently using to make decisions? Will the new product provide something new and useful, will it simply repeat other information, or worse, will it provide distracting or contradictory information and lead to more confusion and flawed decision making?
- Does the intended user operate decision-support tools based on statistical decision theory and need detailed information on the uncertainties associated with probabilistic forecasts? Mechanisms may be needed for providing this information, either through ensembles and historical verification information, or through a Bayesian estimation process that properly considers the multiple sources of uncertainty in the forecast and generates an appropriate uncertainty distribution.

### 2.4.3 Engaging the Social and Behavioral Sciences

The discussions in the preceding sections indicate that social and behavioral science expertise is needed at several levels and for several tasks within NOAA. Although it may be possible to outsource many of these tasks and/or to commission the research[18] and testing of products necessary for the design of successful probabilistic forecast products, it may be less expensive and more effective (in terms of organizational emphasis and carry-over from task to task and product to product) to also acquire in-house social and behavioral science expertise. This would be beneficial not only to NOAA but to the behavioral decision community as well. Decision making under hydrometeorological uncertainty is an area where theory and empirical insights have obvious and immediate implications, and it is quite surprising that there has not been more work in this area of application compared to, for example, medical decision making.

**Finding:** Social and behavioral science expertise will help NOAA identify and solve possible user confusions and misinterpretations of both existing and future (probabilistic) forecasting products. These scientists would also support better processes in the design and evaluation of forecasts.

**Recommendation 2.4: NOAA should acquire social and behavioral science expertise including psychologists trained in human cognition and human factors, with training in behavioral decision theory, statistical decision theory, survey design and sampling, and communication theory, with special focus on graphics and product development.**

## SUMMARY

This chapter provides guidance on how to identify and characterize needs for uncertainty information among various users of forecasts. To do so, it first discusses the different types of forecast users and general user needs for uncertainty information, along with several examples of specific users' needs. Because users' information needs derive largely from their use of that information in decision making, the chapter then reviews how decision makers interpret and use uncertain information, from two related perspectives. The descriptive perspective of psychology provides insights about the cognitive and affective processes involved when people make intuitive decisions that involve uncertainty. The prescriptive perspective of statistical decision theory provides insights into how uncertain information is used in analytic decision-making processes, and it supports the explicit incorporation of uncertain information into decisions through decision-

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[18] Through provision of internships for pre- or postdoctoral students and PhD dissertation fellowships, for example.

support systems. This review of background knowledge is provided both to help NWS and the Enterprise understand key relevant concepts in decision making under uncertainty and to support recommendations on how to identify and characterize users' needs for uncertainty information. The final section of the chapter discusses how NWS and the Enterprise might apply this knowledge to better understand users' needs for uncertainty information.

The psychological perspective indicates that there is a variety of ways in which people use prior personal experience, available forecasts, and other sources of information to decide on an appropriate action in a given situation. How people make decisions depends on their abilities, training, and personality, the question to be answered, and the information available. This complexity makes it clear that NWS cannot provide a single forecast product that would satisfy all users. Instead, the committee recommends designing a variety of methods to present and distribute uncertainty information, as a function of type of users and type of decisions. Determining which presentation formats best provide different users with the information they need will require effective, frequent NWS-user-Enterprise interactions and a sustained, coherent social and behavioral science research effort. The prescriptive perspective provides a framework for NWS and the broader Enterprise to identify users and application areas that are most likely to benefit from uncertainty information.

The detailed recommendations in this chapter (along with those in Chapter 4) point NWS and the broader Enterprise toward a process that will help them generate precise questions about various users' needs for uncertainty information and reliable and valid answers. If implemented, this process will help NWS address users' needs for uncertainty information into the future as users' needs, forecasting capabilities, and technologies evolve.

# 3

# Estimating and Validating Uncertainty

To address the almost unbounded variety of possible uses of uncertainty information in hydrometeorological forecasts (see, e.g., Box 3.1 and Section 2.1), it is essential for NWS to transition to an infrastructure that produces, calibrates, verifies, and archives uncertainty information for all parameters of interest over a wide range of temporal and spatial scales. This chapter focuses on the limitations of current methods for estimating and validating forecast uncertainty and recommends improvements and new approaches. The committee takes the view that these changes are a fundamental first step in transitioning from a deterministic approach to one that enables all users to ultimately harness uncertainty information.

By no means exhaustive, this chapter reviews aspects of the current state of NWS operational probabilistic forecasting, discusses related efforts in the research community, and provides recommendations for improving the production of objective[1] uncertainty information. The chapter also discusses subjective approaches to producing uncertainty information that are utilized by human forecasters.

Many groups within NWS generate forecasts and guidance. Those included in this chapter are the Environmental Modeling Center (EMC), the Climate Prediction Center (CPC), the Office of Hydrologic Development (OHD), the Hydrometeorological Prediction Center (HPC), the Weather Forecast Offices (WFOs), the Storm Prediction Center (SPC) and the Space Environment Center (SEC). This sample was chosen because it demonstrates the range of NWS products and also places particular emphasis on the NWS's numerical "engines," that is, the centers from which NWS forecast guidance is generated.

The forecasting system components (Table 3.1) of each of the NWS centers covered in this chapter are broadly equivalent in function, but the differences in underlying physical challenges and operational constraints require that each entity be treated differently. The chapter begins with the EMC and discusses the production of global and regional objective probabilistic guidance. It then covers the CPC's seasonal forecasts that include numerical, statistical, and subjective approaches to probabilistic forecast generation. The multiple space- and time-scale forecasts of the OHD are covered next, and the hydrologist's unique role as both user and producer of NWS forecast products is highlighted. The subjective generation of forecasts by groups like the WFOs, the HPC, and the SPC is covered, and the chapter ends with a detailed discussion of verification issues. The SEC is presented as an example of an NWS center that makes the quantification and validation of uncertainty central to its operations. The SEC is an example of what can be accomplished within NWS once uncertainty is viewed as being central to the forecasting process (Box 3.2).

## 3.1 ENVIRONMENTAL MODELING CENTER: GLOBAL AND MESOSCALE GUIDANCE

The EMC[2] is one of the National Centers for Environmental Prediction (NCEP[3]) and is responsible for the nation's weather data assimilation and numerical weather and climate prediction. The primary weather-related goals of the EMC include the production of global and mesoscale atmospheric analyses through data assimilation, the production of model forecasts through high-resolution control runs and lower-resolution ensemble runs, model development through improved numerics and physics parameterizations,

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[1] Subjective estimates are based directly on the judgment of human experts. In this report, the term "objective probabilistic forecast" is used to mean estimates of stable frequencies derived using statistical theory, measurements, and model forecasts. The committee's use of the term "objective probability forecast" should not be confused with the common usage of the term "objective probability" to refer to true, underlying physical propensity.

[2] http://www.emc.ncep.noaa.gov/.

[3] http://www.ncep.noaa.gov/.

### BOX 3.1
### Wide Breadth and Depth of User Needs

User needs for hydrometeorological information span a wide variety of parameters and time and spatial scales. For instance, minimum daily temperature is important for citrus farming but has little relevance for water conservation, where seasonal total streamflow is of primary importance. In addition, requirements for uncertainty information are not always well defined among users. Even in the cases where they are well defined, they can vary greatly among users and even for a single user who has multiple objectives. The citrus farmer may require local bias information for a 10-day temperature projection, and at the same time require probability information for a winter-season temperature and precipitation projection. The manager of a large multiobjective reservoir facility may require ensemble inflow forecast information with a seasonal (or longer) time horizon for flood and drought mitigation but with hourly resolution for hydroelectric power production.

TABLE 3.1 Forecasting System Components

| Component | Description |
|---|---|
| Observations | Observations are the basis of verification and are critical to the data assimilation process. Observations in conjunction with historical forecasts provide a basis for forecast post-processing (e.g., Model Output Statistics, or MOS) and associated uncertainty estimates. |
| Data assimilation | Data assimilation blends observation and model information to provide the initial conditions from which forecast models are launched. Data assimilation can also provide the uncertainty distribution associated with the initial conditions. |
| Historical forecast guidance | An archive of historical model forecasts combined with an associated archive of verifying observations enables useful post-processing of current forecasts. |
| Current forecast guidance | Model forecasts are used by human forecasters as guidance for official NWS forecasts. |
| Models | Models range from first-principle to empirical. Knowledge of the model being used and its limitations helps drive model development and model assessment. |
| Model development | Models are constantly updated and improved, driven by computational and scientific capabilities and, ultimately, the choice of verification measures. |
| Ensemble forecasting system | A collection of initial conditions, and sometimes variations in models and/or model physics, that are propagated forward by a model. The resulting collection of forecasts provides information about forecast uncertainty. Ensemble forecasting systems are developing into the primary means of forecast uncertainty production. |
| Forecast post-processing | Forecast post-processing projects forecasts from model space into observation space. Given a long record of historical forecasts and associated verifying observations it is possible to make the forecasts more valuable for a disparate set of forecast users. Post-processing can be cast in a probabilistic form, naturally providing quantitative uncertainty information. Examples of post-processing include bias correction, MOS, and Gaussian mixture model approaches like Bayesian model averaging (BMA). |
| Forecast verification | Forecast verification is the means by which the quality of forecasts is assessed. Verification provides information to users regarding the quality of the forecasts to aid in their understanding and application of the forecasts in decision making. In addition, verification provides base-level uncertainty information. Verification also drives the development of the entire forecasting system. Choices made in model development, observing system design, data assimilation, etc., are all predicated on a specified set of norms expressed through model verification choices. |

and model verification to assess performance. This section focuses on the global weather modeling component of the Global Climate and Weather Modeling Branch (GMB[4]) and on the mesoscale weather modeling component of the Mesoscale Modeling Branch (MMB[5]) of EMC.

### 3.1.1 Ensemble Forecasting Systems

Ensemble forecasting systems form the heart of EMC's efforts to provide probabilistic forecast information.[6] The aim of ensemble forecasting is to generate a collection of forecasts based on varying initial conditions and model

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[4] http://www.emc.ncep.noaa.gov/gmb/.

[5] http://www.emc.ncep.noaa.gov/mmb/indexMMB.shtml.

[6] http://wwwt.emc.ncep.noaa.gov/gmb/ens/index.html and http://wwwt.emc.ncep.noaa.gov/mmb/SREF/SREF.html.

## BOX 3.2
## Space Environment Center

The Space Environment Center (SEC)[a] monitors and forecasts Earth's space environment. It is an example of an NWS center that successfully engages its users, works with users to enhance existing products and develop new products, and conscientiously estimates and includes uncertainty and verification information with its forecasts.

The SEC has created a culture and infrastructure that provides quantitative uncertainty information, real-time and historical verification information, and comprehensive product descriptions. Examples of official SEC forecast products that explicitly provide uncertainty information include Geomagnetic Activity Probability forecasts, whole disk flare probabilities, and explicit error bars on graphical and text forecasts of sunspot number. Uncertainty and verification information are explicitly available both for model (or guidance) forecasts and for official forecasts. For example, guidance forecasts from the Costello Geomagnetic Activity Index model include both error bars and an indication of recent model performance by plotting a time series of recent forecasts along with their verifying observations (e.g., Figure 3.1). The SEC has a Web site for communicating the verification statistics of its official (human-produced) forecast products.[b] On this site the geomagnetic index and short-term warning products are verified using contingency tables (hit rate, false alarm rate, etc.), and the geomagnetic probability forecasts are verified using measures like ranked probability score (and are compared with scores from climatology), reliability, and resolution.

*continued*

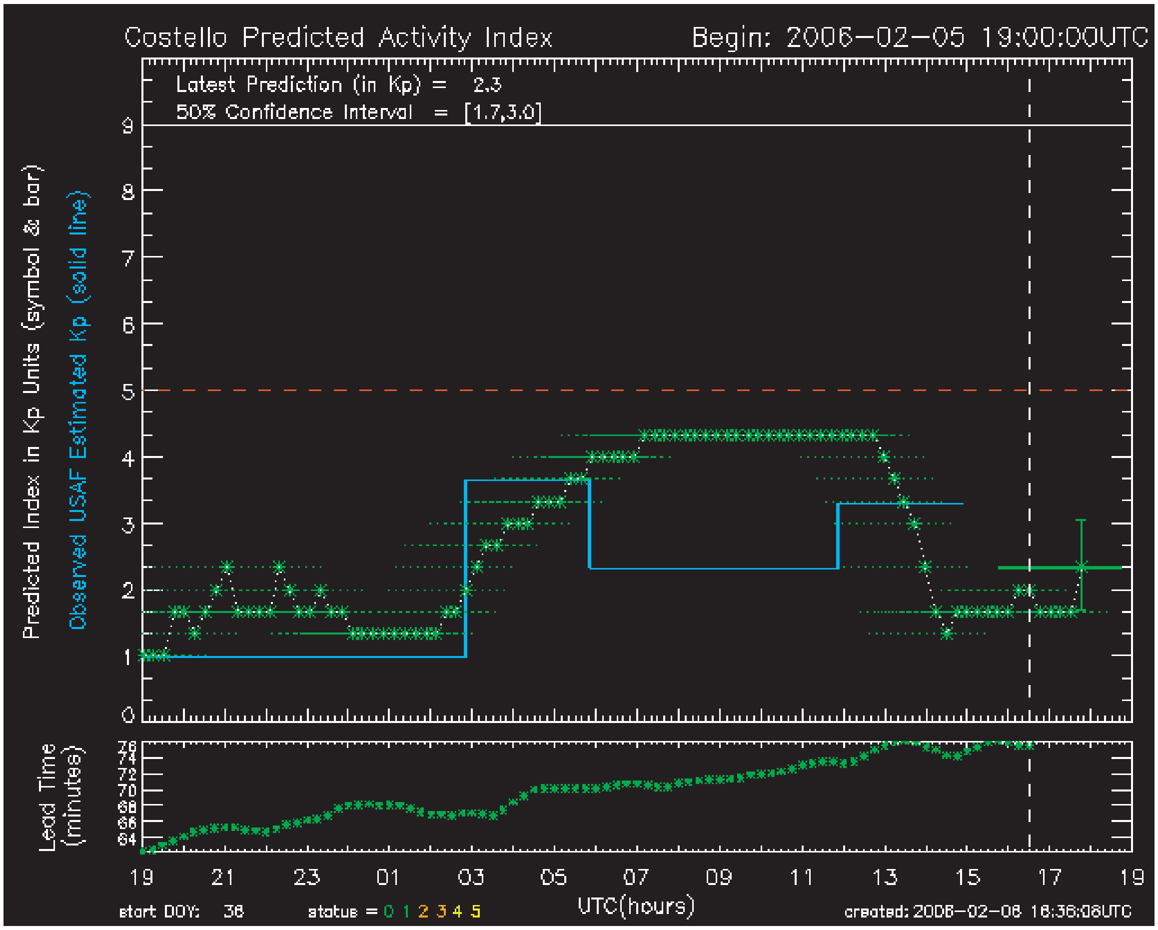

FIGURE 3.1 Model forecast (symbol and bar) and verification (solid line) of the Kp geomagnetic activity index. Note the error bars on the Kp forecast. Historical verification information is available through the associated Web site. SOURCE: SEC Web site, http://www.sec.noaa.gov/index.html.

## BOX 3.2 Continued

The SEC appreciates the importance of providing archives of both observations and forecasts to best serve their users. The observations utilized by the SEC are listed and described on the SEC Data and Products Web site.[c] In addition, links are provided to the most recent observations and archived measurements. Historical observations are archived by the SEC itself, by the Advance Composition Explorer (ACE) Science Center,[d] and the National Geophysical Data Center (NGDC[e]). The SEC Web site provides links to all the relevant archives. A short archive of forecasts and model guidance is available on the SEC Data and Products Web site, and all forecasts are archived at the NGDC.

The SEC is a new member of NWS. Prior to January 2005, it was under the National Oceanic and Atmospheric Administration (NOAA) office of Oceanic and Atmospheric Research (OAR). It is a small center with a relatively small number of products and verifying observations. This facilitates interaction among different groups within the SEC and close contact with forecast users. While under OAR the SEC forged strong links with the research community, and its products were directly driven by their user community rather than indirectly through NWS directives. Since joining NWS it has maintained this culture and recognizes the benefits derived from close interaction with the university and user communities.[f] The SEC is lightly regulated by NWS directives,[g] allowing continuity of its OAR culture. Admittedly, the number of variables forecast by and the diversity of user groups served by the SEC are much smaller than for other NWS centers, making it easier to provide uncertainty and verification information and to forge links with the user community. Concomitantly, the SEC is much smaller than other NWS centers, suggesting that their success in engaging the user community is more cultural than resource based.

Each year the SEC hosts a "Space Weather Week" meeting that draws internationally from the academic, user, and private communities.[h] The bulk of the meeting takes place in a single room with approximately 300 participants, leading to strong interactions between the academic, government, private, and user communities. The user community consists of organizations ranging from power companies, airlines, the National Aeronautics and Space Administration (NASA), and private satellite operators. The SEC uses the meeting to identify the needs and concerns of its users and to monitor and influence the efforts of the research community. The SEC values the meeting to such an extent that it has maintained it even while sustaining significant budget cuts.

Other examples of links with the extended space weather community are found in SEC's model development efforts. All the operational models currently utilized by SEC are empirically based; the community does not yet fully understand the relevant physics, and there is not enough of the right type of data to drive physics-based models. SEC's model development is routed through the Rapid Prototyping Center (RPC[i]). The aim of the RPC is to "expedite testing and transitioning of new models and data into operational use" and encompasses modeling efforts ranging from simple empirical methods to large-scale numerical modeling. In addition to SEC's internal efforts, the multiagency Community Coordinated Modeling Center (CCMC[j]) encompasses over a dozen physics-based research models. Complementing CCMC's government agency-driven approach is the University-centric Center for Integrated Space Weather Modeling (CISM[k]). CISM aims to develop physics-based models from the Sun to Earth's atmosphere. The SEC expects to incorporate physics-based models into its operational suite in the coming years and anticipates making full use of data assimilation and ensemble forecasting approaches to improve the forecast products (Kent Doggett, personal communication).

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[a] See http://www.sec.noaa.gov/index.html.

[b] http://www.sec.noaa.gov/forecast_verification/index.html.

[c] http://www.sec.noaa.gove/Data/index.html.

[d] http://www.srl.caltech.edu/ACE/ASC.

[e] http://www.ngdc.noaa.gov/stp/stp.html.

[f] Kent Doggett, presentation to the committee.

[g] http://www.weather.gov/directives/010/010.htm.

[h] http://www.sec.noaa.gov/sww/.

[i] http://www.sec.noaa.gov/rpc/.

[j] http://ccmc.gsfc.nasa.gov/.

[k] http://www.bu.edu/cism/index.html.

specifications that attempts to sample from the uncertainty in both. This collection of forecast states contains information about the uncertainty associated with the forecast. Global ensemble forecasting has been run operationally at NCEP since 1993 (Toth and Kalnay, 1993), and mesoscale ensemble forecasting, also known as short-range ensemble forecasting (SREF), has run operationally since 2001 (Du et al., 2003). Global ensemble forecasts currently consist of 15 ensemble members whereas SREF consists of 21 (McQueen et al., 2005).

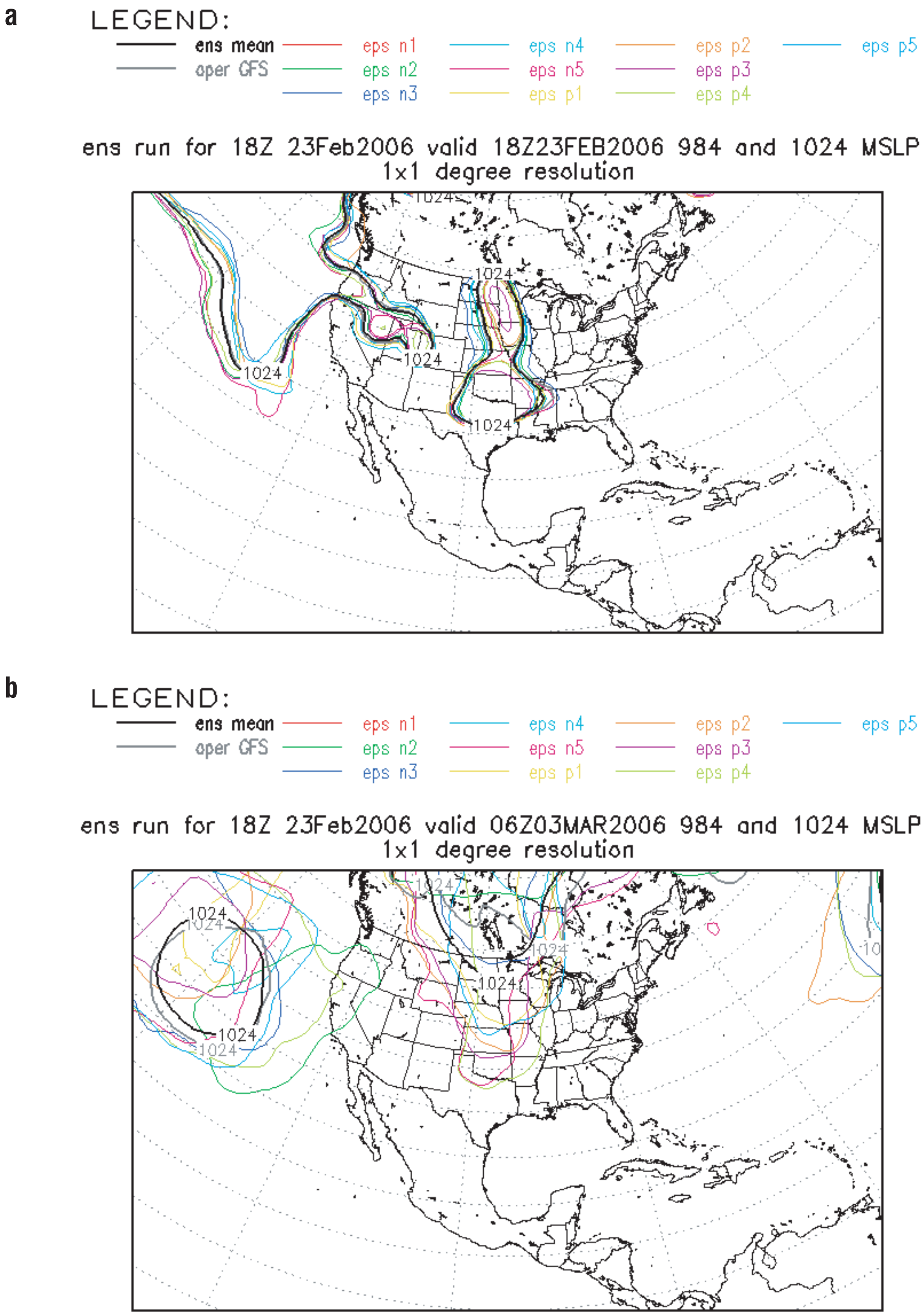

FIGURE 3.2 "Spaghetti" diagrams with contours of the 1024-mb sea-level pressure contour of 11 ensemble members (see legend for a description of the different colors) for (a) the ensemble of initial conditions and (b) after running the model 7.5 days into the future. SOURCE: EMC, http://wwwt.emc.ncep.noaa.gov/gmb/ens/fcsts/ensframe.html.

Many products are derived from the ensemble forecasts. Figure 3.2 shows an example of a GMB ensemble product (the MMB produces a similar product). These so-called spaghetti diagrams plot contours from all ensemble members in a single figure. The degree of difference between the forecast contours provides information about the level of uncertainty associated with the forecast of each parameter (e.g., sea-level pressure). Figure 3.3 shows an example of an MMB product—a meteogram that provides information about five weather parameters at a single location as a function of time.

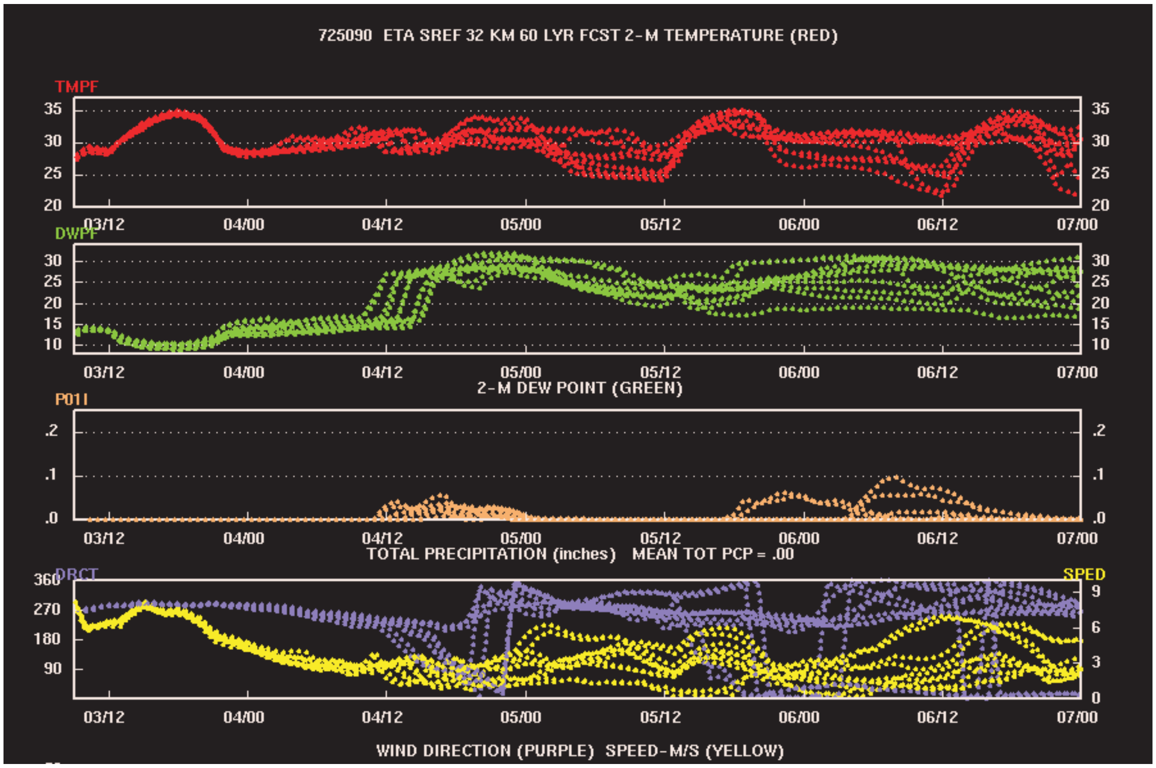

FIGURE 3.3 Example of an experimental SREF ensemble meteogram for Boston. The red curves trace temperature (at 2 meters above the surface) for each ensemble member as forecast time increases, the green curves provide information about dew point temperatures at 2 meters above the surface, the orange curves are precipitation, the purple curves are wind direction, and the yellow curves are wind speed. SOURCE: EMC, http://wwwt.emc.ncep.noaa.gov/mmb/srefmeteograms/sref.html.

This product is experimental and uncalibrated, but provides information about the uncertainty associated with each parameter from the spread of lines within each panel. Both GMB and MMB provide links from their ensemble Web page to many other methods of visualizing and communicating the information contained in their ensemble forecasts.

Mesoscale ensemble systems are also being run in the university environment. For example, a mesoscale ensemble system with 36- and 12-km grid spacing has been run at the University of Washington since 1999. The academic community is studying variants of the ensemble Kalman filter (EnKF) approach (Evensen, 1994), including the University of Washington implementation of a real-time EnKF data assimilation (Box 3.3) and ensemble forecasting system for the Pacific Northwest.[7] The National Center for Atmospheric Research (NCAR) hosts a Data Assimilation Research Testbed[8] which enables researchers to use state-of-the-science EnKF data assimilation with their model of choice. The testbed also enables observationalists to explore the impact of possible new observations on model performance and allows data assimilation developers to test new ideas in a controlled setting.

Selection of initial conditions for ensemble forecasting is critically important. The GMB and MMB both use a "bred vector" approach to generate initial ensemble members. This approach relies on model dynamics to identify directions that have experienced error growth in the recent past (see Box 3.4). The primary benefits of the breeding methodology are that it provides an estimate of analysis uncertainty (Toth and Kalnay, 1993) and that it is computationally inexpensive. Recognizing the intimate links between data assimilation and the specification of initial ensemble members, the research community has taken a lead in developing ensemble-based approaches to data assimilation and ensemble construction using the EnKF approach (e.g., Torn and Hakim, 2005; Zhang et al., 2006). The GMB has recently implemented an "ensemble transform" ensemble generation technique that utilizes an approximation to the ensemble transform Kalman filter ideas of Wang and Bishop (2005). The EMC is also experimenting with ensemble-based data assimilation through its involvement in THORPEX (Box 3.5),

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[7] http://www.atmos.washington.edu/~enkf/.

[8] http://www.image.ucar.edu/DAReS/DART/.

## BOX 3.3
## Data Assimilation

Numerical Weather Prediction (NWP) is primarily an initial condition problem, and data assimilation (DA) is the process by which initial conditions are produced. DA is the blending of observation information and model information, taking into account their respective uncertainty, to produce an improved estimate of the state called the analysis. DA is also capable of providing uncertainty estimates associated with the analysis, which, in addition to quantifying the uncertainty associated with the initial state estimate, can be used to help construct initial ensembles for ensemble forecasting efforts.

Numerous forms of data assimilation exist, and they can be broadly classified as either local in time or distributed in time. Distributed-in-time approaches use trajectories of observations rather than single snapshots. Within each classification one can choose to take a variation approach to solving the problem or a linear algebra, direct-solve approach. Local-in-time techniques include the Kalman Filter, three-dimensional variational assimilation (3d-Var), the various versions of EnKFs, and ensemble-based perturbed observation versions of 3d-Var. Distributed-in-time techniques include the Kalman smoother, four-dimensional variational assimilation (4d-Var), the various versions of ensemble Kalman smoothers, and ensemble-based perturbed observation versions of 4d-Var. In the operational context, the NCEP Spectral Statistical Interpolation (SSI) uses a 3d-Var approach and the European Centre for Medium-range Weather Forecasts (ECMWF) and the Canadian Meteorological Centre (CMC) use 4d-Var.

Data assimilation requires estimates of uncertainty associated with short-term (typically 6-hr) model forecasts, and the uncertainty associated with these forecasts is expected to change as a function of the state of the atmosphere. The computational costs associated with the operational DA problem can make estimation of the time-varying forecast uncertainty prohibitively expensive, but the benefits of doing so are likely to be felt both in the quality of the analysis and in the quality of the uncertainty associated with the analysis. This uncertainty can then be used to help in the construction of initial ensemble members, ultimately improving ensemble forecasts. There is thus an intimate link between the DA problem and the ensemble forecasting problem.

The ensemble approach to DA is one way to incorporate time-varying uncertainty information. The CMC now runs an experimental EnKF data assimilation system that compares favorably with 4d-Var,[a] demonstrating that accounting for time-varying uncertainty information is possible in the operational setting. The move by the EMC to the Gridpoint Statistical Interpolation system will, among other things, enable the inclusion of time-varying forecast uncertainty information in the DA process. Work funded by NOAA's THe Observing system Research and Predictability Experiment (THORPEX) initiative[b] is exploring both ensemble-based filtering and hybrid ensemble/3d-Var approaches aimed at the operational DA problem.

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[a] http://www.emc.ncep.noaa.gov/gmb/ens/THROPEX/PI-workshop/houtekamer-talk.pdf.

[b] http://www.emc.ncep.noaa.gov/gmb/ens/THORPEX/THORPEX-grants.html.

with planned prototype testing and a tentative operational transition date of 2009 if the approaches prove useful.[9] Other operational centers use different approaches to ensemble construction (see Box 3.4).

**Finding:** A number of methods for generating initial ensembles are being explored in the research and operational communities. In addition, ensemble-based data assimilation approaches are proving beneficial, especially at the mesoscale.

**Recommendation 3.1: As the GMB and the MMB of the EMC continue to develop their ensemble forecasting systems, they should evaluate the full range of approaches to the generation of initial ensembles and apply the most beneficial approach. The EMC should focus on exploring the utility of ensemble-based data assimilation approaches (and extensions) to couple ensemble generation and data assimilation at both the global and the mesoscale levels.**

### 3.1.2 Accounting for Model Error in Ensemble Forecasting

A limitation of any ensemble construction methodology based on a single model is the difficulty in accounting for model inadequacy. This is related to the problem of ambiguity in Chapter 2—the notion of the uncertainty in the estimate of the uncertainty. One approach that attempts to account for model inadequacy during ensemble forecasting is to use different models and/or different parameterizations in the same model. This approach is theoretically underpinned by an extensive literature on Bayesian statistical approaches to explicitly considering multiple models/parameterizations

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[9] http://wwwt.emc.ncep.noaa.gov/gmb/ens/THORPEX/PI-shop-2006.html.

## BOX 3.4
## Ensemble Forecasting and Ensemble Initial Conditions

### Background

The aim of ensemble forecasting is to provide uncertainty information about the future state of the atmosphere. Rather than running models once from a single initial condition, a collection of initial conditions are specified and the model is run forward a number of times. The range of results produced by the collection (ensemble) of forecasts provides information about the confidence in the forecast.

There are two important conditions that must be met for the ensemble of forecast values to be interpreted as a random draw from the "correct" forecast probability density function (PDF): (1) the ensemble of initial conditions must be a random draw from the "correct" initial-condition PDF, and (2) the forecast model must be perfect. In practice these conditions are never met, but a probabilistically "incorrect" ensemble forecast is not necessarily useless; with a sensible initial ensemble and appropriate post-processing efforts and verification information, useful information can be extracted from imperfect ensemble forecasts.

### NCEP Ensembles

The GMB utilizes the so-called bred vector approach to ensemble construction (Toth and Kalnay, 1993). Ensemble perturbations are "bred" by recording the evolution of perturbed and unperturbed model integrations. Every breeding period (typically 6 model hours), the vector between a 6-hour high-resolution control forecast and each 6-hour forecast ensemble member is identified. The magnitude of the perturbation vector is reduced and its orientation is rotated via a component-wise comparison between the perturbation vector and an observation "mask" which is meant to reflect the spatial distribution of observations; components in data-rich areas are shrunk by a larger factor than those in data-sparse regions. Data assimilation is performed on the 6-hour high-resolution control forecast, and each of the rescaled and rotated ensemble perturbations is added to the new analysis. The structure of initial-condition uncertainty is defined by the data assimilation scheme. Because the bred-vector approach only crudely accounts for the impact of data assimilation through the use of the observation mask the initial ensemble draws from an incorrect initial distribution. However, utilizing the model dynamics to "breed" perturbations still provides useful information.

In addition to using the bred-vector method to generate perturbations in the model initial conditions, the regional ensemble system of the MMB (the SREF) attempts to account for model inadequacy by utilizing a number of different models and a number of different sub-gridscale parameterizations within models. The global ensemble system is also moving toward a multimodel ensemble approach through its involvement with the THORPEX Interactive Grand Global Ensemble (TIGGE), and the North American Ensemble Forecasting System (NAEFS).

### ECMWF Ensembles

The ECMWF has a different ensemble construction philosophy. They utilize a "singular vector" approach to ensemble construction where they attempt to identify the directions with respect to the control initial condition that will experience the most error growth over a specified forecast period. These very special directions are clearly not random draws from an initial condition PDF,[a] but they are dynamically important directions that will generate a significant amount of forecast ensemble spread and have been shown to provide useful forecast uncertainty information.

### CMC Ensembles

The CMC takes a third approach. They utilize an EnKF for their operational ensemble construction scheme (Houtekamer and Mitchell, 1998). Ensemble filters utilize short-term ensemble forecasts to define the uncertainty associated with the model first guess. The product of the data assimilation update is not a single estimate of the state of the system but rather an ensemble of estimates of the state that describe the expected error in the estimate. The EnKF naturally provides an ensemble of initial conditions that are a random sample from what the data assimilation system believes is the distribution of initial uncertainty. The CMC uses a multimodel approach to the EnKF where different ensemble members have different model configurations. This allows for partial consideration of model inadequacy in the EnKF framework. Model inadequacy in the context of ensemble forecasting is discussed in Section 3.1.2.

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[a] Even if the forecast model is perfect and one could provide the correct initial-time norm for singular vector calculations, the resulting directions would parameterize an initial-time Gaussian PDF rather than be a random draw.

## BOX 3.5
## THORPEX—A World Weather Research Program[a]

THORPEX is a part of the World Meteorological Organization (WMO) World Weather Research Programme (WWRP). It is an international research and development collaboration among academic institutions, operational forecast centers, and users of forecast products to accelerate improvements in the accuracy of 1-day to 2-week high-impact weather forecasts for the benefit of society, the economy, and the environment, and to effectively communicate these products to end users.[b] Research topics include global-to-regional influences on the evolution and predictability of weather systems; global observing system design and demonstration; targeting and assimilation of observations; and societal, economic, and environmental benefits of improved forecasts.

A major THORPEX goal is the development of a future global interactive, multimodel ensemble forecast system that would generate numerical probabilistic products that are available to all WMO members. These products include weather warnings that can be readily used in decision-support tools. The relevance of THORPEX to this report is primarily through its linkage of weather forecasts, the economy, and society. Social science research is an integral component of the THORPEX science plan.[c] For example, THORPEX Societal/Economic Applications research will (1) define and identify high-impact weather forecasts, (2) assess the impact of improved forecast systems, (3) develop advanced forecast verification measures, (4) estimate the cost and benefits of improved forecast systems, and (5) contribute to the development of user-specific products. This research is conducted through a collaboration among forecast *providers* (operational forecast centers and private-sector forecast offices) and forecast *users* (energy producers and distributors, transportation industries, agriculture producers, emergency management agencies and health care providers).

THORPEX also forms part of the motivation for the GMB of the EMC to implement multimodel ensemble forecasting, sophisticated post-processing techniques, and comprehensive archiving of probabilistic output. The goals of TIGGE are[d]

- enhanced international collaboration between operational centers and universities on the development of ensemble prediction;
- development of new methods of combining ensembles of predictions from different sources and of correcting for systematic errors;
- increased understanding of the contribution of observation, initial, and model uncertainties to forecast error;
- increased understanding of the feasibility of an operational interactive ensemble system that responds dynamically to changing uncertainty and exploits new technology for grid computing and high-speed data transfer;
- evaluation of the elements required of a TIGGE Prediction Centre to produce ensemble-based predictions of high-impact weather, wherever it occurs, on all predictable time ranges; and
- development of a prototype future Global Interactive Forecasting System.

NOAA is an active participant and has funded a range of THORPEX-related external research on observing systems, data assimilation, predictability, socioeconomic applications, and crosscutting efforts.[e]

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[a] http://www.wmo.int/thorpex/.
[b] http://www.wmo.int/thorpex/mission.html.
[c] http://www.wmo.int/thorpex/pdf/CD_ROM_international_science_plan_v3.pdf.
[d] http://www.wmo.int/thorpex/pdf/tigge_summary.pdf.
[e] http://www.emc.ncep.noaa.gov/gmb/ens/THORPEX/THORPEX_brief.ppt.

(e.g., Draper, 1995; Chatfield, 1995). The GMB does not account for this type of uncertainty but is addressing it in part through its participation in TIGGE (Box 3.5) and the NAEFS with Canada and Mexico (which will be extended to include the Japan Meteorological Agency, UK Meteorological Office, and the Navy's operational forecasting efforts). The NAEFS will facilitate the real-time dissemination of ensemble forecasts from each of the participating countries in a common format. Research is under way among NWS and its international partners to provide coordinated bias-correction, calibration, and verification statistics.

On the mesoscale, the MMB ensemble system uses multiple models and varied physics configurations.[10] In such multimodel ensemble forecasting efforts it is important to account for differences in (1) methods of numerically solving the governing dynamics and (2) physical parameterizations. Within the 21 NWS SREF ensemble members there is some

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[10] Of the 21 ensemble members, 10 use the Eta model, 5 use the Regional Spectral Model, 3 use the Weather Research and Forecasting (WRF) Nonhydrostatic Mesoscale Model core, and 3 use the WRF Advanced Research core.

diversity in model physics, with particular emphasis given to varying convective parameterizations. A number of major sources of uncertainty still need to be explored, including variations in surface properties and uncertainties in the boundary-layer parameterizations.

An alternative approach to generating ensemble initial conditions that takes information about model differences into account is the use of initial conditions (and boundary conditions in the case of mesoscale models) from a variety of operational centers. Grimit and Mass (2002) demonstrated the utility of this approach in the mesoscale modeling context and Richardson (2001) explored it in the global modeling context. Richardson found that for their chosen means of verification, a significant portion of the value of multimodel ensemble forecasts was recovered by using a single model to integrate the initial conditions from the collection of available models. Model error can also be accounted for stochastically. Such an approach is in operational use at ECMWF and is being explored by EMC.

**Finding:** There is a range of approaches to help account for model inadequacy in ensemble forecasting. So far, NCEP has explored varying physics parameterizations, multimodel initial conditions, and stochastic methods.

**Recommendation 3.2: The NCEP should complete a comprehensive evaluation to determine the value of multiple dynamical cores and models, in comparison to other methods, as sources of useful diversity in the ensemble simulations.**

### 3.1.3 Model Development

The MMB SREF approach uses an ensemble system with 32-km grid spacing and the output available on 40-km grids. Such a resolution is inadequate to resolve most important mesoscale features, such as orographic precipitation, diurnal circulations, and convection, and greatly lags the resolution used in deterministic mesoscale prediction models (generally 12 km or less). An inability to resolve these key mesoscale features will limit the utility of the ensemble forecasting system. Although post-processing (Section 3.1.5) can be applied to the SREF system in an effort to downscale model forecasts to higher resolution, comparisons between the University of Washington SREF system (run at 12-km resolution) and MOS have shown that even without post-processing the SREF system was superior in predicting the probability of precipitation (E. P. Grimit, personal communication). In addition, Stensrud and Yussouf (2003) demonstrated the value of an SREF system in comparison to nested grid model MOS in a NOAA pilot project on temperature and air quality forecasting in New England. Generically, SREF systems have the ability to be adaptive to flow-dependent errors to a greater degree than MOS, as MOS depends on a long training period (typically 2 years). SREF systems can easily accommodate rapidly developing forecasting systems.

Moving the NCEP SREF system to higher spatial resolution will require substantial computer resources, but the near-perfect parallelization of ensemble prediction makes possible highly efficient use of the large number of processors available to NCEP operations.

**Finding:** The spatial resolution of the MMB SREF ensemble system is too coarse to resolve important mesoscale features (see also Chapter 5, recommendation 4). Moving to a finer resolution is computationally more expensive, but necessary to simulate key mesoscale features.

**Recommendation 3.3: The NCEP should (a) reprioritize or acquire additional computing resources so that the SREF system can be run at greater resolution or (b) rethink current resource use by applying smaller domains for the ensemble system or by releasing time on the deterministic runs by using smaller nested domains.**

### 3.1.4 Archiving Observations and Forecasts

To provide maximum value, a forecasting system must make available all the information necessary for interested parties to post-process and verify ensemble forecasts of variables and/or diagnostics. Required information includes an archive of historical analyses (initial conditions), historical forecasts, and all the associated verifying observations. Historical model information is available in four forms: archived analyses, reanalyses, archived forecasts, and reforecasts. The archived analyses and forecasts reflect the state of the forecast system at the time of their generation; data assimilation methodologies, observations, and models change with time. The reanalyses and reforecasts attempt to apply the current state of the science retroactively. Archived analyses, reanalyses, archived forecasts, and a wide range of observations with records of various lengths are archived and searchable at the National Climatic Data Center (NCDC[11]). Within NCDC is the NOAA National Operational Model Archive and Distribution System (NOMADS[12]), which provides links to an archive of global and regional model output and forecast-relevant observations in consistent and documented formats.

NOMADS provides the observation and restart files necessary to run the operational data assimilation system (SSI). NWS does not produce a reforecast product, but reforecasts are available from the NOAA Earth System Research Laboratory (ESRL[13]). The model used is crude by current standards, but the long history of ensemble forecasts permits calibration that renders long-lead probabilistic fore-

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[11] http://www.ncdc.noaa.gov.

[12] http://nomads.ncdc.noaa.gov/nomads.php.

[13] http://www.cdc.noaa.gov/people/jeffrey.s.whitaker/refcst/.

casts superior to those produced operationally. The reforecast product has numerous applications (Hamill et al., 2006) and is most useful when the model used to produce the reforecast dataset is the same model that is used for the production of operational guidance.

**Finding:** An easily accessible observation and forecast archive is a crucial part of all post-processing or verification of forecasts (see also Chapter 5, recommendation 6).

**Recommendation 3.4: The NOAA NOMADS should be maintained and extended to include (a) long-term archives of the global and regional ensemble forecasting systems at their native resolution, and (b) reforecast datasets to facilitate post-processing.**

**Finding:** Reforecast data provide the information needed to post-process forecasts in the context of many different applications (e.g., MOS, hydrology, seasonal forecasts). NWS provides only limited reforecast information for some models and time periods. In addition, post-processing systems need to change each time the numerical model changes. To facilitate adaptation of applications and understanding of forecast performance, reforecast information is needed for all models and lead times whenever a significant change is made to an operational model.

**Recommendation 3.5: NCEP, in collaboration with appropriate NOAA offices, should identify the length of reforecast products necessary for time scales and forecasts of interest and produce a reforecast product each time significant changes are made to a modeling/forecasting system.**

## BOX 3.6
## Post-processing

Post-processing of model output has been a part of the forecasting process at least as long as the MOS (Box 3.7) approach has been used to produce forecast guidance. Post-processing has become a critical component of the interpretation and use of predictions based on ensemble forecasts. Post-processing makes it possible for meaningful and calibrated probabilistic forecasts to be derived from deterministic forecasts or from ensembles.

Post-processing of models projects forecasts from model space into observation space and produces improved forecasts of the weather element of interest. Post-processing has a role across a spectrum of applications, including the calibration of ensemble predictions of specific prognostic variables; the interpretation of sets of upper-air prognostic variables in terms of a surface weather variable; and the combination of ensemble-based distribution functions. Post-processing can be cast in a probabilistic form and thus naturally provides quantitative uncertainty information. Examples of post-processing methods include bias corrections based on regression, MOS interpretation of upper air prognostic variables, and Gaussian mixture model approaches like BMA (Raftery et al., 2005) to combine probability distributions. Verification is an important aspect of post-processing, since the choice of post-processing depends on how the forecast is optimized (see Section 3.4). Post-processing is a necessary step toward producing final guidance forecasts based on model forecast output.

### 3.1.5 Post-processing

It is difficult to overemphasize the importance of post-processing for the production of useful forecast guidance information. The aim of post-processing (Box 3.6) is to project model predictions into elements and variables that are meaningful for the real world, including variables not provided by the modeling system. Common examples of post-processing include bias correction, downscaling, and interpolation to an observation station. Post-processing methods specifically for ensemble forecasts also exist.

NWS does little post-processing of its ensemble forecasts to provide reliable (calibrated) and sharp probability distributions (see also Chapter 5, recommendation 5). NWS's Meteorological Development Laboratory (MDL) provides post-processed, operational guidance products through their MOS[14] (Box 3.7), with several of them providing probabilistic guidance. MOS finds relationships between numerical forecasts and verifying observations and is applied to output from both global and mesoscale models. MOS can often remove a significant portion of the long-term average bias of model predictions and can provide some information on local or regime effects not properly considered by the model. The MOS flagship products are minimum and maximum temperature along with probability of precipitation (PoP; e.g., Figure 3.4), but it is also applied to variables like wind speed and direction, severe weather probabilities, sky cover and ceiling information, conditional visibility probabilities, and probability of precipitation type. Online verification statistics are available for maximum temperature, minimum temperature, and PoP as a function of geographical region, forecast lead time, and numerical model.[15]

The probabilistic MOS products are based on deterministic forecasts. An experimental ensemble MOS product exists, but because climatology is included as a MOS predictor all ensemble MOS forecasts tend to converge to the same answer for longer forecasts. The implied uncertainty decreases rather than increases at the longest lead times. There are

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[14] http://www.nws.noaa.gov/mdl/synop/.

[15] http://www.nws.noaa.gov/mdl/verify.

## BOX 3.7
## Model Output Statistics

MOS is a technique used to objectively interpret numerical model output and produce site-specific guidance.[a] MOS was developed in the late 1960s as the original form of post-processing (Box 3.6) and was designed to improve forecasts of surface weather variables based on the output from deterministic NWP models.

To develop the MOS equations, statistical methods are used to relate predictors (i.e., NWP output variables) to observations of a weather element. Typically, MOS equations are based on multiple linear regression techniques (Neter et al., 1996). Each MOS equation is relevant for a single predictand, region, model, projection, and season, and the equations are applied at individual locations to produce NWS guidance forecasts. Single regression equations can be used directly to produce probability forecasts for binary events. For probability forecasts of elements with multiple categories (e.g., precipitation amount), the multiple probabilities are typically derived using a procedure called “Regression Estimation of Event Probabilities” in which the predictand space is subdivided and separate regression equations are developed and applied to each subcategory. This procedure approximates a forecast of a probability distribution. More information about these methods and processes can be found in Wilks (2006).

PoP is the most recognizable official probabilistic forecast produced by MOS, but MOS probability forecasts are produced for a number of other variables (e.g., precipitation amount, ceiling) and these probabilities are used to identify the most likely category, which is subsequently provided in the official forecasts. These underlying probabilities are available graphically at the MOS Web site. Currently, MDL is developing gridded MOS forecasts that can be used by forecasters as guidance for preparing forecasts for the National Digital Forecast Database.

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[a] http://www.nws.noaa.gov/mdl/synop/products.shtml.

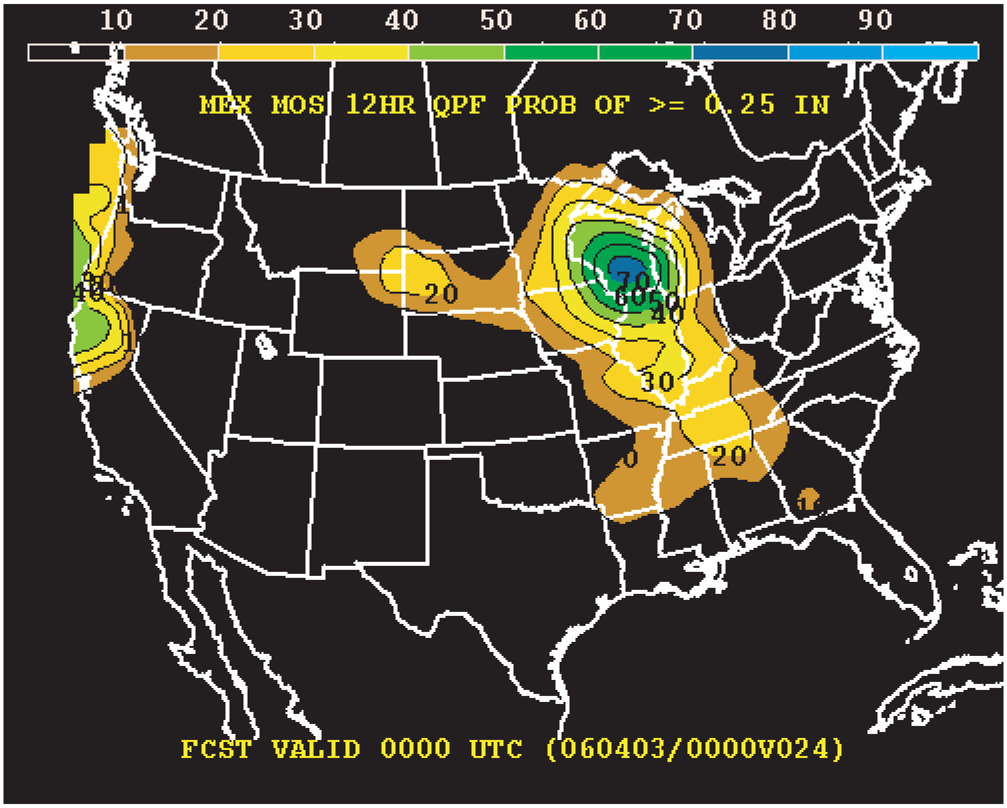

FIGURE 3.4 Example of probabilistic forecast of precipitation amount based on MOS applied to the Global Forecasting System model output. SOURCE: NWS.

other means of ensemble post-processing. For example, the ESRL reforecasting product can produce ensemble analogs, whereas the BMA approach of Raftery et al. (2005) attempts to fit and combine Gaussian distributions to output from multimodel ensemble forecasts. The EMOS procedure of Gneiting et al. (2005) also combines multimodel ensemble forecast information but with the additional constraint that the post-processed PDF be a Gaussian.

NWS is considering a National Digital Guidance Database (NDGD) to support the National Digital Forecast Database (NDFD; Zoltan Toth, personal communication). In much the same way as the NDFD can be interrogated by users to provide deterministic forecast information, the NDGD could be interrogated to provide probabilistic forecast information. NWS intends to provide a database of raw and post-processed guidance for this purpose. The plans for the initial post-processed product are to provide gridded probability thresholds for near-surface weather variables produced from bias-corrected NAEFS ensembles. The EMC also plans to implement a post-processing procedure for the ensemble spread. Ultimately, the NDGD would include information from both the global and the mesoscale modeling systems.

**Finding:** A database such as the NDGD would provide a wealth of information for the NWS forecaster and academic researcher and provide a basis for significant added value by the private sector, catalyzing economic activity. In addition, there is a strong complementarity between NDGD and NOMADS.

**Recommendation 3.6: Efforts on the proposed NDGD should be accelerated and coordinated with those on the NOAA NOMADS (recommendation 3.4).**

### 3.1.6 The Enterprise as a Resource

Scientists in GMB and MMB are aware of the issues raised in this chapter and are eager to continue their development of the forecast guidance system in an increasingly probabilistic manner. Indeed, there are several internal documents that make similar recommendations.[16,17] NWS scientists are making strides with their ensemble guidance products and are performing internal research in multimodel ensemble forecasting and the probabilistic post-processing of ensemble guidance.

Funding and personnel are always limiting factors, but a huge resource exists in the form of the Enterprise external to NWS, particularly the academic community. There are examples of successful academia partnerships at NWS, including at GMB and MMB, but wider-reaching, more formalized partnerships are needed.

Without frequent and close interaction with NCEP, it is difficult for academics to appreciate the constraints of an operational setting. For example, outside researchers cannot anticipate the potential difficulty of implementing a seemingly trivial change because they do not have a working knowledge of the relevant software systems and how they interact. In addition, after implementing each new idea a series of experiments need to be run to assess the impact of the change. These experiments are expensive, and there are far more ideas than available computer time.

Beyond the partnership of NCEP with external research entities, and given the great variety of potential users and uses, it will be necessary to involve users in designing the form and content of forecast products and intermediaries in developing useful products and decision-support systems. The interaction of forecasters and emergency managers, for instance, could establish norms of communication, providing forecasters with the opportunity to understand better the objectives of emergency management and their temporal and spatial determinants and providing emergency managers with information on what is feasible in terms of forecast uncertainty descriptors from operational forecast systems.

The transition of NWS (and the entire Enterprise) to uncertainty-centric prediction will require advances in forecasting and communication technologies that demand the close cooperation of the research, operational, and user communities. An approach to fostering such cooperation is through testbeds. Testbeds provide laboratories for evaluating new prediction and dissemination approaches in a pseudo-operational setting before they are used on a national scale, bringing expertise and experience outside of national centers to bear on key problems. Testbeds have been shown to be an effective approach to promoting closer cooperation between academic, government, and private sectors of the Enterprise, while enhancing communication with users.

Testbeds have been developed in a variety of forms. In California, a Hydrometeorological Testbed has brought together NOAA, universities, and state and local agencies to study heavy precipitation and flooding along the mountainous western states. Another testbed in northern California has brought together hydrologic forecast and water resources management agencies with researchers from academic and nonacademic institutions to assess the utility of operational weather and climate information for operational reservoir management in large reservoir facilities. In the Pacific Northwest, the Northwest Consortium—a group that includes state, federal, and local agencies, as well as local universities and private firms—has promoted the development and real-time evaluation of new mesoscale forecasting approaches. On a national scale, the Developmental Testbed Center (DTC) combines the efforts of several federal agencies and NCAR to evaluate and support advances in the WRF modeling system, and the joint NOAA-Navy-NASA Hurricane

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[16] See http://www.nws.noaa.gov/ost/ifps_sst/pdf_docs/SOO_DOH_IFPSWhitepaperImplementation-Aug22_final.pdf.

[17] See http://www.nws.noaa.gov/ost/ifps_sst/pdf_docs/Final_Whitepaper.pdf.

Testbed aims to advance the transfer of new research and technology into operational hurricane forecasting systems by serving as a conduit between the operational, academic, and research communities.

Considering the profound changes in practices that a shift to probabilistic prediction and communication will entail, the entrainment of the larger community made possible by the testbed approach will enable rapid advancement. For example, regional testbeds can evaluate methods of ensemble generation and post-processing, as well as new approaches for communicating uncertainty information. An example of the potential of this approach is the Northwest Consortium's mesoscale ensemble system. The information from this ensemble system is displayed on a variety of Web sites that experiment with intuitive approaches to display and communication.[18] Other testbeds could focus on providing uncertainty information for specific forecasting challenges (e.g., hurricanes, severe convection, flooding). A national uncertainty testbed could also be established within the DTC to bring together a broad community to evaluate generally applicable approaches to ensemble generation, post-processing, verification, communication, and application development. In short, testbeds offer a powerful extension and multiplier of the efforts at major national modeling centers such as NCEP and the Fleet Numerical Meteorology and Oceanography Center.

**Finding:** The United States suffers from a separation between operational numerical weather prediction and the supporting research community (see, for example, NRC, 2000). This separation increases the challenge of communicating operationally relevant scientific problems to academia and providing resources and motivation for NWS scientists to work more closely with their academic colleagues. In addition, for a paradigm shift from deterministic to probabilistic forecasting to be useful for a variety of users, a means of participation of such users and intermediaries in the forecast product design and communication phases is critical. Potential approaches for strengthening the links between the operational and research communities range from development and support of testbeds to development of lists of operational goals and research needs[19] to ensuring that supporting and descriptive documentation on NWS Web sites is up to date.

**Recommendation 3.7: NWS should work toward a culture and systems that encourage interactions among all components of the Enterprise and should use testbeds as a means of bringing together diverse groups from different disciplines and operational sectors. With the help of external users and researchers, NWS centers and research groups should construct and disseminate a prioritized list of operational goals and associated research questions. These lists should be dynamic, providing mechanisms by which NWS can elicit feedback from the research and user communities and the research and user communities can support and drive the direction of NWS. Potential solutions to these research questions could then be explored in testbeds.**

## 3.2 CLIMATE PREDICTION CENTER

The charge of the CPC[20] is to monitor and forecast short-term climate fluctuations. In addition, CPC provides information on the effects climate patterns can have on the nation. This section focuses only on CPC's monthly and seasonal outlooks and the approach used to estimate the uncertainty associated with these forecasts. CPC also provides a variety of other forecasts, including 6- to 10- and 8- to 14-day outlooks, tropical cyclone outlooks, and weekly hazard assessments that are not considered here.

### 3.2.1 Scientific Basis and Forecast Methodology

The primary basis for skill in monthly and seasonal climate predictions lies in the ability to forecast sea surface temperatures, especially those associated with El Niño conditions, along with linkages of the El Niño-Southern Oscillation (ENSO) state and, less importantly, the state of other climate system oscillations to global seasonal temperature and precipitation anomalies. Additional capability is associated with the use of information about land surface conditions (e.g., soil moisture). The CPC approach to seasonal forecasting involves the combination of information from a variety of statistical and analog models with the output of the recently implemented Climate Forecast System (CFS) numerical weather prediction model, which was developed and is run operationally by the NCEP Global Climate and Weather Modeling Branch. Information from these different sources is subjectively combined by CPC forecasters to create the operational outlooks (Saha et al., 2006). These outlooks are probabilistic and thus provide direct information about the uncertainty associated with the forecasts.

The CFS is a fully coupled ocean-land-atmosphere dynamical model, with initial conditions obtained from the Global Ocean Data Assimilation System. The model is well described and evaluated by Saha et al. (2006). An ensemble mean based on 40 members is used in the seasonal forecasting process. To facilitate optimal use of the CFS, NCEP has created many years of reforecasts (i.e., applications of the CFS to historical observations) for seasonal projections. The reforecast data provide useful information for understanding the performance characteristics of the CFS and for correcting

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[18] For example, http://www.probcast.com.

[19] See, for example, the CPC list at http://www.cpc.ncep.noaa.gov/products/ctb/Laver.ppt, and the research plans associated with the WMO THORPEX program.

[20] http://www.cpc.ncep.noaa.gov/.

model biases, and they provide opportunities for a wealth of forecasting experiments. Reforecast data are available for the seasonal forecasts but not for shorter lead times due to the large ocean data requirements. Recommendation 3.5 is addressed at this limitation.

The statistical and analog methods that are used to create the CPC forecasts include canonical correlation analysis, ENSO composites, Optimal Climate Normals, Constructed Analog on Soil moisture, and Screening Multiple Linear Regression. The output of these guidance forecasts, used in creating the final outlooks, is also presented on the CPC's Web page.[21] The CPC has begun to experiment with objective approaches for combining the various pieces of information (i.e., results of the CFS and statistical/analog approaches) to create the final forecasts, rather than using the heuristic, subjective approach that has been the operational standard. Relatively large improvements in forecasting performance have been obtained even with the simple objective approach applied so far. Not only are the forecasts more skillful, but the areas with forecasts that differ from climatology are larger. These positive initial efforts toward objective combination of the different forms of information are based on the historical performance of the forecast methods. More sophisticated approaches are under development.

**Finding:** The CPC is making great strides in improving information to guide development of their monthly and seasonal forecasts (e.g., development and implementation of the CFS), but there is room for further improvement through post-processing and use of the full CFS ensemble.

**Recommendation 3.8: The CPC should investigate methods to use the full distribution of the CFS ensemble members (e.g., through a post-processing step) rather than relying solely on the ensemble mean or median. In addition, the center should make use of reforecast datasets and historical forecast performance information for developing the monthly and seasonal probabilities.**

**Finding:** The CPC has had success with its initial efforts to use objective approaches to combine its various sources of forecast information using simple weighting schemes. More sophisticated methods (e.g., expert systems, statistical models) for combining the forecast components are likely to lead to further improvements in forecast performance.

**Recommendation 3.9: The CPC should develop more effective objective methods for combining forecast components to improve forecast performance.**

### 3.2.2 Performance of NCEP/CPC Monthly and Seasonal Predictions

Limited information regarding forecast skill is provided on the CPC Web pages. This information is primarily in the form of time-series plots of the Heidke skill score (HSS)[22] accumulated across all continental U.S. climate districts. These plots indicate that the forecasts have limited overall skill (e.g., an average HSS of around 0.10 to 0.20 for temperature forecasts and 0.0 to 0.10 for precipitation forecasts, which suggests that the forecasts are 0 to 20 percent better than random forecasts). However, the scores exhibit significant year-to-year variability (i.e., sometimes the skill is strongly positive and at other times it is strongly negative). Results presented to the committee by Robert Livezey (September 2005) and Ed O'Lenic (August 2005) indicate that the skill also varies greatly across regions and seasons and that skill is minimal at longer lead times for most locations. The best performance occurs when there is strong forcing (e.g., from an El Niño). When this forcing does not exist, the skill of the outlooks may be about the same as a climatological forecast. The precipitation outlooks, in particular, have very little skill in non-ENSO years. Recommendation 6 in Chapter 5 is addressed at the issues raised in this and related sections.

**Finding:** In many cases the CPC's monthly and seasonal forecasts have little skill, especially at long lead times. Other forecasting groups, such as the International Research Institute, only provide forecasts out to 6 months due to the limited—or negative—skill for longer projections.

**Recommendation 3.10: The CPC should examine whether it is appropriate to distribute forecasts with little skill and whether projections should be limited to shorter time lengths. Information about prediction skill should be more readily available to users.**

### 3.2.3 Research on Seasonal Prediction

Research on seasonal prediction includes improvements in land surface observations, development of improved land surface models, and improved methods for incorporating the land surface information in the prediction models. In addition, the use of multimodel ensembles for seasonal prediction and interpretation of the ensemble output are areas of current research. There is a strong research community focused on the climate forecasting problem. For example, seasonal prediction is being studied at a variety of research laboratories and educational institutions, including the Center for Ocean-Land-Atmosphere Studies, NCAR, and the Geophysical

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[21] http://www.cpc.ncep.noaa.gov/products/predictions/90day/tools/briefing/.

[22] The HSS measures the skill of the CFS in assigning the correct precipitation or temperature categories, relative to how well the categories could be assigned by chance. See Box 3.9.

Fluid Dynamics Laboratory, among other groups, as well as at many universities.

NCEP recently established a Climate Test Bed (CTB), associated with the CPC, to accelerate the transfer of new technology into operational practice.[23] The CTB provides a natural link between the seasonal prediction research community and the operational center and facilitates the ability for researchers to develop and test tools, models, and methodologies in an operational context. Given adequate resources, this setting should make it easier and more straightforward for the CPC to quickly incorporate new research results into operational practice and will thus have the potential to greatly improve CPC's forecasts and services.

**Finding**: The CTB provides an opportunity for the CPC to efficiently incorporate new knowledge and technologies into their forecasting processes.

**Recommendation 3.11: The NWS and the NCEP should fully support the CTB to engage the Enterprise, particularly the research community, in operational problems and develop meaningful approaches that enhance and improve operational predictions.**

## 3.3 OFFICE OF HYDROLOGIC DEVELOPMENT

The vision statement from the NWS OHD (NWS, 2003) expands the NWS operational hydrology role and responsibilities from the long-time focus on producing river and stream forecasts to such fields as drought prediction, soil moisture estimation and prediction, precipitation frequency, and pollutant dispersion. Primary customers for this information are the forecasters of the NWS River Forecast Centers (RFCs), WFOs, and National Centers. In addition, the OHD vision states that development and tools are produced to inform the appropriate elements of federal, state, and local government, industry, and the public to help manage water resources. There are many ways that NWS's RFCs use meteorological information (forecasts and data) to produce deterministic and ensemble hydrology forecasts. The procedures and products vary significantly from center to center, and in several cases forecaster subjective judgment is involved in product generation. The following discussion presents several types of operational hydrologic forecast products, emphasizing the associated sources of uncertainty. The discussion then highlights recent activities within OHD that target the production of probabilistic and ensemble hydrologic forecasts and suggests improvements.

### 3.3.1 Operational Hydrology as a User of NCEP and Weather Forecast Office Products and a Producer of Streamflow Forecasts

The OHD, the Hydrology Laboratory, and 13 regional RFCs provide hydrologic forecast services for the nation. Such forecast services require upstream input (e.g., precipitation forecasts) produced by NCEP, and, thus, the hydrologic service offices are direct users of input products generated by other parts of NWS. In addition, the NWS hydrologic services offices and centers provide advanced hydrologic forecast products for the public, flood risk managers, and other users. Thus, the NWS hydrologic service has a dual role as both a user and a provider of NWS forecasts.

#### *3.3.1.1 Operational Hydrology Products*

River and streamflow forecasts are the main operational hydrology products. Their development under the current operational forecast system in most RFCs is based on water volume accounting over hydrologic catchments using a variety of numerical and conceptual models that include some type of channel routing procedure. Most of these models preserve mass in the snow/soil/channel system of the land surface drainage and parameterize internal and output flow versus storage relationships with a set of parameters whose values require estimation from historical input (precipitation and temperature) and output (flow discharge) data (e.g., Burnash, 1995; Fread et al., 1995; Larson et al., 1995; Anderson, 1996). Short-term flow forecasts out to several days with 6-hourly resolution and ensemble streamflow forecasts out to several months with 6-hourly or daily resolution are routinely produced by RFCs around the country. In addition, very-short-term flash-flood guidance estimates are produced for the development of flash-flood warnings on small scales (counties) out to 6 hours with hourly resolution (e.g., Sweeney, 1992; Reed et al., 2002).

The short-term streamflow forecasts are generated in a deterministic way using the RFC models and best estimates of mean areal model forcing (Figures 3.5 and 3.6). In some cases (e.g., forks of the American River in California) state estimators based on Kalman filtering are used with streamflow observations to update the model states (e.g., water stored in various soil zones and water stored in channel reaches) and to generate estimates of variance in short-term forecasts (e.g., Seo et al., 2003). An outline of the types of observations relevant to the hydrological prediction problem and their uncertainty is given in Box 3.8.

A variety of long-term forecasts is produced routinely for water managers to provide them with guidance in water supply decisions. Two common approaches are regression on the basis of observed hydrologic states and seasonal temperature and precipitation forecasts, and ensemble streamflow prediction (ESP). Seasonal water supply outlooks are produced for several western states on the basis of regres-

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[23] http://www.cpc.ncep.noaa.gov/products/ctb/.

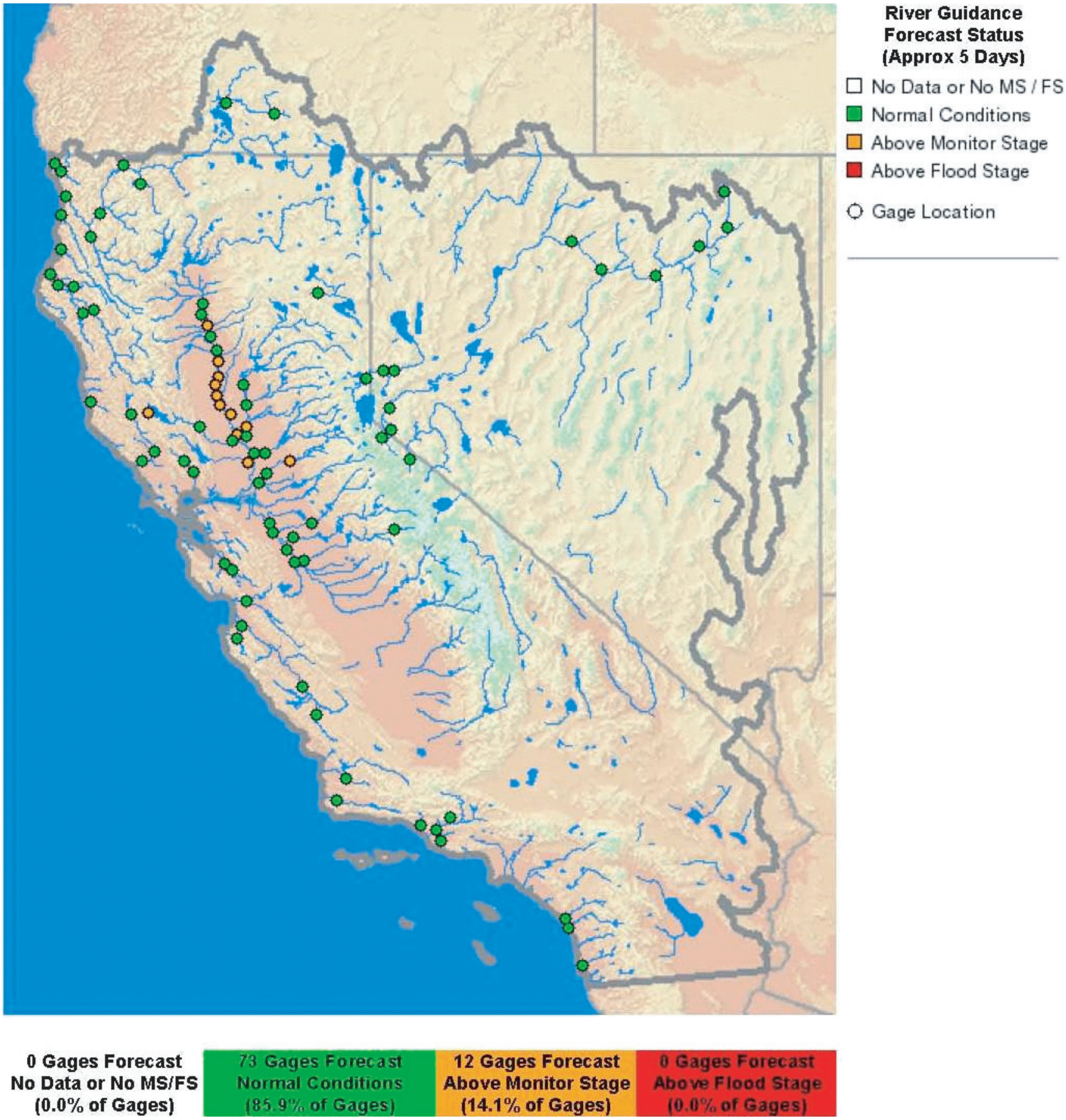

FIGURE 3.5 Example map with official river forecast points for the California Nevada River Forecast Center (CNRFC). The colors indicate the severity of river conditions and are updated in real time. SOURCE: CNRFC, http://www.cnrfc.noaa.gov.

sion equations as collaborative efforts of NWS with other agencies (e.g., National Resources Conservation Service and Bureau of Reclamation). These typically involve water supply volume regressions on several variables including snow pack information and seasonal forecasts of temperature and precipitation. The regressions provide a deterministic water supply volume (representing the 50 percent exceedance forecast). Uncertainty is produced by assuming a normal error distribution with parameters estimated from historical data. The resultant range of expected errors is adjusted to avoid negative values. Lack of representation of the skewed streamflows by this approach generates significant questions of reliability for the generated exceedance quantiles.[24]

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[24] See Natural Resources Conservation Service seasonal flow methods, for example.

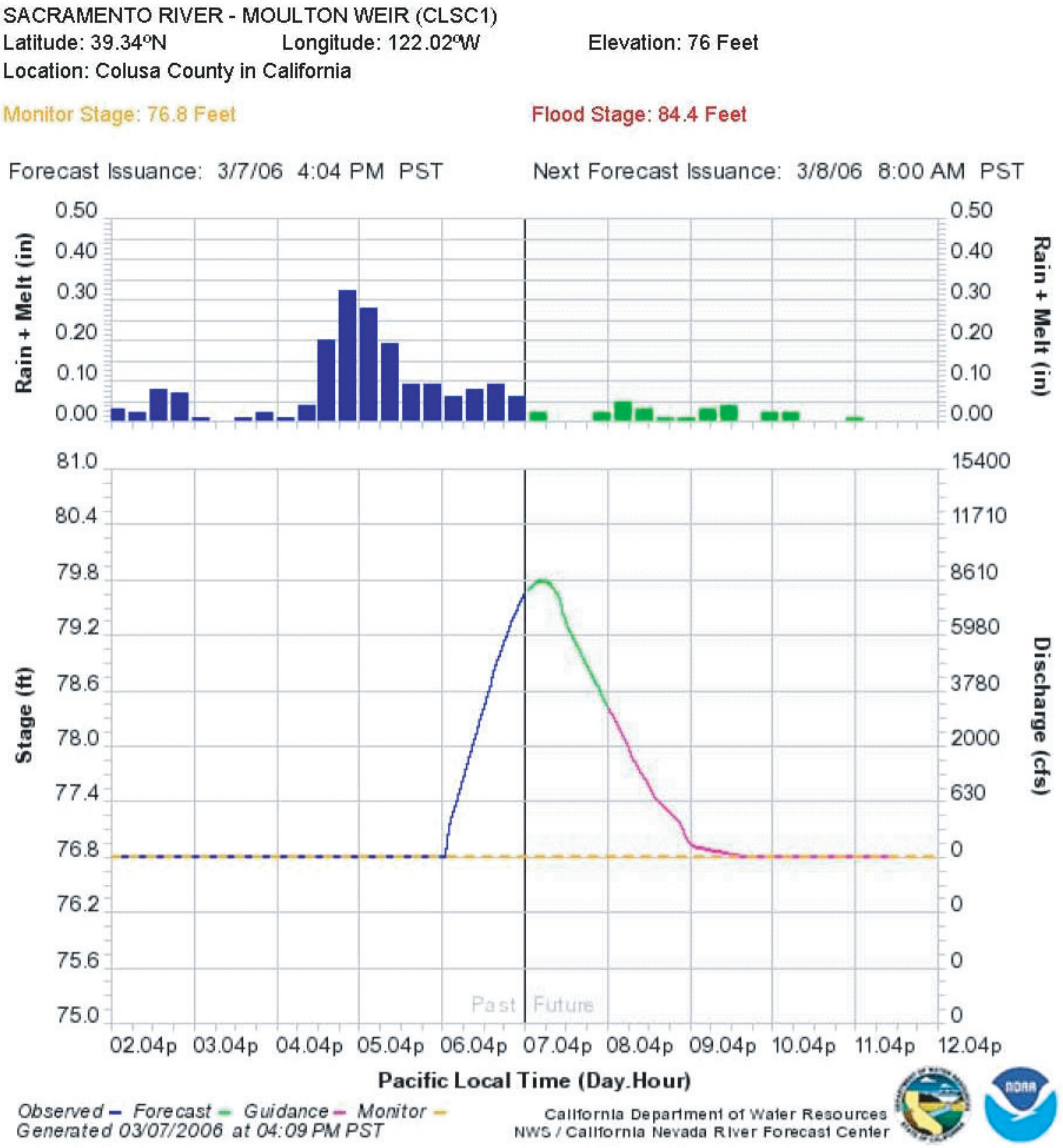

FIGURE 3.6 Example deterministic stream stage forecast from the CNRFC map of Figure 3.5. SOURCE: California Department of Water Resources/NWS California Nevada River Forecast Center.

Longer-term ensemble flow forecasts are also based on the ESP technique, which utilizes the RFC hydrologic models and historical 6-hourly mean areal precipitation and temperature time series (e.g., Smith et al., 1991). For a given date of forecast preparation time and for a given initial condition of model states, the ESP procedure feeds into the models historical time series of concurrent observed mean areal precipitation and temperature from all the previous historical years, extending to the duration of the maximum forecast lead time (a few months; Figure 3.7). For the river location of interest, the generated output flow time series forms the flow forecast ensemble, which is used to compute the likelihood of flood or drought occurrence and various other flow statistics.

## BOX 3.8
## Operational Hydrology Observations

### Onsite Data

Onsite data are obtained from precipitation gauges of various kinds (weighing or tipping bucket, heated or not heated, shielded or not shielded), surface meteorological stations, soil moisture data, and stream stage or discharge stations. In all cases there is measurement error with uncertainty characteristics (a bias and random component) that must be considered during hydrologic model calibration (Finnerty et al., 1997). Not only is individual sensor error important (e.g., snowfall in windy situations), but interpolation error is also important for the production of catchment mean areal quantities for use by the hydrologic models. For stream discharge estimates, the conversion of commonly measured stage to discharge through the rating curve contributes to further observation uncertainty. Quantifying the latter uncertainty is particularly important for forecast systems that assimilate discharge measurements to correct model states.

### Remotely Sensed Data

Weather radar systems are routinely used in conjunction with precipitation gauges for producing gridded precipitation products for operational hydrology applications. Satellite platforms are also routinely used for precipitation, snow cover extent, and land surface characterization. Although the information provided by these remote sensors is invaluable due to its spatially distributed nature over large regions, the data is not free from errors. Ground clutter, anomalous propagation, incomplete sampling, and nonstationary and inhomogeneous reflectivity versus rainfall relationships, to name a few, are sources of radar precipitation errors (Anagnostou and Krajewski, 1999). Indirect measurements of precipitation and land surface properties from multispectral geostationary satellite platform sensors are also responsible for significant errors in the estimates that are derived from the raw satellite data (Kuligowski, 2002).

### Challenges

The main challenge for operational hydrology measurements remains the development of reliable and unbiased estimates of precipitation from a variety of remotely sensed and onsite data for hydrologic model calibration and for real-time flow forecasting. Measures of observational uncertainty in the final product are necessary (e.g., Jordan et al., 2003). A second challenge is to develop methodologies and procedures suitable for implementation in the operational environment that allow hydrologic models that have been calibrated using data (mainly precipitation) from a given set of sensors (e.g., in situ gauges) to be used for real-time flow forecasting using data from a different set of sensors (e.g., satellite and radar). Although bias removal of both datasets guarantees similar performance to first order, simulation and prediction of extremes requires similarity in higher moments of the data distributions. This challenge is particularly pressing after the deployment of the WSR-88D radars in the United States given the desirability to use radar data to feed operational flood prediction models with spatially distributed precipitation information.

Flash-flood guidance is the volume of rainfall of a given duration over a given small catchment that is sufficient to cause minor flooding at the draining stream outlet. It is computed on the basis of geomorphological and statistical relationships and utilizes soil water deficits computed by the RFC operational hydrologic models (Carpenter et al., 1999; Georgakakos, 2006). Flash-flood guidance estimates may be compared to nowcasts and very-short-term precipitation forecasts of high spatial resolution over the catchment of interest to determine the likelihood of imminent flash-flood occurrence (Figure 3.8). Current implementation of these guidance estimates and their operational use is deterministic.

### *3.3.1.2 Types of Input Observations and Forecasts Used by Operational Hydrology*

The production of streamflow forecasts in most RFCs requires 6-hourly areally averaged precipitation and temperature input as well as monthly or daily mean areal potential evapotranspiration input over hydrologic catchments (see Box 3.8 for a discussion of typical observations and their uncertainties). Although the specific procedures for producing these mean areal quantities vary among different RFCs, NCEP forecasts are used as input to numerical and conceptual procedures for the development of local and catchment-specific precipitation and temperature estimates (e.g., Charba, 1998; Maloney, 2002). Monthly and daily potential evapotranspiration estimates are produced on a climatological basis or daily using formulas that utilize observed or forecast surface weather variables (e.g., Farnsworth et al., 1982). For the production of ensemble streamflow forecasts, observations of mean areal precipitation and temperature, as well as monthly or daily estimated potential evapotranspiration are used in the ESP technique described earlier. Flash-flood guidance estimates require mainly operational estimates of soil water deficit produced

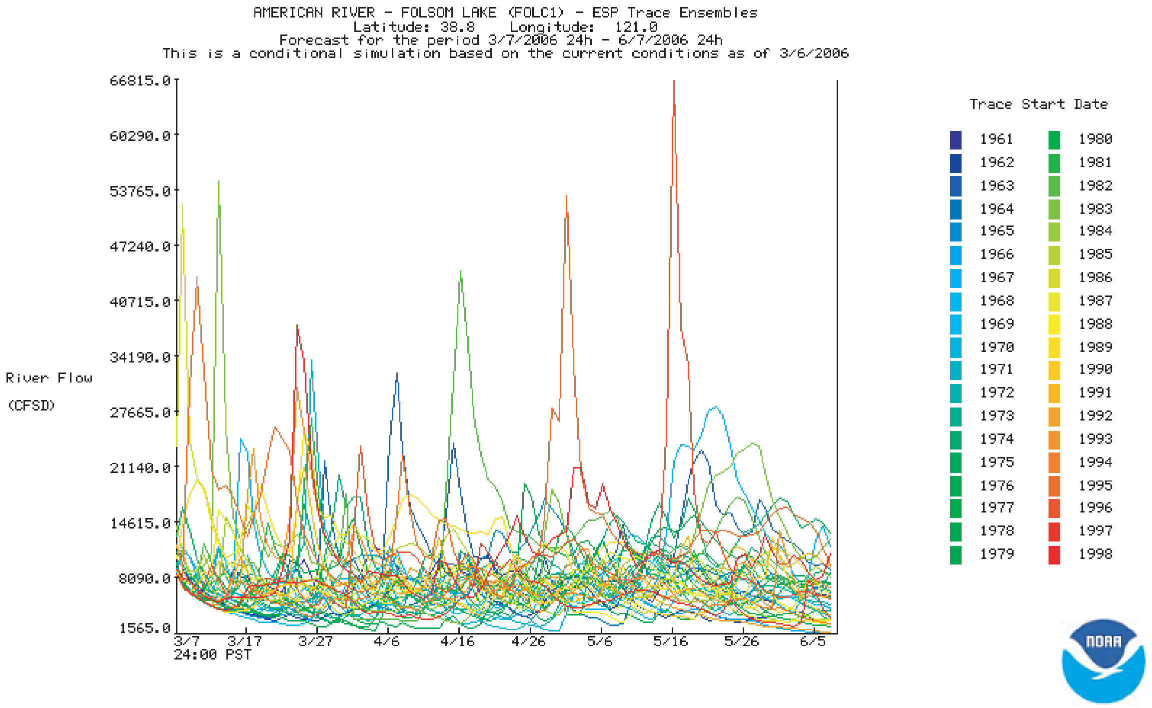

FIGURE 3.7 Example of ensemble streamflow prediction for Folsom Lake inflows in California produced by CNRFC. Precipitation data from historical years 1961 through 1998 are used to create this product. SOURCE: CNRFC, http://www.cnrfc.noaa.gov/ahps.php.

by the operational hydrologic models, and the production of flash-flood warnings on the basis of flash-flood guidance estimates requires spatially resolved mean areal or gridded precipitation nowcasts or very short forecasts (e.g., Warner et al., 2000; Yates et al., 2000).

### 3.3.1.3 Sources of Uncertainty in Input, Model Structure and Parameters, and Observations

Uncertainty in operational streamflow and river forecasts is due to errors in (a) the input time series or fields of surface precipitation, temperature, and potential evapotranspiration; (b) the operational hydrologic model structure and parameters; and (c) the observations of flow discharge, both for cases when state estimators use them to update model states and when such observations are used to calibrate the models (e.g., Kitanidis and Bras, 1980; NOAA, 1999, Duan et al., 2001). Errors in the input may be in (a) operational forecasts used in short-term flow forecasting, and (b) observations used in the ESP technique to produce longer-term ensemble flow forecasts. A primary source of uncertainty in short-term hydrologic forecasting is the use of quantitative precipitation forecasts (QPFs) for generating model mean areal precipitation input (Olson et al., 1995; Sokol, 2003). For elevations, latitudes, and seasons for which snowmelt contributes significantly to surface and subsurface runoff, surface temperature forecasts also contribute significant uncertainty to short-term river and streamflow forecasts (Hart et al., 2004; Taylor and Leslie, 2005).

### 3.3.1.4 Challenges

The NWS operational hydrology short-term forecast products carry uncertainty that is to a large degree due to forecasts of precipitation and temperature that serve as hydrologic model input and which are generated by objective or in some cases subjective procedures applied to the operational NCEP model forecasts. These procedures aim to remove biases in the forecast input to allow use of the operational hydrologic models, calibrated with observed historical data, in the production of unbiased operational streamflow forecasts. The challenges are to (1) develop quantitative models to describe the process of hydrologic model input development from NCEP products when a mix of objective and subjective (forecaster) methods are used (Murphy and Ye, 1990; Baars and Mass, 2005), and (2) characterize uncertainty in the hydrologic model input on the basis of the estimated NCEP model uncertainty under the various scenarios of QPF and surface temperature generation (Krzysztofowicz et al., 1993; Simpson et al., 2004).

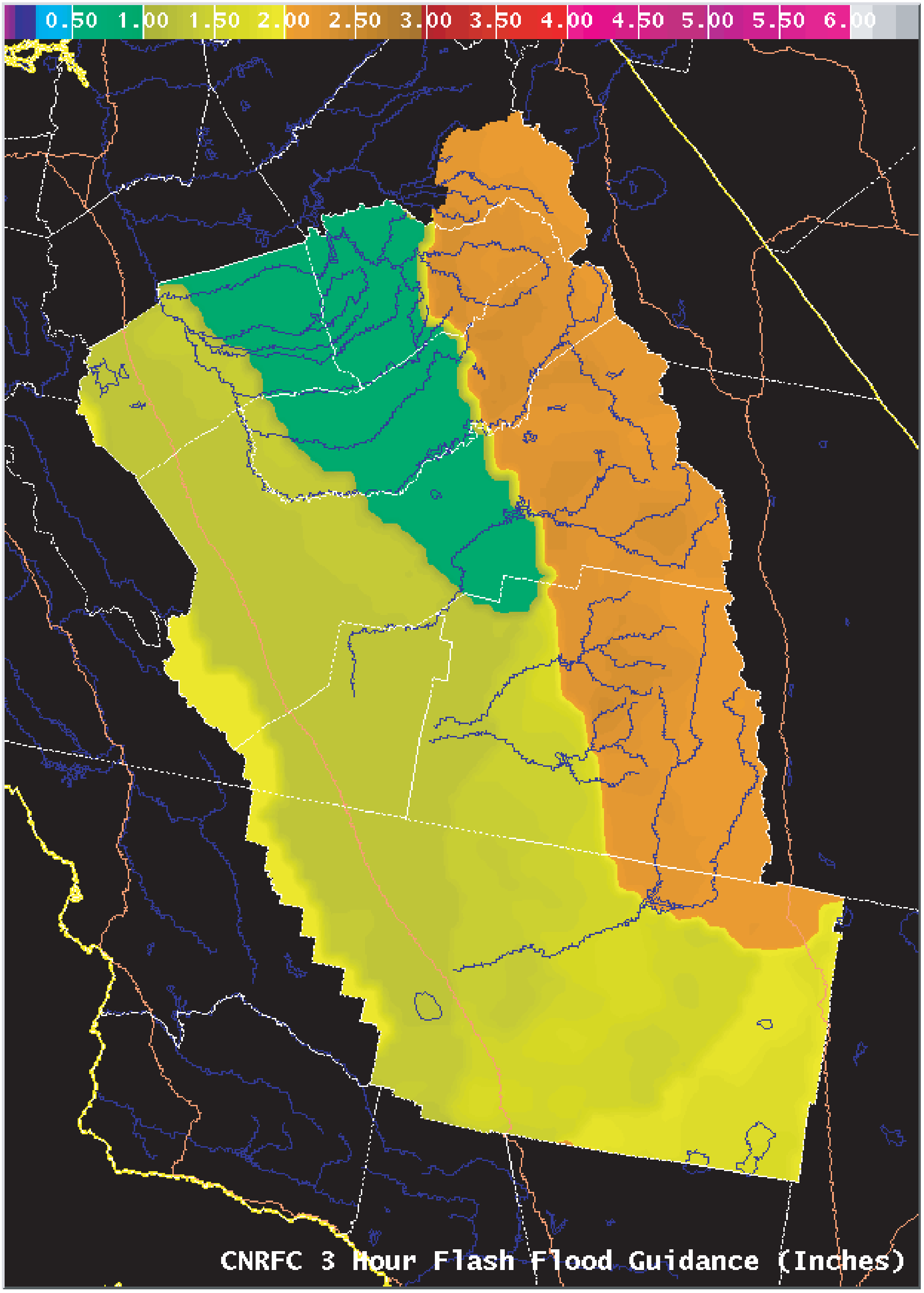

FIGURE 3.8 Areal flash-flood guidance (inches) of 3-hour duration for the San Joaquin Valley/Hanford, California. SOURCE: CNRFC.

The production of longer-term (out to a season or longer) streamflow forecasts is done on the basis of historical observed time series using the ESP technique. The challenge in this case is to develop objective procedures to use NCEP short-term and seasonal surface precipitation and temperature forecasts in conjunction with the ESP-type forecasts for longer-term ensemble flow predictions of higher skill and reliability (e.g., Georgakakos and Krzysztofowicz, 2001).

Prerequisites to successfully addressing the aforementioned challenges are the development of (1) adequate historical-forecast databases at NCEP to allow bias removal of the NCEP forecasts, and (2) automated ingest procedures to allow direct use of NCEP products into objective hydrologic procedures designed to produce appropriate model input for operational hydrologic models.

Currently, there is a one-way coupling between meteorological and hydrologic forecasts in the operational environment. Another challenge is therefore to develop feedback procedures so that hydrologic model states, such as soil moisture and snow cover, may be used to better condition the meteorological models that provide short-term QPF and surface temperature forecasts (Cheng and Cotton, 2004).

**Finding:** The transition from deterministic to probabilistic/ensemble hydrologic forecasting over broad time and small spatial scales will require a number of steps. Availability of data is an important step. In addition to the availability of reforecast products by NCEP as discussed earlier (see recommendation 3.5), it will be necessary to improve operational hydrology databases in the short term with respect to their range of time and space scales (e.g., temporal resolutions of hours for several decades and spatial resolution of a few tens of square kilometers for continental regions) and their content (e.g., provide measures of uncertainty as part of the database for the estimates of precipitation that are obtained by merging radar and rain gauge data).

**Recommendation 3.12: The OHD should implement operational hydrology databases that span a large range of scales in space and time. The contribution of remotely sensed and onsite data and the associated error measures to the production of such databases should be delineated.**

## 3.3.2 Operational Hydrologic Forecasts with Uncertainty Measures

### *3.3.2.1 Ensemble Prediction Methods*

The Advanced Hydrologic Prediction Service (AHPS; McEnery et al., 2005) is perhaps the most important NWS national project that pertains to the development of explicit uncertainty measures for streamflow prediction. Short- to long-term forecasts by AHPS are addressed within a probabilistic context. Enhancements of the ESP system are planned to allow the use of weather and climate forecasts as input to the ESP system, and post-processing of the ensemble streamflow forecasts is advocated to adjust for hydrologic model prediction bias. In addition, AHPS advocates the development of suitable validation methods for ensemble forecasts. This requires historical databases of consistent forcing for long enough periods to allow assessment of performance not only in the mean but also for flooding and drought extremes.

Real-time modifications of hydrologic model input or model states are a common mode of operations associated with a deterministic approach to hydrologic forecasting. A fully probabilistic system such as AHPS, which includes validation and model-input bias adjustment, will enable the elimination of this type of real-time modification so that the model state probability distribution evolves without discontinuities and remains always a function of the model elements. The probability distribution of the model state is the new state of the fully probabilistic system, and any changes (including forecaster changes) in real time must result in temporal evolution consistent with probability theory and Bayes theorem (such as when assimilation of real-time discharge measurements is accomplished with extended Kalman filtering).

The evolution of AHPS represents a positive development toward the shift from deterministic to probabilistic forecasting in operational hydrology. As is often the case when first steps are taken to infuse science into operational methods and techniques, the details of how to go about doing this are matters of scientific debate. Such debate could be promoted by the NWS's AHPS team by encouraging participation of the academic and research community in workshops targeting specific methods of uncertainty analysis and probabilistic prediction. In addition, and specifically for (1) designing the new AHPS products to be useful for users and (2) developing appropriate performance measures for validation of probabilistic and ensemble products, the NWS could encourage contributions to AHPS design from potential product users and analysts who are concerned with decision making under uncertainty. Demonstration testbeds with the participation of forecasters and managers addressing concerns of specific hydrologic forecast users (e.g., reservoir managers, irrigation districts) are a feasible and direct way to accomplish this goal (see also recommendation 3.7).

**Finding:** Developing and testing alternatives to AHPS components (e.g., downscaling of surface meteorological forcing for hydrological models, manner of incorporating model structure and parameter uncertainty in the ensemble streamflow predictions, assimilation of observations) will require participation from across the Enterprise. In the short term, workshops organized by NWS and with wide participation would be necessary to implement this process.

**Recommendation 3.13: The OHD should organize workshops with participation from all sectors of the Enterprise to design alternatives to the AHPS ensemble prediction system components and develop plans for intercomparisons through retrospective studies, demonstration with operational data, and validation, and for participation in testbed demonstration experiments.**

### *3.3.2.2 Limitations of Theory and Input Forecast Requirements for Successful Application*

As operational hydrology transitions from deterministic to probabilistic/ensemble short-term hydrologic forecasting it also transitions from larger to smaller spatial scales (down to the scales of flash-flood prediction). The latter transition makes estimation of the uncertainty in the hydrologic forecasts even more important as there is higher hydrologic simulation uncertainty at smaller scales (Smith et al., 2004). This, for instance, generates the immediate requirement for converting flash-flood guidance systems from deterministic to probabilistic systems. Successful application of ensemble streamflow predictions depends not only on the reliability of the forecasts but also on the manner with which these forecasts are made available (e.g., probability estimates versus an ensemble streamflow time series), communicated, and used by the decision maker or decision-support system (Georgakakos and Krzysztofowicz, 2001).

Ensemble streamflow forecast reliability depends critically on (1) the reliability of the meteorological model ensemble forecasts that are fed into the hydrologic model, (2) the manner with which short-term ensemble weather predictions are blended with longer-term (e.g., seasonal or longer) ensemble climate predictions to create seamless ensemble forcing for the hydrologic models, and (3) the development of reliable methods for model error contribution to the streamflow ensemble forecasts. As the operational hydrologic models transition from spatially lumped to spatially distributed formulations, these critical reliability prerequisites become increasingly difficult to meet with present-day observing networks and meteorological model resolution (e.g., Carpenter and Georgakakos, 2004; Ntelekos et al., 2006).

The issue of blending (point 2, above) is particularly challenging. This issue can be correctly resolved only if the same meteorological model structure and ensemble prediction methodology is used in short-term weather forecasts and long-term climate predictions, and the full range of products becomes available routinely by NCEP from both weather and climate model output.

**Finding:** Blending of short-term predictions with longer-term predictions to force hydrologic models is particularly difficult. This is an area in which hydrologists, as weather and climate forecast users, can provide significant input to meteorologists.

**Recommendation 3.14: The OHD should develop methods for seamlessly blending short-term (weather) with longer-term (climate) ensemble predictions of meteorological forcing within the operational ensemble streamflow prediction system. This will require NCEP model output downscaling and bias adjustment, and real-time data availability.**

## 3.4 SUBJECTIVELY CREATING UNCERTAINTY INFORMATION

Objective uncertainty information in the form of ensemble forecasts and statistical post-processing is made available as guidance for forecasters, but the majority of official probabilistic forecasts are human generated. This section covers some of NWS's subjectively generated official uncertainty forecasts. One such approach and product was already discussed in the context of the CPC. Here, the discussion is extended to include the WFO[25] and to briefly consider forecasts produced by the HPC,[26] the SPC,[27] and the Aviation Weather Center (AWC).[28]

Although objective uncertainty information is provided by the EMC ensemble systems and through MOS based on deterministic model predictions, human forecasters within NWS play a very important role in producing uncertainty information. Since 1965, NWS forecasters have produced subjective predictions of probability of precipitation for cities across the country. Such subjective uncertainty information is based on forecaster knowledge and experience informed by model output, observations, and statistical guidance such as MOS and local prediction aids. Several experimental studies have demonstrated that forecasters are able to produce reliable and accurate probability forecasts of a number of additional elements, such as temperature, humidity, tornadoes, winds (e.g., Murphy and Winkler, 1982; Brown and Murphy, 1987). However, NWS forecasters have not produced such forecasts operationally.

NWS staff also communicate the uncertainty in their forecasts through a variety of text discussion products. At the local level, each forecast office produces Area Forecast Discussions several times a day that analyze the weather situation and provide insights into the forecaster's analysis, including his or her relative certainty regarding the forecast. At some NWS offices, short-range area forecast discussions are also created. Both the short- and longer-term forecast discussions play a critical role in providing the user community with a measure of forecast confidence. For most parameters, there is no other means of providing such uncertainty information. An additional way for forecasters to indicate a significant probability for severe weather events is through watches and advisories. Neither have specific probabilities associated with them, but the wording used may indicate levels of confidence.

The primary tool used by NWS forecasters to produce and distribute their forecasts is the Interactive Forecast Preparation System (IFPS). IFPS is the outcome of a recent paradigm shift in forecast preparation whereby NWS forecasters create graphic renditions of the weather out to 7 days that are dis-

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[25] http://www.weather.gov/organizations.php#local.

[26] http://www.hpc.ncep.noaa.gov/.

[27] http://www.spc.ncep.noaa.gov/.

[28] http://aviationweather.gov/.

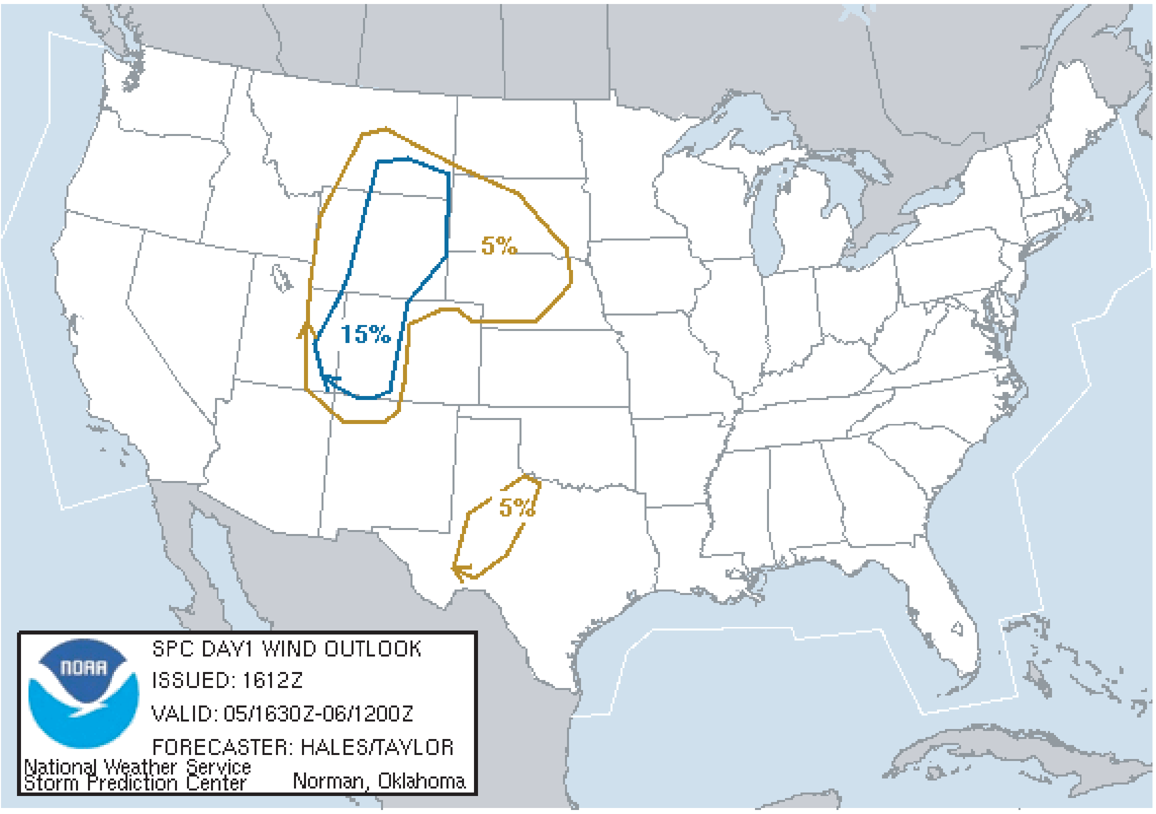

FIGURE 3.9 Probabilistic outlook for damaging winds. SOURCE: Storm Prediction Center.

tributed digitally as well as automatically translated into text. The digital forecast grids, known as the NDFD, represent an entirely deterministic, single-valued approach to prediction with the exception of 6- and 12-hour PoP. It is also possible for forecasters to pair probabilities of precipitation with major weather elements (e.g., thunderstorms, fog, and snow) to provide probabilities of such weather conditions.

On a national level, the HPC produces a variety of forecast discussions that communicate uncertainty, including a Short Range Public Forecast Discussion, an Extended Forecast Discussion, a Quantitative Precipitation Forecast Discussion, an Excessive Rainfall Discussion, a Heavy Snow Discussion, and others. They also produce graphical probabilistic surface low tracks, and the national PoP products as well as several winter weather products[29] including snowfall probability and freezing rain probability.[30]

Forecasters at the SPC produce probabilistic 1- and 2-day outlooks of severe weather, including specific probabilistic forecasts for the occurrence of hail, tornadoes, and damaging winds (Figure 3.9). These outlooks are produced spatially, with specific definitions of the event being forecasted (i.e., the occurrence of the phenomenon within 25 nautical miles of any point within a contour) that are tied closely to the verification of the forecasts. In similarity with the subjective forecasts produced by WFO and HPC forecasters, the probabilistic outlooks are based on forecaster experience and knowledge, as well as the model guidance and other observations and tools. Watches and warnings issued by the SPC also may provide some information about the likelihood of severe weather, through wording of the discussions, but they do not explicitly include uncertainty information.

At the AWC forecasters produce 6-hour outlooks and short-term warning areas for phenomena affecting aviation safety and efficiency, including icing, turbulence, ceiling and visibility, and convection.[31] Most of these products include wording that indicates likely changes in the situation with time through the outlook period but they do not indicate the actual likelihood of occurrence of the particular phenomenon. An exception to this is the Collaborative Convective Forecast Product, which shows areas of likely convective activity at projections of 2, 4, and 6 hours. This product

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[29] http://www.hpc.ncep.noaa.gov/wwd/winter_wx.shtml.

[30] http://www.hpc.ncep.noaa.gov/medr/pop_12hr.shtml.

[31] See http://aviationweather.gov/.

indicates both the expected areal coverage of convection and the forecaster's confidence that convection will occur in the region identified. Although these parameters are not direct estimates of the probability of convection, they do provide an indication of the uncertainty associated with the occurrence and characteristics of future convective activity.

Although the production of subjective probabilities by NWS (and throughout the Enterprise) is limited, the importance of the human forecaster in the production of forecasts for end users cannot be underestimated. The availability of more and better probabilistic guidance products will lead to the production of improved and more extensive probabilistic forecasts by human forecasters.

## 3.5 VERIFICATION

All forecasts must be verified. Regardless of whether the forecast was produced by a numerical model, a post-processing procedure, or a human forecaster, verification provides information to users about the performance and uncertainty associated with the forecasts (to guide their use of the forecasts and as input to decision-support systems; see Chapter 2) and ultimately drives the development of a forecasting system. Verification also fosters intellectual honesty about forecasting capabilities: essentially, verification information provides base-level uncertainty information for any measured weather element. A number of types of verification approaches are needed to evaluate the quality of probabilistic and ensemble forecasting systems (Box 3.9), facilitate development of improved forecasting systems, and meet the specific needs of users.

Forecast verification is the process of evaluating the *quality* of forecasts. Verification includes the measurement of various attributes of forecasting performance, including such quantities as accuracy, skill, and reliability (Box 3.9). The availability of appropriate information about the quality of forecasts and forecasting systems is important for many purposes and for a variety of types of users. In particular, forecasters and forecast developers need information about forecast quality to help improve forecasts; program managers need verification information to monitor forecasting performance; and end users need verification information to make optimal use of forecasts. Although forecast quality, as measured through verification processes, is related to forecast value, quality and value are not the same thing—improvements in forecast *quality* may not always result in increases in *value* (Murphy, 1993). In general, a different set of methodologies, involving users and decision-making or econometric models, is required to estimate forecast value.

Nevertheless, forecast verification approaches can (and should) be designed to provide information about forecast quality that is relevant in the context of how users interpret and use forecasts. Two examples of ways verification information can be made more relevant are (1) the provision of verification information for weather conditions that are

### BOX 3.9
### Verification Measures and Approaches for Probability Forecasts

Forecast verification involves the comparison of forecasts and observations using various approaches to evaluate the quality of the forecasts. The selection of an appropriate verification approach depends on the type of forecast as well as the purpose for the verification. For example, forecasts of rain/no rain require different verification approaches than forecasts of temperature; end users of forecasts require different information than managers.

During the past half-century, specific methods and measures (e.g., the Brier score) have been developed to evaluate probabilistic forecasts. More recently, verification method development has begun to focus on the evaluation of forecasts of probability distributions, such as can be obtained from ensemble forecasts. Development of these approaches remains an area of active research. Examples of measures that can be applied for the evaluation of probabilistic and ensemble forecasts include the decomposed Brier score, the Ranked Probability Score (Wilks, 2006), the Continuous Ranked Probability Score (e.g., Hersbach, 2000), the ignorance score (Roulston and Smith, 2002), Relative Entropy, the Minimum Spanning Tree (Wilks, 2004), the Rank Histogram (Hamill, 2001; Talagrand et al., 1997), and the Relative Operating Characteristic (Mason, 1982; Jolliffe and Stephenson, 2003).

Attributes of probability forecasts that must be considered in verification include accuracy, reliability (also called calibration), resolution, sharpness, discrimination, and skill. Similar attributes could be defined for forecasts of probability distributions. The two attributes *calibration* and *sharpness* are sometimes relied on to provide an overall assessment of the quality of probabilistic forecasts. *Calibration* measures whether, over a large set of events, individual probability values are equivalent to the relative frequency of occurrence of the event. For example, for a large subset of PoP forecasts in which the probability forecast is 0.25, precipitation would occur 25 percent of the time if the forecasts are calibrated. *Sharpness* represents the variability of the forecasts. A completely unsharp set of forecasts (e.g., based on the climatological probability) would have no variability (i.e., only one probability value would always be used). A completely sharp set of forecasts would use only the probability values 0 and 1. In general, sharp forecasts have a U-shaped frequency distribution, with the highest frequencies of use at the lower and upper ends—near 0 and 1. *Discrimination* measures the ability of the probability forecasts to correctly categorize the observed occurrence/nonoccurrence of the event. *Skill* measures how well a forecast performs relative to a naïve standard of comparison, such as climatology or persistence. Many of these attributes, approaches, and measures are explained on the Web site of the WMO WWRP/Working Group on Numerical Experimentation Joint Working Group on Verification[a] and by Jolliffe and Stephenson (2003) and Wilks (2006).

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[a] http://www.bom.gov.au/bmrc/wefor/staff/eee/verif/verif_web_page.html.

meaningful to users (e.g., for surface variables as opposed to 500-mb heights[32]) and (2) the use of diagnostic approaches as opposed to the summary scores that are commonly presented on NWS Web sites (e.g., components of the Brier score versus the overall Brier score). With respect to the first example, GMB assesses its ensemble products primarily (but not exclusively) against analyzed 500-mb heights. This approach naturally results in an ensemble system that shows steady improvement in its ability to probabilistically assess the height of the analyzed 500-mb surface. If one is interested in forecasting the 500-mb analysis then there is nothing wrong with this choice of assessment, but this goal may not be the most relevant for most users, and NWS is making implicit value judgments about what variables are important.

With regard to the second example, *diagnostic* verification approaches generally provide much broader information about forecast performance than can be obtained from a more traditional verification approach that focuses on single verification *measures*. The diagnostic approach considers verification from a "distributions oriented" statistical perspective. A basic principle of the diagnostic verification approach is that a variety of verification statistics is needed to provide meaningful information about the quality of any type of weather forecast and to meet the needs of the variety of users and purposes for verification. Clearly, *no single measure can adequately represent all aspects of forecast performance for all users*. Nevertheless, single measures are commonly presented for many variables (e.g., CPC monthly and seasonal outlooks).

The diagnostic verification approach is characterized by its incorporation of graphical methods, the stratification of verification results into meaningful subsets, and the use of relevant standards of comparison. Graphical approaches are an important component of diagnostic verification and can provide much more information about the distributions of errors than can ever be provided in single summary measures (e.g., Wilks, 2006). In addition, new research on spatial diagnostic verification approaches has led to new methods that provide more user-centric verification of spatial forecasts of variables such as precipitation. With respect to stratification, forecasts are grouped into meaningful subsets so that performance characteristics are not an artifact of combining forecasts too broadly—for example, across climatological zones or time periods. Finally, because verification is essentially a "relative" process, verification results are most meaningful when presented in comparison to the performance of a naïve "standard" (e.g., climatology or persistence).

NWS Instruction 10-1601[33] provides guidance on verification requirements for NWS offices and centers. This directive defines the verification measures that are required for public and fire forecasts, severe weather watches and warnings, marine forecasts, hydrologic forecasts, aviation forecasts, tropical cyclone forecasts, and climate forecasts. In general, the verification analyses that are publicly provided by NWS for many forecasts (e.g., CPC seasonal forecasts) rely on single summary measures of performance. Exceptions to this approach include the extensive diagnostic verification information provided by the SEC[34] and some other centers and offices (e.g., MDL[35]). Thus, these verification approaches generally do not meet the need for diagnostic or user-focused verification.

Two other aspects of verification that are typically ignored are the nonindependence of nearby grid points and the uncertainty associated with the verification measures themselves. With regard to the first issue, ensemble (and other model) forecast verification efforts tend to treat model gridpoints independently.[36] The implication is that the NWS goal is to produce unbiased, reliable probabilistic forecasts of individual weather elements at individual locations. This is a worthwhile effort, and with further development it would allow users to evaluate the probabilistic skill of global and mesoscale PDFs for different variables, locations, and time periods. But covarying uncertainty information can also be important to users. For example, if a hydrologist is concerned about flooding, the covariance of rainfall amounts becomes extremely important. There may be a chance of significant rainfall on opposite ends of a drainage basin, but does high rainfall on one end imply low rainfall on the other, does high rainfall on one end imply high rainfall on the other, or are the two truly independent? It is possible to imagine a forecasting system that is good for individual locations but poor when multiple locations are considered. An emphasis on improving the former (i.e., ignoring the covariances) likely requires a much different development path than an emphasis on improving the latter.

Comparisons of models and forecasting systems often are made using verification information based on simple scalar scores. In some cases these comparisons lead to choices among model or forecast characteristics and parameterizations. Thus the choice of verification measures and approaches is critical. To compound the difficulty in making such comparisons, verification measures and statistics themselves are uncertain. This uncertainty arises from several sources—observational error, sampling variability, and so on—but is almost always ignored in verification studies. To provide meaningful comparisons of probabilistic forecasting systems, this variability is explicitly considered through the use of statistical confidence intervals or hypothesis tests.

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[32] The geographic distribution of the height of the 500-mb-pressure surface above Earth's surface.

[33] http://www.nws.noaa.gov/directives/010/pd01016001c.pdf.

[34] http://www.sec.noaa.gov/forecast_verification/.

[35] http://www.nws.noaa.gov/mdl/verif/.

[36] See, for example, http://www.emc.ncep.noaa.gov/gmb/ens/verif.html, http://www.emc.ncep.noaa.gov/mmb/SREF/VERIFICATION_32km/new_html/system_48km_30day.html, and http://bma.apl.washington.edu/verify.jsp.

Diagnostic verification information can be considered base-level forecast uncertainty information. For example, a straightforward way for NWS to provide forecast uncertainty information is to augment existing forecast products with the error bars implied by historical verification statistics. This approach has been used effectively by the National Hurricane Center[37] (Figure 1.6). The radius of the uncertainty circle at each lead is the average historical track error over the observational record. This product has (1) provided useful information to the public and the Enterprise, (2) stimulated research to provide improved uncertainty information, and (3) generated debate about what information the public and emergency managers require. A more sophisticated approach that utilizes ensemble information is given by the "dressing" technique described by Roulston and Smith (2003).

Finally, many of the issues considered in Chapter 4 regarding the communication of uncertainty information are relevant for the communication of verification information. Thus, careful consideration is needed for the way this information is presented to users. In addition to the verification measures and approaches considered here, it also is important that the components that went into the verification be made readily available to all forecast users (see Chapter 5, recommendation 6) to allow specialist users to perform their own post-processing and verification.

**Finding:** Verification drives forecast system development and affects the use of forecast information. By focusing on providing meaningful information to users about forecast quality and by being more explicit about its choice of verification measures for the forecast development process, NWS will enable open Enterprise debate about the choice of verification measures and the implied NWS role and values. Such debate will allow user interests to directly influence the development of NWS forecasting systems. Application of a broad set of diagnostic approaches, including new approaches developed through verification research, and incorporation of statistical standards (e.g., stratification into meaningful subsets, use of confidence intervals, comparison to a naïve standard) will allow the provision of information that is needed by a broad spectrum of users.

**Recommendation 3.15: NWS should expand its verification systems for ensemble and other forecasts and make more explicit its choice of verification measures and rationale for those choices. Diagnostic and new verification approaches should be employed, and the verification should incorporate statistical standards such as stratification into homogeneous subgroups and estimation of uncertainty in verification measures. Verification information should be kept up to date and be easily accessible through the Web.**

## SUMMARY

In spite of the variety of time and space scales, the differences in quality of numerical models, the range of different forcings, and the assortment of phenomena under consideration, four themes emerge relating to estimation and validation of uncertainty of weather, climate, and hydrologic forecasts within NWS.

1. There is a need for the production of guidance databases that include raw and post-processed probabilistic information that can be interrogated by all users of hydrometeorological information, including NWS forecasters, the private sector, and members of the public. There is also a strong need for the construction and maintenance of databases of historical forecasts and the associated observations for the purpose of post-processing and verification.

2. Before such a database can be usefully constructed, improvements are needed in post-processing efforts for the production of objective probabilistic guidance for all parts of NWS.

3. An increased emphasis on verification is needed across all parts of NWS. A wide range of verification measures that are appropriately applied with a valid statistical basis are necessary to properly assess forecasts and provide meaningful information to users. In addition, diagnostic verification information provides a simple approach for adding uncertainty information to forecasts. Because the choice of verification drives forecast system development, verification measures should be carefully chosen.

4. The Enterprise, and in particular the academic community, is a vast resource that is underutilized by NWS. Testbeds are one way in which productive links can be forged among NWS, the academic and private-sector communities, and the users they serve, but only if sufficient emphasis is given and NWS buys into the testbed concept.

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[37] http://www.nhc.noaa.gov/.

# 4

# Communicating Forecast Uncertainty

Communication is the critical link between the generation of information about forecast uncertainty (Chapter 3) and how information is used in decision making (Chapter 2). This chapter discusses issues at the interface of generation and use. It builds on the foundation laid in Chapter 2, which describes the theoretical aspects of uncertainty in decision making, and focuses on practical aspects of communicating uncertainty in hydrometeorological forecasts.

This chapter addresses the committee's third task: identifying sources of misunderstanding in communicating forecast uncertainty, including vulnerabilities dependent on the means of communication, with recommendations on improvements in the ways used to communicate forecast uncertainty. It explores the roles of graphics, animation, and language; consistency; dissemination technologies; and the media in uncertainty communication. In addition, it presents ideas on refinements to NWS's product development process and education and research needs to support NWS and Enterprise-wide progress on communicating uncertainty information. The chapter is supported by an annex with examples of approaches and products with (and without) an uncertainty component.

As noted in Chapter 2, there is an extensive and rich literature on uncertainty communication in a variety of fields, including medicine, health, and hazards. Given the breadth of this literature, it is beyond the scope of this report to comprehensively review the general topic of communicating uncertainty. Nonetheless, Chapter 2 summarizes aspects from other fields that are central to this report, and for an introduction to the broader literature on uncertainty communication, the reader is referred to Morgan and Henrion (1990) and Morgan et al. (2002) in addition to references in Chapter 2. Because this literature is rapidly evolving, NWS and the rest of the Enterprise will need to entrain expertise on communicating uncertainty from outside the hydrometeorological community on a regular basis to effectively use this knowledge. Chapter 2 presents a process by which NWS could learn to utilize relevant expertise from within the Enterprise and from other disciplines to improve communication of uncertainty information. The present chapter draws on lessons from these other disciplines as needed to support recommendations for improving uncertainty communication in hydrometeorology.

## 4.1 BACKGROUND

Full disclosure of forecast uncertainty information is consistent with—and in fact fundamental to—NWS's established vision for communicating information (Box 4.1). This vision emphasizes dissemination of a wide range of NWS information. As discussed in Chapters 2 and 3, this means not only NWS forecasts and products but also the fundamental supporting information (such as verification and past performance) that is central to improving uncertainty communication throughout the Enterprise.

Beyond NWS's philosophy of information availability, though, there are practical considerations on how to effectively communicate uncertainty information that help set the context of this chapter. For instance, the National Research Council (NRC) workshop on "Communicating Uncertainties in Weather and Climate Information" (Box 4.2) observed that understanding, communicating, and explaining uncertainty should be an integral and ongoing part of what forecasters do and are essential to delivering accurate and useful information.

## 4.2 COMMUNICATING UNCERTAINTY IN EVERYDAY AND HAZARDOUS WEATHER FORECAST PRODUCTS

Forecast uncertainty can be communicated in such products as maps (Figure 4.1), graphs, tables, charts, flip books, images, and written or oral narrative (see Annex 4 for a range of examples). Selecting an appropriate product type and carefully crafting its content can substantially reduce the likelihood of misunderstandings. Each approach to communicating uncertainty will inherently have strengths

### BOX 4.1
### National Weather Service Vision for Communicating Information

The NWS vision of communicating information to users is to

- Make a wide range of information readily available to a diverse user community;
- Disseminate all NWS information nationwide;
- Disseminate broad user community-specific information using a subset of NWS information; and
- Deliver critical information to the public, the hazards community, and other users.

SOURCE: NWS, http://www.nws.noaa.gov/om/disemsys.shtml.

and weaknesses, and each may best communicate a different type of uncertainty to a different user group. Products can be tailored to specific user needs, but when communicating with a diverse audience such as the public, one product is unlikely to meet all users' needs or to be readily understandable to all subgroups (Chapter 2). When such a broad audience is anticipated, a mix of products will likely be most useful (Chapter 2). In addition, an NWS National Digital Guidance Database (recommendation 3.6) would help support this mix of products by providing users and intermediaries with data and tools for customizing communication of uncertainty information.

NWS and other members of the Enterprise generate a variety of textual, verbal, and visual products that communicate uncertainty (Annex 4). However, most weather forecasts specifically generated for the public contain little or no useful uncertainty information; they are simplified and deterministic. Members of the public have been conditioned to these deterministic forecasts and have been given little objective information on the inherent errors in these simplified predictions. Instead, users in the public have developed their own informal methods of estimating the uncertainty. This highlights the need for user education as the Enterprise transitions to probabilistic forecasting.

One major example of a predominantly deterministic product is the NWS public weather forecasts produced by the Interactive Forecast Preparation System (IFPS) and distributed as the National Digital Forecast Database (NDFD). IFPS/NDFD's strength is that it allows forecasters to generate, present, and communicate forecasts of multiple weather elements as a digital database, both for the local area and as a nationally unified grid. Its main weakness is that the forecasts contain limited information about uncertainty. Most variables are estimated and presented as "point forecasts"

### BOX 4.2
### Suggestions for Improving Communication of Uncertainty Information

The following practical suggestions were made during an NRC workshop to improve information delivery (NRC, 2003b):

- View communicating uncertainty to all information users as a key part of the decision-making process.
- Communicate why information is uncertain, not just the fact that it is uncertain.
- Communicate why information about uncertainty is important.
- Use multiple measures of uncertainty and ways of communicating uncertainty to reach diverse audiences.
- Use both qualitative and quantitative forms to communicate uncertainty.

Effectively communicating uncertainty and its context shifts the burden and responsibility of decision making to the information user. The following suggestions from the NRC workshop could improve communications to decision makers:

- The careful and strategic use of context (a tie to a past experience) in the face of complexity and uncertainty frequently makes the meaning of the uncertainty tangible.
- Comprehensively communicate what is known rather than only what it is thought the decision maker needs to know.

Perceived success or failure of forecasts and the portrayal of forecasts by the media and decision makers guide opinions and help determine the credibility of future forecasts. The following actions were suggested:

- Expect misinterpretation. Make an effort to correct problems as soon as possible. Feedback from users is critical.
- Provide a "measuring stick" to decision makers to guide their evaluation of forecasts and forecast uncertainty.
- Avoid overselling or overinterpreting the science.
- Provide follow-on information about forecast quality to help ensure the credibility of future communications. This information is particularly important following the forecast of significant events (e.g., when a forecast was successful despite a large uncertainty or when a forecast was highly credible and failure resulted).

SOURCE: NRC, 2003b.

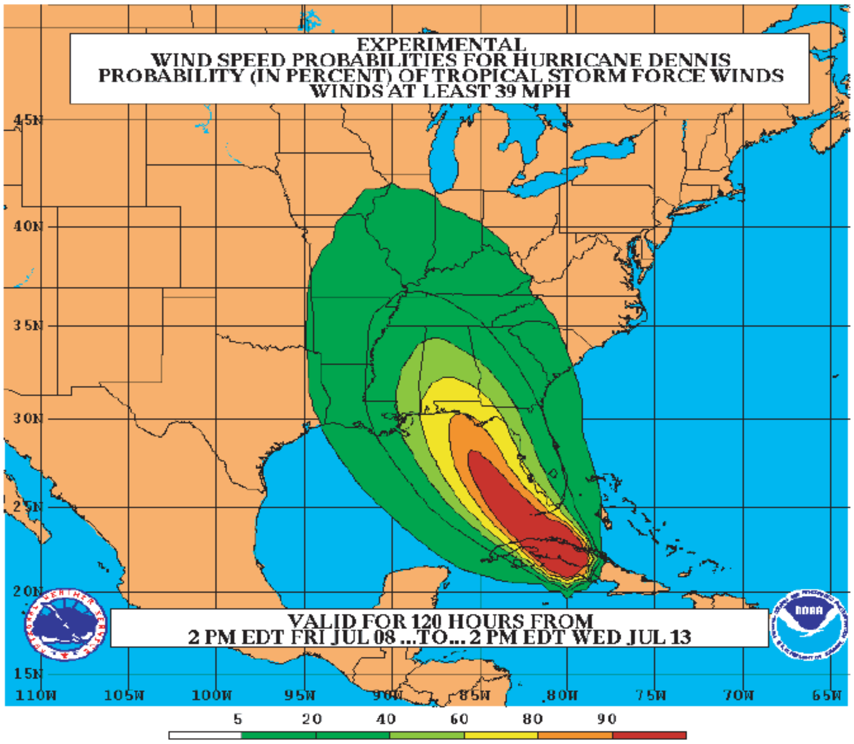


FIGURE 4.1 Probability of wind speeds of greater than 39 mph (tropical storm force) during the specified 120-hour period. The colored bar at the bottom of the figure gives the probability scale in percent. SOURCE: Experimental NWS product generated by the Tropical Prediction Center (TPC).

that appear as deterministic values or graphs for the next 7 days, with no change in format. As discussed in Chapter 3, these deterministic digital values for days into the future are not scientifically valid and could be highly inaccurate and misleading. In addition, the system issues forecasts of precipitation type and thunderstorm risk using vague uncertainty terms such as “slight chance,” “chance,” “likely,” and “occasional.” As discussed in Chapter 2 and developed later in this chapter, research has shown that these terms are interpreted by users as communicating a wide range of probabilities.

The NDFD enables a user to select a site-specific forecast and to extract tailored forecasts from the database. The drawback, though, is that these forecasts include no “qualifier” text or statistical ranges that provide the user with uncertainty information to aid decisions. Fundamentally, IFPS and NDFD are also designed from a deterministic framework (other than the “Probability of Precipitation” component) and thus cannot be easily modified to incorporate communication of forecast uncertainty information.

The provision of single-valued forecasts without uncertainty information (such as error bars on a meteograph) not only exposes a significant limitation of the NDFD/IFPS process but is also fundamentally inconsistent with the science (Chapter 1). Moreover, these digital systems may generate machine-derived text forecasts of “partly cloudy” skies for several days in a row—in essence representing a wide range of weather conditions—and therefore do not effectively communicate the complexity or uncertainty of future weather.

With the importance of digital dissemination of forecasts through the Internet, incorporating uncertainty information into NDFD and IFPS would be advantageous to the public, intermediaries, and specialized users. Many methods of communicating uncertainty are available. Choosing the most effective method (or methods) will require research and two-way interactions with users (see Sections 4.4 and 4.5). Possible methods to consider include displaying skill scores or the standard forecast variance for each forecast variable at different times or providing confidence intervals. Another possibility, to improve consistency, is to communicate cloud cover not as scattered or broken but rather in categories (such as high, medium, and low) or as a percentage (as is currently done for probability of precipitation type and probability of thunderstorms in Model Output Statistics [MOS]).

**Finding:** The public weather forecasts from the IFPS and distributed as the NDFD are one of NWS’s primary forecast products. The system is unable to provide probabilistic forecasts for most fields, and it cannot access probabilistic guidance from the National Centers for Environmental Prediction (NCEP) or other ensemble systems. With the incorporation and communication of uncertainty in most forecast parameters, IFPS and NDFD can reach their full potential as forecast products that meet the NWS vision for communicating information. Development efforts are under way to provide initial probabilistic fields by "dressing" IFPS forecasts with historical error statistics, but making such capabilities operational is years away.

**Recommendation 4.1: The NWS should expedite development of the IFPS toward a system that can access, produce, and communicate uncertainty guidance for most forecast parameters. Such a revised system should be able to access deterministic and ensemble prediction systems, historical error statistics, and statistically post-processed forecast information (e.g., MOS) to allow production of uncertainty information with varying levels of subjective and objective contributions. The system should be capable of preparing probabilistic products to communicate probability density functions and other types of uncertainty information (e.g., probability of temperature less than freezing or wind speed greater than 26 knots).**

Most of the above discussion focuses on communication of uncertainty in public forecasts and outlooks. Communicating uncertainty in hazardous weather situations, particularly for short-fuse, possibly life-threatening events, presents additional challenges. Yet even in these situations, communication of simple uncertainty information may be advantageous (Box 4.3).

### BOX 4.3
### Communication of Forecast Uncertainty in Short-Term Warnings

Communication of uncertainty information within short-term, high-risk weather events such as tornados, flash floods, or severe storms presents a dilemma for forecasters. Research in risk communication suggests that motivating action requires clear, consistent messages that warn of the approaching hazardous event and recommend specific responses, as in current NWS tornado, severe thunderstorm, and other warnings. Adding uncertainty information to these forecasts may confuse the message and possibly delay life-saving actions. Yet every forecast contains some uncertainty, and many members of the public have experience with categorical forecasts of short-fuse hazardous weather events that have not occurred as forecasted. Such experiences can lead people to interpret warnings according to their own perceptions of forecast uncertainty, which may be substantially different than the uncertainty in the actual weather situation. This, too, can delay decisions to take action. Thus, at a minimum, including some consistent information about confidence in short-term forecasts and warnings may help people evaluate the uncertainty in the situation and, in doing so, benefit their decisions.

## 4.3 IMPORTANT ASPECTS OF COMMUNICATING UNCERTAINTY

### 4.3.1 Use of Language and Graphics

Users' interpretations of forecast information can lead to misunderstandings that affect their decisions, sometimes with catastrophic consequences (e.g., Box 4.4). In particular, words or images that a forecaster or scientist thinks are clear may be interpreted differently by users (and differently among users). For example, interpretations of the term "possible" span most of the probability spectrum (Chapter 2). When this term is used to communicate forecast uncertainty, some users will inevitably misinterpret what the forecaster intended to convey.

In addition to reducing the likelihood of misinterpretation in the use of language to characterize uncertainty, NWS can also increase the clarity and accessibility of its uncertainty products. Two examples have immediate potential, the Area Forecast Discussion (AFD) and the Climate Prediction Center's (CPC's) monthly and seasonal forecasts.

#### *4.3.1.1 Area Forecast Discussion*

The NWS AFD is one of the most commonly accessed products on NWS Web sites. Notwithstanding the challenge of effectively using words to convey uncertainty (Chapter 2), these discussions provide one of the few available assessments of forecast uncertainty generated by a human forecaster. They are particularly useful to meteorologists and to specialized users who understand the meteorology. However, the AFDs (and other NWS forecast discussion products) still have a major weakness: although some forecast discussions are now written in easy-to-understand terms for the general user, many are still difficult to understand (e.g., Figure 4.4), making the forecast discussion not as widely useful as it could be. Given the AFD's wide popularity, the forecast discussions might also be adapted into an easily accessible narrative public product that communicates forecast uncertainty to nonmeteorologists.

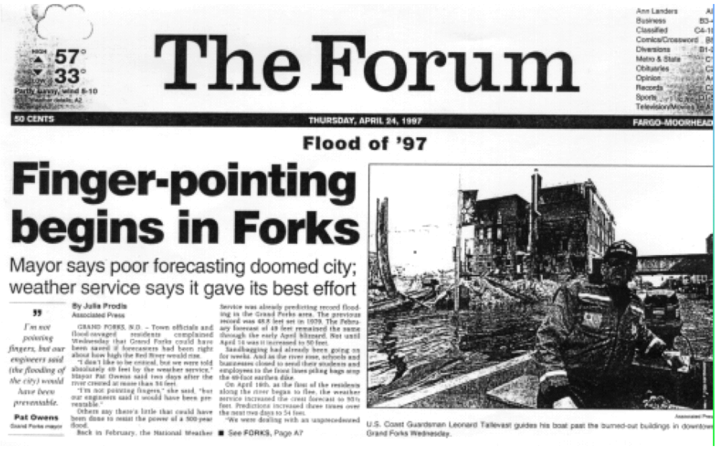
**Finding:** AFDs are popular NWS products that were designed as technical discussions to enhance collaboration among NWS offices and to convey uncertainty to a specialized audience. AFDs are now routinely accessed by broad user community and could be even more widely read and utilized if they were written for the even larger nonspecialist audience.

**Recommendation 4.2: The NWS should release the AFD only in layperson English to facilitate its broad use and understanding. For more sophisticated users, NWS could**

## BOX 4.4
## Communication of Forecast Information During the Red River Flood of 1997 in Grand Forks, North Dakota

Unclear communication of uncertain forecast information can hinder decision making and have significant negative consequences. An example is the 1997 flood in Grand Forks, North Dakota (Figure 4.2). Although NWS prepared flood stage outlooks months in advance, and forecasters were aware that they were predicting a record-breaking, uncertain event, the outlooks were issued as just two deterministic numbers (expected flood stage and low stage). Members of the community interpreted this range of numbers in different ways, generally not realizing that a significantly higher flood was possible (Pielke, 1999; NRC, 2003b). As it turned out, the NWS flood crest forecasts were too low by several feet, until a few days before the flood crest (Figure 4.3, left panel). Although Grand Forks had made significant preparations based on the early outlook, the city was not adequately prepared for the higher flood, and the city experienced major flood damage. Many people blamed NWS for a blown forecast. According to Ken Vein, Grand Forks city engineer (May 4, 1997), "With proper advance notice we could have protected the city to almost any elevation . . . if we had known [the final flood crest in advance], I'm sure that we could have protected a majority of the city."

A river stage forecast that communicated uncertainty more fully and clearly, such as the probabilistic product in Figure 4.3, right panel (which is a more recent NWS hydrologic product), may have led to better flood management decisions. In fact, Pielke found that the actual flood crest in this case was within the error range one would expect for such a forecast which could have been—but was not—communicated along with the forecast.



HIGH 57°
LOW 33°
Partly sunny, wind 8-10
Weather details, A2

**The Forum**

Ann Landers
Business
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50 CENTS THURSDAY, APRIL 24, 1997 FARGO-MOORHEAD

**Flood of '97**

**Finger-pointing begins in Forks**

Mayor says poor forecasting doomed city; weather service says it gave its best effort

> *I'm not pointing fingers, but our engineers said (the flooding of the city) would have been preventable.*
>
> **Pat Owens**
> Grand Forks mayor

By Julia Prodis
Associated Press

GRAND FORKS, N.D. – Town officials and flood-ravaged residents complained Wednesday that Grand Forks could have been saved if forecasters had been right about how high the Red River would rise.

"I don't like to be critical, but we were told absolutely 49 feet by the weather service," Mayor Pat Owens said two days after the river crested at more than 54 feet.

"I'm not pointing fingers," she said, "but our engineers said it would have been preventable."

Others say there's little that could have been done to resist the power of a 500-year flood.

Back in February, the National Weather Service was already predicting record flooding in the Grand Forks area. The previous record was 48.8 feet set in 1979. The February forecast of 49 feet remained the same through the early April blizzard. Not until April 14 was it increased to 50 feet.

Sandbagging had already been going on for weeks. And as the river rose, schools and businesses closed to send their students and employees to the front lines piling bags atop the 49-foot earthen dike.

On April 18th, as the first of the residents along the river began to flee, the weather service increased the crest forecast to 50½ feet. Predictions increased three times over the next two days to 54 feet.

"We were dealing with an unprecedented

■ See FORKS, Page A7

Associated Pres

U.S. Coast Guardsman Leonard Tallevast guides his boat past the burned-out buildings in downtow Grand Forks Wednesday.

FIGURE 4.2 Headline from *The Forum* newspaper, April 24, 1997. SOURCE: Forum Communications Company.

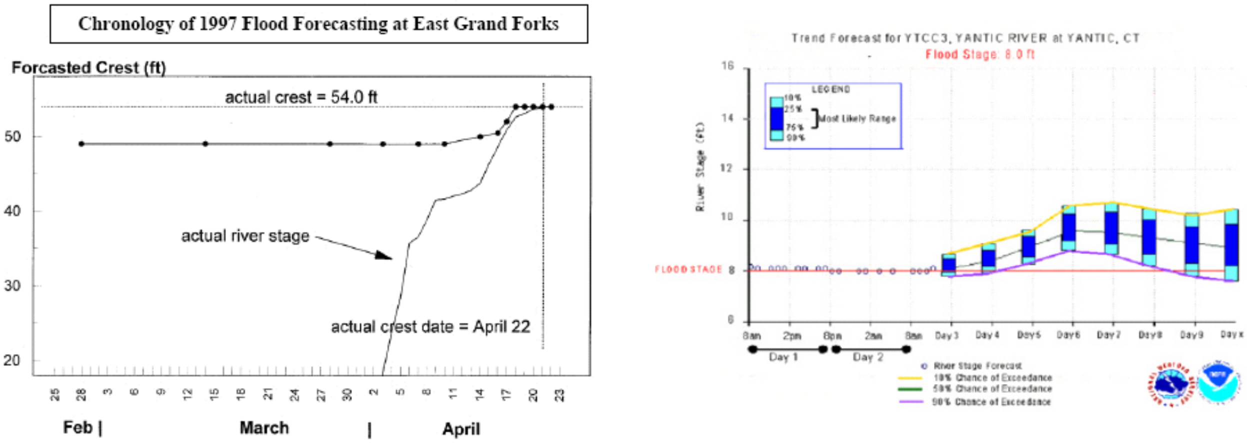
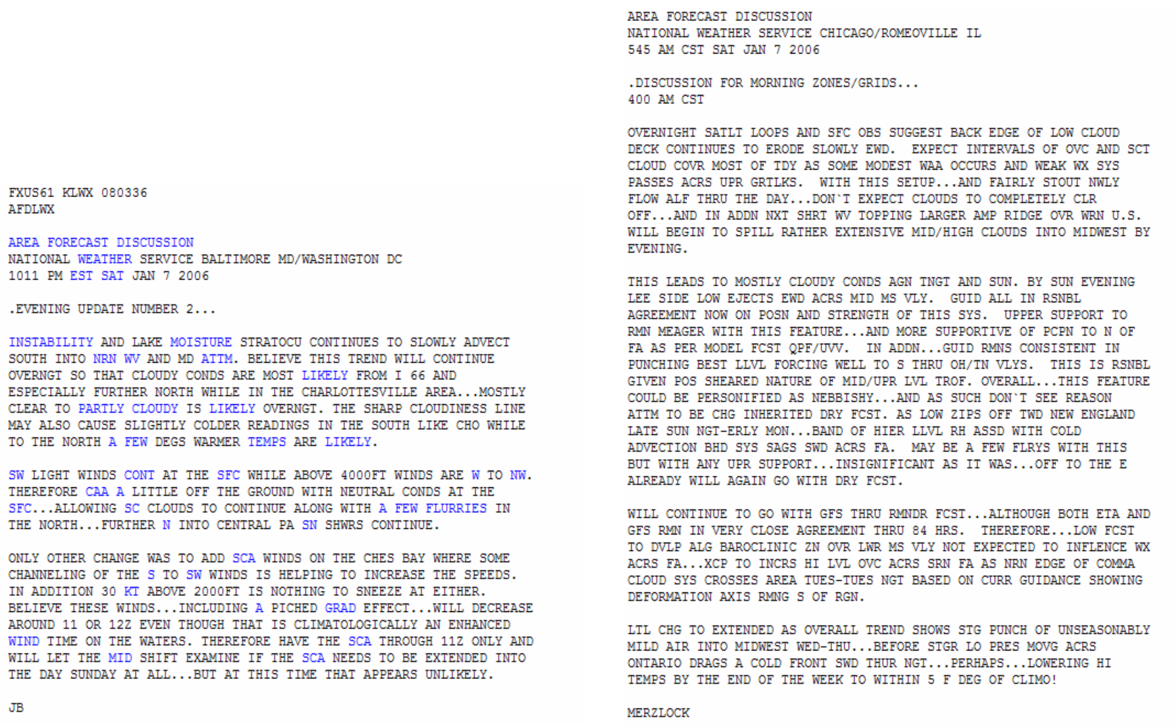


FIGURE 4.3 Left: Deterministic forecasts issued by NWS prior to the Red River flood of 1997. Right: Probabilistic river stage forecast from AHPS. SOURCE: NWS.



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FXUS61 KLWX 080336
AFDLWX

AREA FORECAST DISCUSSION
NATIONAL WEATHER SERVICE BALTIMORE MD/WASHINGTON DC
1011 PM EST SAT JAN 7 2006

.EVENING UPDATE NUMBER 2...

INSTABILITY AND LAKE MOISTURE STRATOCU CONTINUES TO SLOWLY ADVECT
SOUTH INTO NRN WV AND MD ATTM. BELIEVE THIS TREND WILL CONTINUE
OVERNGT SO THAT CLOUDY CONDS ARE MOST LIKELY FROM I 66 AND
ESPECIALLY FURTHER NORTH WHILE IN THE CHARLOTTESVILLE AREA...MOSTLY
CLEAR TO PARTLY CLOUDY IS LIKELY OVERNGT. THE SHARP CLOUDINESS LINE
MAY ALSO CAUSE SLIGHTLY COLDER READINGS IN THE SOUTH LIKE CHO WHILE
TO THE NORTH A FEW DEGS WARMER TEMPS ARE LIKELY.

SW LIGHT WINDS CONT AT THE SFC WHILE ABOVE 4000FT WINDS ARE W TO NW.
THEREFORE CAA A LITTLE OFF THE GROUND WITH NEUTRAL CONDS AT THE
SFC...ALLOWING SC CLOUDS TO CONTINUE ALONG WITH A FEW FLURRIES IN
THE NORTH...FURTHER N INTO CENTRAL PA SN SHWRS CONTINUE.

ONLY OTHER CHANGE WAS TO ADD SCA WINDS ON THE CHES BAY WHERE SOME
CHANNELING OF THE S TO SW WINDS IS HELPING TO INCREASE THE SPEEDS.
IN ADDITION 30 KT ABOVE 2000FT IS NOTHING TO SNEEZE AT EITHER.
BELIEVE THESE WINDS...INCLUDING A PICHED GRAD EFFECT...WILL DECREASE
AROUND 11 OR 12Z EVEN THOUGH THAT IS CLIMATOLOGICALLY AN ENHANCED
WIND TIME ON THE WATERS. THEREFORE HAVE THE SCA THROUGH 11Z ONLY AND
WILL LET THE MID SHIFT EXAMINE IF THE SCA NEEDS TO BE EXTENDED INTO
THE DAY SUNDAY AT ALL...BUT AT THIS TIME THAT APPEARS UNLIKELY.

JB
```

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AREA FORECAST DISCUSSION
NATIONAL WEATHER SERVICE CHICAGO/ROMEOVILLE IL
545 AM CST SAT JAN 7 2006

.DISCUSSION FOR MORNING ZONES/GRIDS...
400 AM CST

OVERNIGHT SATLT LOOPS AND SFC OBS SUGGEST BACK EDGE OF LOW CLOUD
DECK CONTINUES TO ERODE SLOWLY EWD.  EXPECT INTERVALS OF OVC AND SCT
CLOUD COVR MOST OF TDY AS SOME MODEST WAA OCCURS AND WEAK WX SYS
PASSES ACRS UPR GRTLKS.  WITH THIS SETUP...AND FAIRLY STOUT NWLY
FLOW ALF THRU THE DAY...DON`T EXPECT CLOUDS TO COMPLETELY CLR
OFF...AND IN ADDN NXT SHRT WV TOPPING LARGER AMP RIDGE OVR WRN U.S.
WILL BEGIN TO SPILL RATHER EXTENSIVE MID/HIGH CLOUDS INTO MIDWEST BY
EVENING.

THIS LEADS TO MOSTLY CLOUDY CONDS AGN TNGT AND SUN. BY SUN EVENING
LEE SIDE LOW EJECTS EWD ACRS MID MS VLY.  GUID ALL IN RSNBL
AGREEMENT NOW ON POSN AND STRENGTH OF THIS SYS.  UPPER SUPPORT TO
RMN MEAGER WITH THIS FEATURE...AND MORE SUPPORTIVE OF PCPN TO N OF
FA AS PER MODEL FCST QPF/UVV.  IN ADDN...GUID RMNS CONSISTENT IN
PUNCHING BEST LLVL FORCING WELL TO S THRU OH/TN VLYS.  THIS IS RSNBL
GIVEN POS SHEARED NATURE OF MID/UPR LVL TROF. OVERALL...THIS FEATURE
COULD BE PERSONIFIED AS NEBBISHY...AND AS SUCH DON`T SEE REASON
ATTM TO BE CHG INHERITED DRY FCST. AS LOW ZIPS OFF TWD NEW ENGLAND
LATE SUN NGT-ERLY MON...BAND OF HIER LLVL RH ASSD WITH COLD
ADVECTION BHD SYS SAGS SWD ACRS FA.  MAY BE A FEW FLRYS WITH THIS
BUT WITH ANY UPR SUPPORT...INSIGNIFICANT AS IT WAS...OFF TO THE E
ALREADY WILL AGAIN GO WITH DRY FCST.

WILL CONTINUE TO GO WITH GFS THRU RMNDR FCST...ALTHOUGH BOTH ETA AND
GFS RMN IN VERY CLOSE AGREEMENT THRU 84 HRS.  THEREFORE...LOW FCST
TO DVLP ALG BAROCLINIC ZN OVR LWR MS VLY NOT EXPECTED TO INFLENCE WX
ACRS FA...XCP TO INCRS HI LVL OVC ACRS SRN FA AS NRN EDGE OF COMMA
CLOUD SYS CROSSES AREA TUES-TUES NGT BASED ON CURR GUIDANCE SHOWING
DEFORMATION AXIS RMNG S OF RGN.

LTL CHG TO EXTENDED AS OVERALL TREND SHOWS STG PUNCH OF UNSEASONABLY
MILD AIR INTO MIDWEST WED-THU...BEFORE STGR LO PRES MOVG ACRS
ONTARIO DRAGS A COLD FRONT SWD THUR NGT...PERHAPS...LOWERING HI
TEMPS BY THE END OF THE WEEK TO WITHIN 5 F DEG OF CLIMO!

MERZLOCK
```

FIGURE 4.4 Two examples of area forecast discussions, both containing technical terms and abbreviations that limit their communication of information to users without significant meteorological training or experience. SOURCE: NWS.

**provide more detailed technical information linked to the AFD.**

### *4.3.1.2 Climate Prediction Center Monthly and Seasonal Outlooks*

Near the middle of every month, the CPC provides predictions of temperature and precipitation probability anomalies for the coming month, as well as seasonal (3-month) forecasts out to 12.5 months. Monthly outlooks are also updated at the end of the month. These predictions (or "outlooks") are formulated as probability anomalies for three equally probable classes (below normal, near normal, and above normal). The anomalies now specify the probability assigned to the most likely class. The user must further examine the CPC Web site to determine the rules for distributing probability among the other two classes. The three classes are determined by dividing the normal distribution (for temperature), fitted to observations made over 1971-2000, into three equally likely classes (terciles). Because the underlying distribution for precipitation can be highly skewed, the observations are transformed into a normal distribution prior to dividing into terciles.

The primary mode for providing these forecasts is maps depicting the probability value associated with the most likely category at each location. Areas with anticipated above or below normal values are labeled and color coded according to the strength of the probability anomaly; where none of the forecast tools has demonstrated statistically significant skill, the forecasters label the non-colored area as "EC" (Equal Chances; see Figure 4.5). The EC areas can be ambiguous because they may also indicate the forecasters' belief that each of the categories truly is equally likely. Other aspects of the maps can also be difficult for users to understand (e.g., what exactly are the meanings of the terms "above average," "below average," "equal chances," and "normal"?). Morever, the maps do not convey all of the available or needed information. In particular, they prespecify the thresholds for each class (e.g., above average, below average, and normal), which limits users' ability to obtain the information that may be most useful. The EC areas are especially problematic as they provide no information about the likely distribution of values.

To help users understand the rationale for specific forecasts, the CPC provides a discussion of the anomalies, which describes the sources of information and uncertainty used to develop the predictions. Technical discussions are also provided on topics such as the current state and evolution of the El Niño/Southern Oscillation. In addition, terminology definitions are provided. However, these discussions are likely not read or understood by many users.

The probability anomaly maps provide an indication of where conditions are likely to be in one of the four classes (e.g., above normal, below normal, normal, and equal

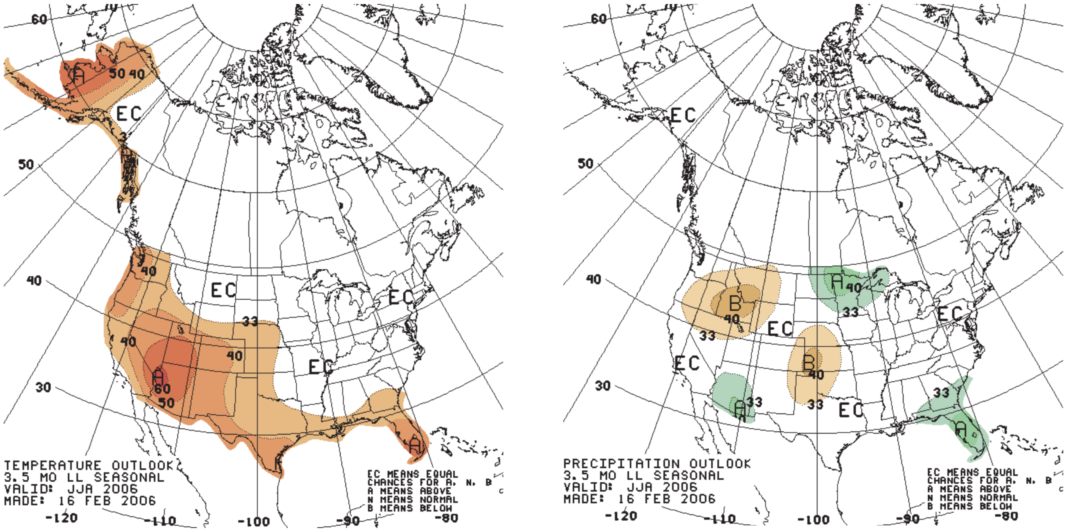

FIGURE 4.5 Sample seasonal outlook maps for temperature and precipitation. SOURCE: CPC, http://www.cpc.ncep.noaa.gov/products/predictions/90day/.

chance), but they do not directly indicate the expected median precipitation and average temperature values or the expected distribution of values. Thus, the CPC also produces maps of the "most likely anomaly" for 3-month temperature and precipitation forecasts[1] (see Figure 4.6). These maps present contours of both the average anomalies as well as the climatologically average values. To supplement these maps, exceedance distribution graphics are available for each climate division (Figure 4.7). These plots present cumulative distribution functions for average conditions, as well as shifted distributions of precipitation and temperature (if a shift from normal is predicted) based on the outlook. The anomaly values for precipitation are based on the difference between the medians of the "normal" and "final forecast" distributions. Thus, anomalies indicated on the precipitation outlooks are not really "most likely." Rather there is a 50 percent chance that the anomaly will be greater or less than the indicated value. The forecast distribution envelope is based on the expected sampling variability of the climatological probability of exceedence using 45 years of data.[2] Thus, the anomaly distribution plots present the most complete information about the uncertainty in the forecasts by providing a complete distribution of possible values. The anomaly distribution plots provide sufficient information that a user can specify the precipitation or temperature threshold that is relevant for their use and obtain the associated probability. Some of this information is also available in tabular form.[3]

**Finding:** The graphics conveying monthly and seasonal outlooks are difficult for many users to understand and do not convey all the information (both graphical and tabular) that is available or needed. Exceedance probability distributions provide the most complete information about the climate probabilities at particular locations. These distributions do not rely on pre-specified categories or definitions of "normals." Overall, more research is needed regarding user needs for these graphical and tabular formats, as well as more forecaster-user interactions to provide two-way feedback on this and other products.

**Recommendation 4.3: The CPC should provide full exceedence probability distributions of the projected monthly and seasonal temperature and precipitation values in both graphical and tabular forms. A straightforward graphical presentation of this information should be developed that is understandable to relevant user groups.**

### *4.3.1.3 Icons and Text Modifiers*

Weather icons and text modifiers are becoming widespread within the Enterprise as a method of communicating forecast information. Understanding how users interpret these graphics is therefore important in the context of communicating uncertainty. According to one study (Box 4.5), users' interpretations of icons may even introduce perceived uncertainty when none is intended.

In another example, from a local NWS office (Figure 4.8), it is unclear how users will interpret the message conveyed

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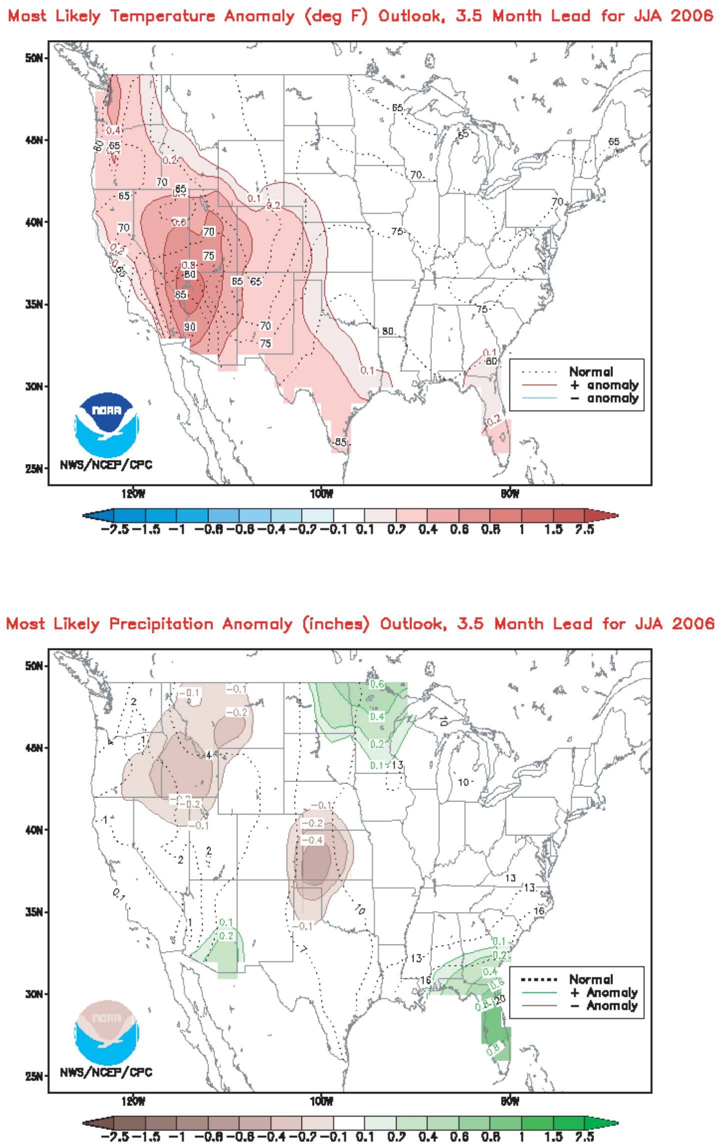
[1] http://www.cpc.ncep.noaa.gov/pacdir/NFORdir/HOME3.shtml.

[2] http://www.cpc.ncep.noaa.gov/pacdir/NFORdir/INTR.html.

[3] For example, http://www.cpc.ncep.noaa.gov/pacdir/NFORdir/HUGEdir2/cpcllftd.dat.


Most Likely Temperature Anomaly (deg F) Outlook, 3.5 Month Lead for JJA 2006

Most Likely Precipitation Anomaly (inches) Outlook, 3.5 Month Lead for JJA 2006

FIGURE 4.6 Sample plot of most likely temperature and precipitation anomalies. SOURCE: CPC (http://www.cpc.ncep.noaa.gov/products/predictions/90day/).

in the product. For example, are the icons in the Tuesday and Thursday forecasts confusing given the accompanying text?

More generally, there seems to be little knowledge of how weather forecast icons will be interpreted by users, and insufficient incorporation of users into the icon development process. Fortunately, there is knowledge outside NWS and from other fields on how people interpret language and graphics (Chapter 2), and there are many ideas on how to use language and graphics to communicate uncertainty (e.g., Figure 4.9). Incorporating this knowledge into NWS and Enterprise efforts to communicate forecast uncertainty will create efficiencies and enable faster adoption of new methods.

### 4.3.2 Consistency

Conflicting messages can increase uncertainty or confusion, hampering decision making. This section discusses the lack of consistency in use of uncertainty words and images.

As noted in the preceding section, icons have the capability to communicate complex information in an easily

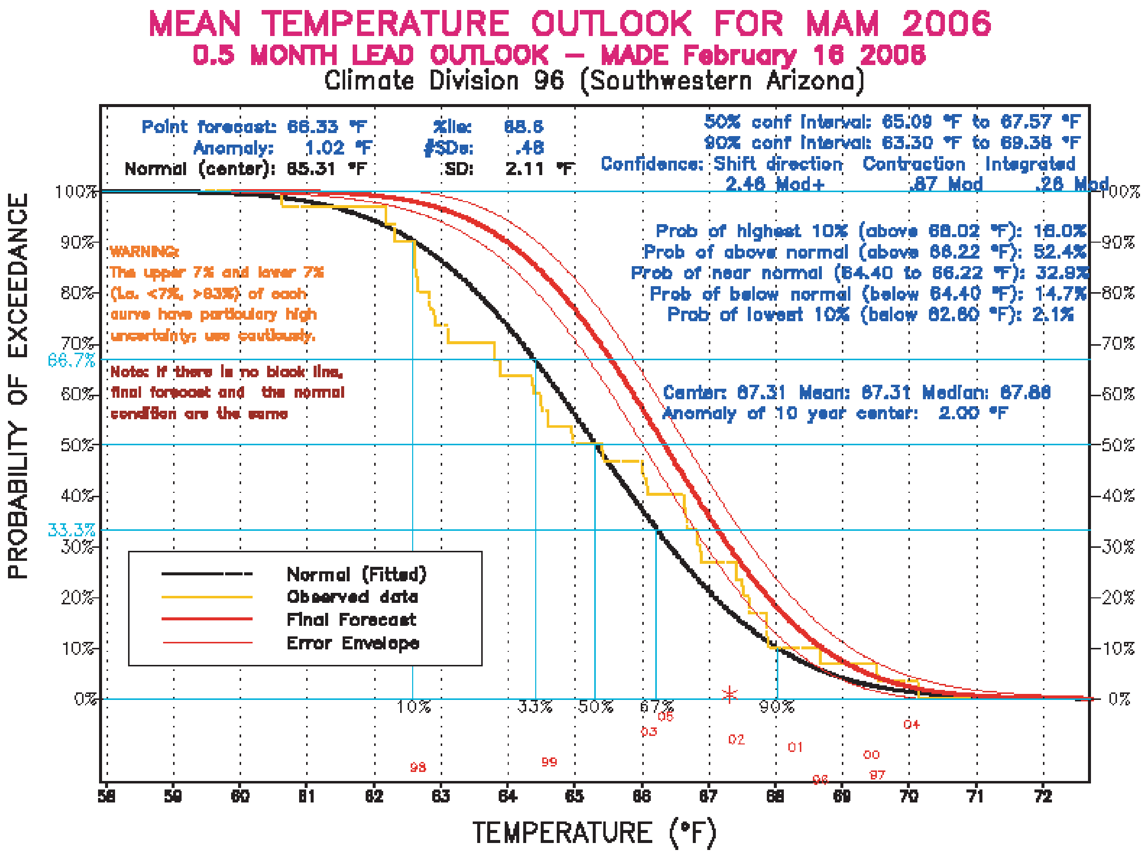
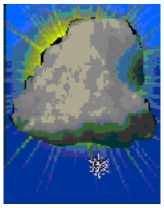


FIGURE 4.7 Example anomaly distribution for a 3-month temperature prediction for southwest Arizona. SOURCE: CPC.

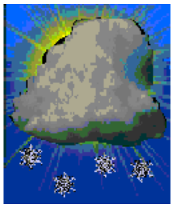
## BOX 4.5
## Internet Survey of Icon Interpretations

In 2001, NBC4 in Washington, DC conducted an Internet-based survey[a] showing a cloud with one snowflake and a cloud with four snowflakes and asked respondents: What does picture B mean to you, in relation to picture A?[b]

A



B



Overall, about half of the respondents thought the symbol with four flakes meant more snow, and slightly less than half thought it meant the forecast was more certain it would snow. In other words, many respondents interpreted a deterministic icon as if it were conveying uncertainty. This suggests that forecast providers cannot necessarily predict how users will interpret graphics without careful and thorough study of user interpretations and needs.

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[a] Results of online surveys, while interesting, are not necessarily representative of the entire user population (see section 2.4.1).

[b] SOURCE: NBC Universal. Any reuse of this material requires the express written consent of NBC Universal.

Your National Weather Service forecast

Dallas, TX

Enter Your "City, ST" or zip code ☐ Go

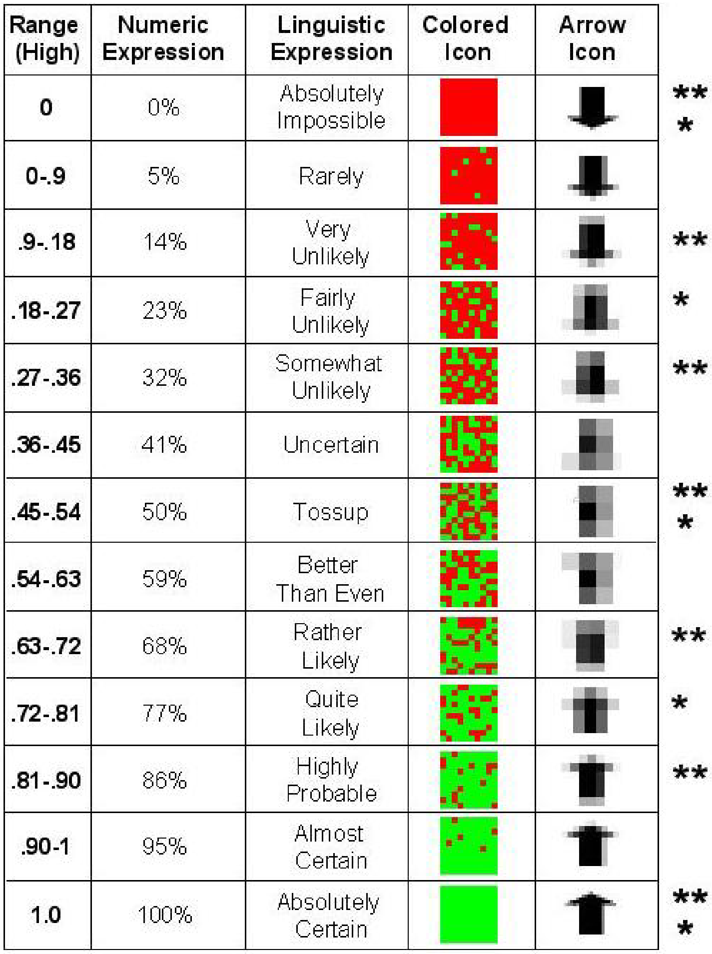
WS Dallas/Fort Worth, TX
oint Forecast: Dallas, TX
2.73N -96.78W (Elev. 417 ft)

Cell Phone Weather Link: www.srh.noaa.gov/wml
Last Update: 5:00 pm CST March 5, 2006

Forecast at a Glance

| Tonight | Monday | Monday Night | Tuesday | Tuesday Night | Wednesday | Wednesday Night | Thursday | Thursday Night |
|---|---|---|---|---|---|---|---|---|
| | | | 20% | 20% | 40% | 60% | 60% | |
| Partly Cloudy | Partly Cloudy | Partly Cloudy | Slight Chc Tstms | Slight Chc Tstms | Chance Tstms | Tstms Likely | Tstms Likely | Partly Cloudy |
| Lo 56°F | Hi 80°F | Lo 59°F | Hi 77°F | Lo 62°F | Hi 76°F | Lo 55°F | Hi 71°F | Lo 50°F |

FIGURE 4.8 Example of potentially confusing icons and accompanying text. SOURCE: NWS.



| Range (High) | Numeric Expression | Linguistic Expression | Colored Icon | Arrow Icon | |
|---|---|---|---|---|---|
| 0 | 0% | Absolutely Impossible | 🟥 | ⬇ | **<br>* |
| 0-.9 | 5% | Rarely | 🟥 | ⬇ | |
| .9-.18 | 14% | Very Unlikely | 🟥 | ⬇ | ** |
| .18-.27 | 23% | Fairly Unlikely | 🟥 | | * |
| .27-.36 | 32% | Somewhat Unlikely | 🟥 | | ** |
| .36-.45 | 41% | Uncertain | ▨ | | |
| .45-.54 | 50% | Tossup | ▨ | | **<br>* |
| .54-.63 | 59% | Better Than Even | ▨ | | |
| .63-.72 | 68% | Rather Likely | 🟩 | | ** |
| .72-.81 | 77% | Quite Likely | 🟩 | | * |
| .81-.90 | 86% | Highly Probable | 🟩 | ⬆ | ** |
| .90-1 | 95% | Almost Certain | 🟩 | ⬆ | |
| 1.0 | 100% | Absolutely Certain | 🟩 | ⬆ | **<br>* |

FIGURE 4.9 Symbols for communicating uncertainty. SOURCE: Reprinted with permission from *Human Factors*, Vol. 47, No. 4, 2005. Copyright 2005 by the Human Factors and Ergonomics Society. All rights reserved.

accessible way. However, the icons that accompany the digitally generated forecasts on NWS homepages are sometimes inconsistent with the accompanying numerical/text forecast. In some instances, these "icon forecasts" can be more confusing than helpful; for example, the same icons are sometimes used for a variety of forecasts (Figure 4.10) and, indeed, significantly different forecasts.

Uncertainty words are used inconsistently within NWS and, more generally, across the Enterprise. This inconsistency makes it challenging for users to calibrate the meaning of uncertainty forecasting terms based on experience. In addition, such inconsistency is sometimes evident in different products from the same NWS office during the same period. Box 4.6 contains an extended example from one local NWS office.

Local innovation and individual forecaster creativity within NWS is important to help the agency serve local and national needs. But by relying on evolving, ad hoc, and experimental systems without more extensive, consistent, and scientifically valid communication techniques, NWS's communication of uncertainty information may be interpreted differently by users looking at different products from the same NWS forecaster. A variety of products is needed to effectively communicate uncertainty to the broad range of users that NWS serves. But these need to be consistent across all regions, platforms, and product language and communication methods. Related to this, the NRC *Fair Weather* report (NRC, 2003a) recommends that "NWS headquarters and regional managers should develop an approach to managing the local forecast offices that balances a respect for local innovation and creativity with greater control over the activities that affect the public-private partnership, especially those that concern the development and dissemination of new products or services."

**Finding:** A variety of products is needed to communicate uncertainty to a broad range of users. Consistency of language, icons, and graphical representations of uncertainty among all these products is critical for the effective communication of uncertainty information. A necessary first step toward ensuring consistency is understanding users' interpretations.

**Recommendation 4.4: To ensure consistency in the communication of uncertainty information and user comprehension, NWS should more fully study and standardize uncertainty terms, icons, and other communications methods through all pathways of forecast dissemination.**

### 4.3.3 Dissemination Technologies

The main channels through which NWS distributes information directly to the user are the NWS home pages (such as those of the Storm Prediction Center, Tropical Prediction Center, Hydrometeorological Prediction Center, and the various Weather Forecast Offices), National Oceanic and Atmospheric Administration (NOAA) Weather Radio (NWR), and the Emergency Managers Weather Information Network (EMWIN). In addition, NWS distributes information to intermediaries through the NOAA Weather Wire Service (NWWS), Interactive Weather Information Network, NOAAPORT, and Family of Services.

NWR and NWS home pages have formats in which NWS can and already does incorporate uncertainty information into forecasts. Systems such as the NWWS and/or EMWIN, which emergency managers and some private-sector entities (e.g., utilities, transportation industry) use to receive NWS forecasts and special weather statements, can also be used to communicate uncertainty information through text descriptions. In addition, both NWWS and EMWIN allow display of graphical products that could communicate uncertainty.

Dissemination technologies are evolving rapidly, affecting how NWS and the other members of the Enterprise approach communicating uncertainty information. Communication devices such as cell phones, personal digital assistants (PDAs), portable MP3 players, computer toolbar "bugs," and pagers have become commonplace, and the Enterprise is moving closer to being able to communicate information to nearly anyone, anytime, anywhere.

These developments present both opportunities and challenges. The opportunity is that the Enterprise can now reach more people in more places and at more times than ever before. One challenge is to understand the strengths

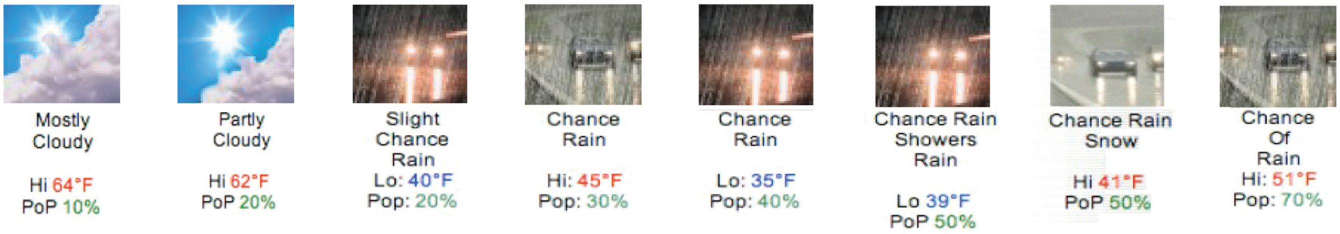


FIGURE 4.10 Examples of graphics used to communicate different Probability of Precipitation (PoP) forecasts in NWS public forecasts.
SOURCE: NWS Web pages.

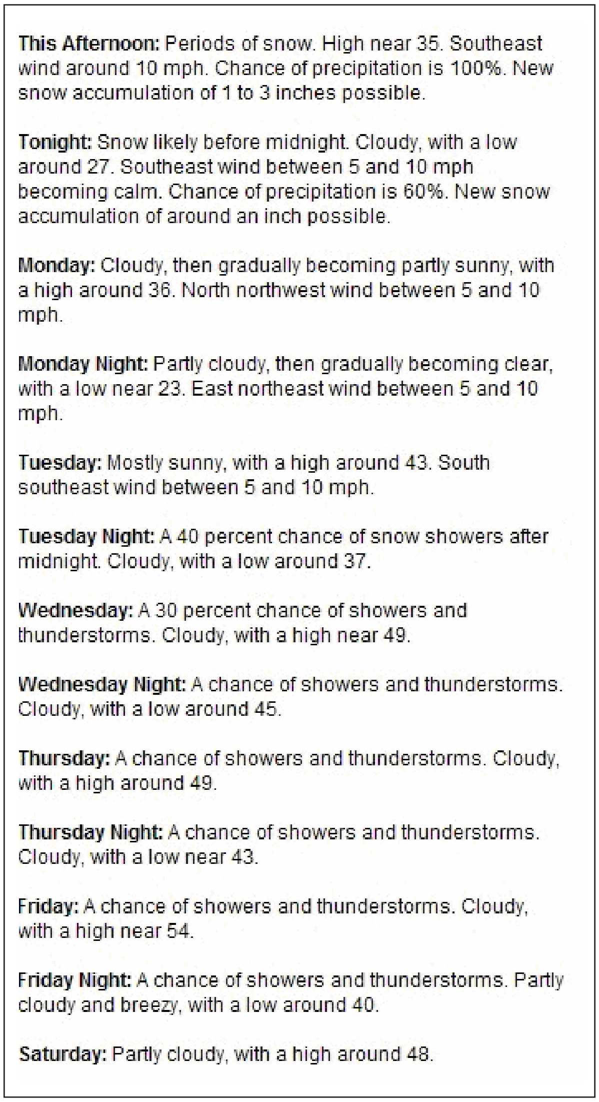
## BOX 4.6
## Consistency in Communicating Forecast Uncertainty Using Words and Graphics

Four forecast products containing uncertainty words or graphics are used in this example: the text forecast (Figure 4.11) for March 5 to 11 (Sunday to Saturday), the hourly weather graphs for the Sunday to Tuesday in that period (Figure 4.12) and Friday and Saturday of that period (Figure 4.13), and the digital IFPS product for the Sunday through Wednesday (Figure 4.14). For the same period of time on the Sunday afternoon, and for the same region, different NWS products generated by the same local office present the short-term forecast for the snow event as any one of

1. "Periods of snow" (public text forecast product; Figure 4.11)
2. Snow "occl" (occasional) (hourly graph product; Figure 4.12)
3. Snow def (definite) (digital product; Figure 4.14)

Users looking at different products are likely to have different interpretations, and users looking at multiple products are likely to be confused. In addition to this inconsistency, Figure 4.12 indicates no precipitation in its lower panel concurrently with showing the PoP at 21 percent (middle panel), whereas the same percentage PoP triggers "chc" or chance of rain in Figure 4.13. Furthermore, this product (Figure 4.13) generates the category "occasional" for a PoP of 100 percent on Sunday, March 5. This could confuse users who are not familiar with the official meteorological definition of PoP. Other products communicating uncertainty in the same forecast are also available, such as the Hydrometeorological Prediction Center's (HPC's) snow product (Figure 4.15). Users could derive value from this product, but many are unlikely to be aware of it because it is not linked from the local forecast.

The local Area Forecast Discussion for the same region and time as in Figures 4.11 to 4.14 (not shown here) provides sophisticated users with additional insights into the forecast situation. For the March 5 snow event, the forecaster also prepared a simpler discussion, called a "regional synopsis" (Figure 4.16). The technical discussion gives useful additional information about the forecast situation, including the forecaster's insight into uncertainty. This includes mention of possible rain/snow mix and slush—potentially important information for a range of users—whereas the public text forecast (Figure 4.11) is only for "snow." The regional synopsis describes the coming event as a "mixed bag" (a phrase with unclear meaning) and uses "possible," this time to describe snow accumulations.



**This Afternoon:** Periods of snow. High near 35. Southeast wind around 10 mph. Chance of precipitation is 100%. New snow accumulation of 1 to 3 inches possible.

**Tonight:** Snow likely before midnight. Cloudy, with a low around 27. Southeast wind between 5 and 10 mph becoming calm. Chance of precipitation is 60%. New snow accumulation of around an inch possible.

**Monday:** Cloudy, then gradually becoming partly sunny, with a high around 36. North northwest wind between 5 and 10 mph.

**Monday Night:** Partly cloudy, then gradually becoming clear, with a low near 23. East northeast wind between 5 and 10 mph.

**Tuesday:** Mostly sunny, with a high around 43. South southeast wind between 5 and 10 mph.

**Tuesday Night:** A 40 percent chance of snow showers after midnight. Cloudy, with a low around 37.

**Wednesday:** A 30 percent chance of showers and thunderstorms. Cloudy, with a high near 49.

**Wednesday Night:** A chance of showers and thunderstorms. Cloudy, with a low around 45.

**Thursday:** A chance of showers and thunderstorms. Cloudy, with a high around 49.

**Thursday Night:** A chance of showers and thunderstorms. Cloudy, with a low near 43.

**Friday:** A chance of showers and thunderstorms. Cloudy, with a high near 54.

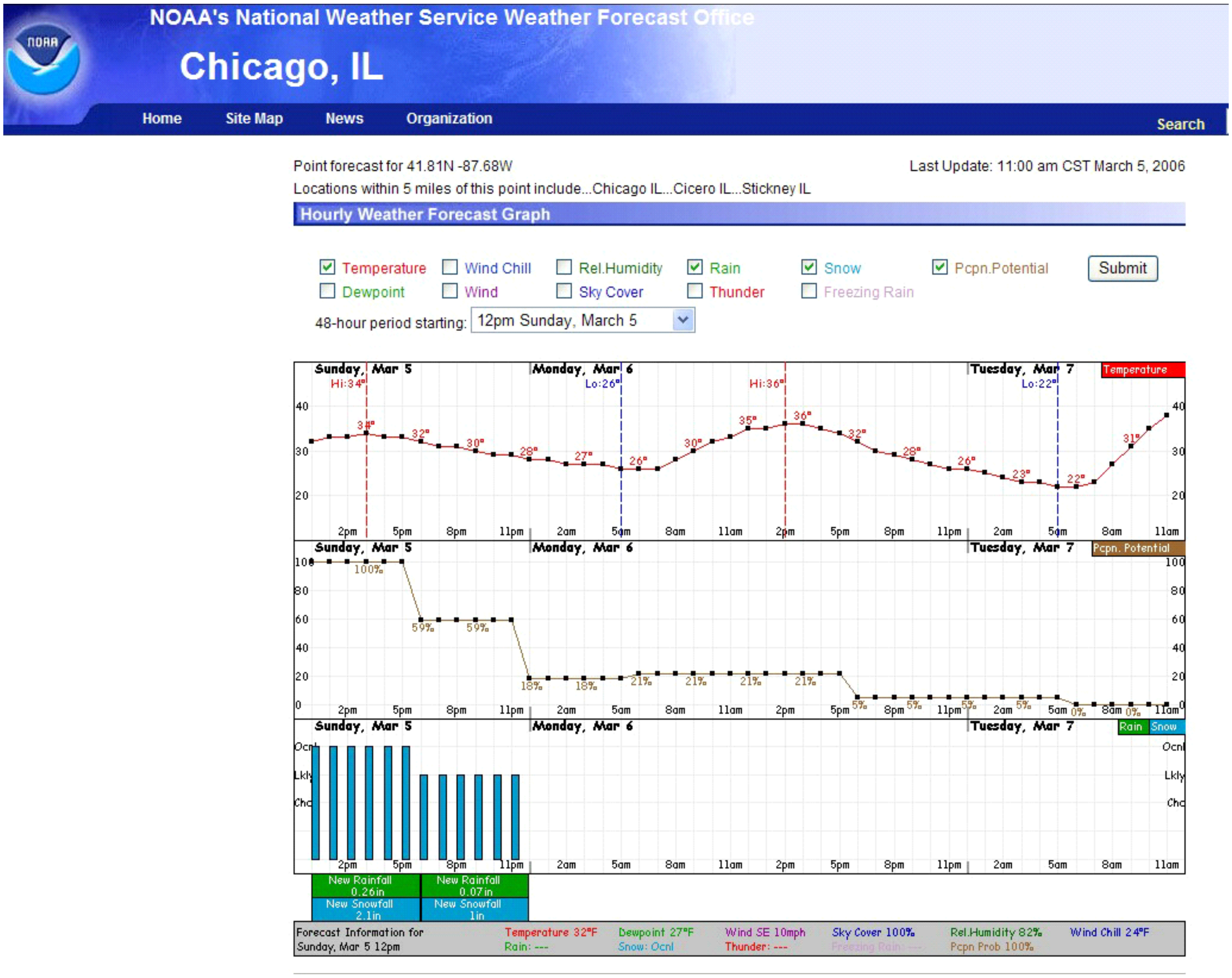
**Friday Night:** A chance of showers and thunderstorms. Partly cloudy and breezy, with a low around 40.

**Saturday:** Partly cloudy, with a high around 48.

FIGURE 4.11 Text forecast for Sunday, March 5 to Saturday, March 11, 2006. SOURCE: NWS.

*Continued*

## BOX 4.6 Continued



NOAA's National Weather Service Weather Forecast Office

Chicago, IL

Point forecast for 41.81N -87.68W

Last Update: 11:00 am CST March 5, 2006

Locations within 5 miles of this point include...Chicago IL...Cicero IL...Stickney IL

**Hourly Weather Forecast Graph**

☑ Temperature ☐ Wind Chill ☐ Rel.Humidity ☑ Rain ☑ Snow ☑ Pcpn.Potential
☐ Dewpoint ☐ Wind ☐ Sky Cover ☐ Thunder ☐ Freezing Rain

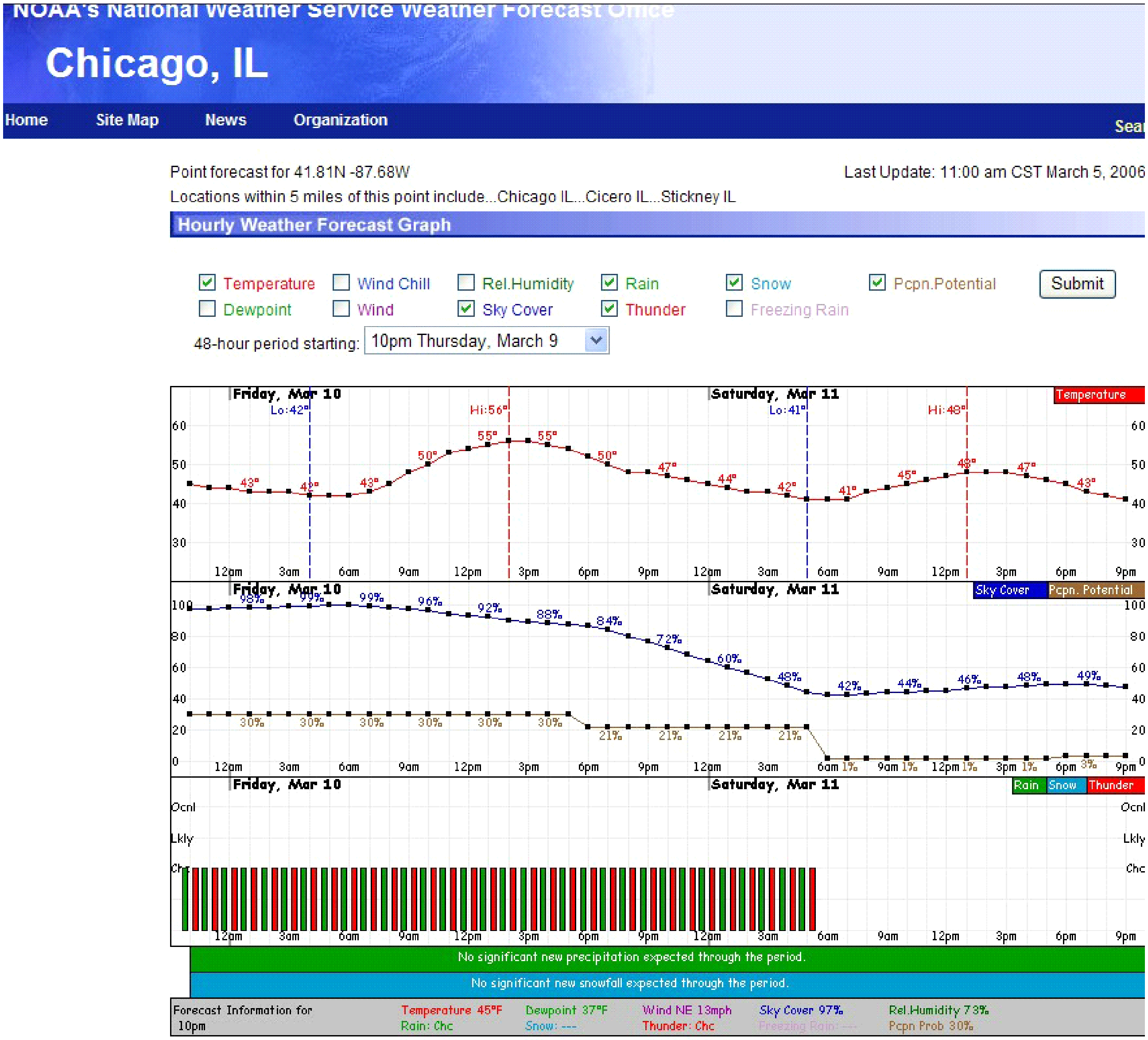
48-hour period starting: 12pm Sunday, March 5

New Rainfall 0.26in
New Snowfall 2.1in
New Rainfall 0.07in
New Snowfall 1in

Forecast Information for Sunday, Mar 5 12pm
Temperature 32°F
Rain: ---
Dewpoint 27°F
Snow: Ocnl
Wind SE 10mph
Thunder: ---
Sky Cover 100%
Freezing Rain: ---
Rel.Humidity 82%
Pcpn Prob 100%
Wind Chill 24°F

FIGURE 4.12 Hourly weather graph for Sunday, March 5 to Tuesday, March 7. SOURCE: NWS.

## BOX 4.6 Continued



Point forecast for 41.81N -87.68W

Last Update: 11:00 am CST March 5, 2006

Locations within 5 miles of this point include...Chicago IL...Cicero IL...Stickney IL

☑ Temperature ☐ Wind Chill ☐ Rel.Humidity ☑ Rain ☑ Snow ☑ Pcpn.Potential
☐ Dewpoint ☐ Wind ☑ Sky Cover ☑ Thunder ☐ Freezing Rain

48-hour period starting: 10pm Thursday, March 9

No significant new precipitation expected through the period.

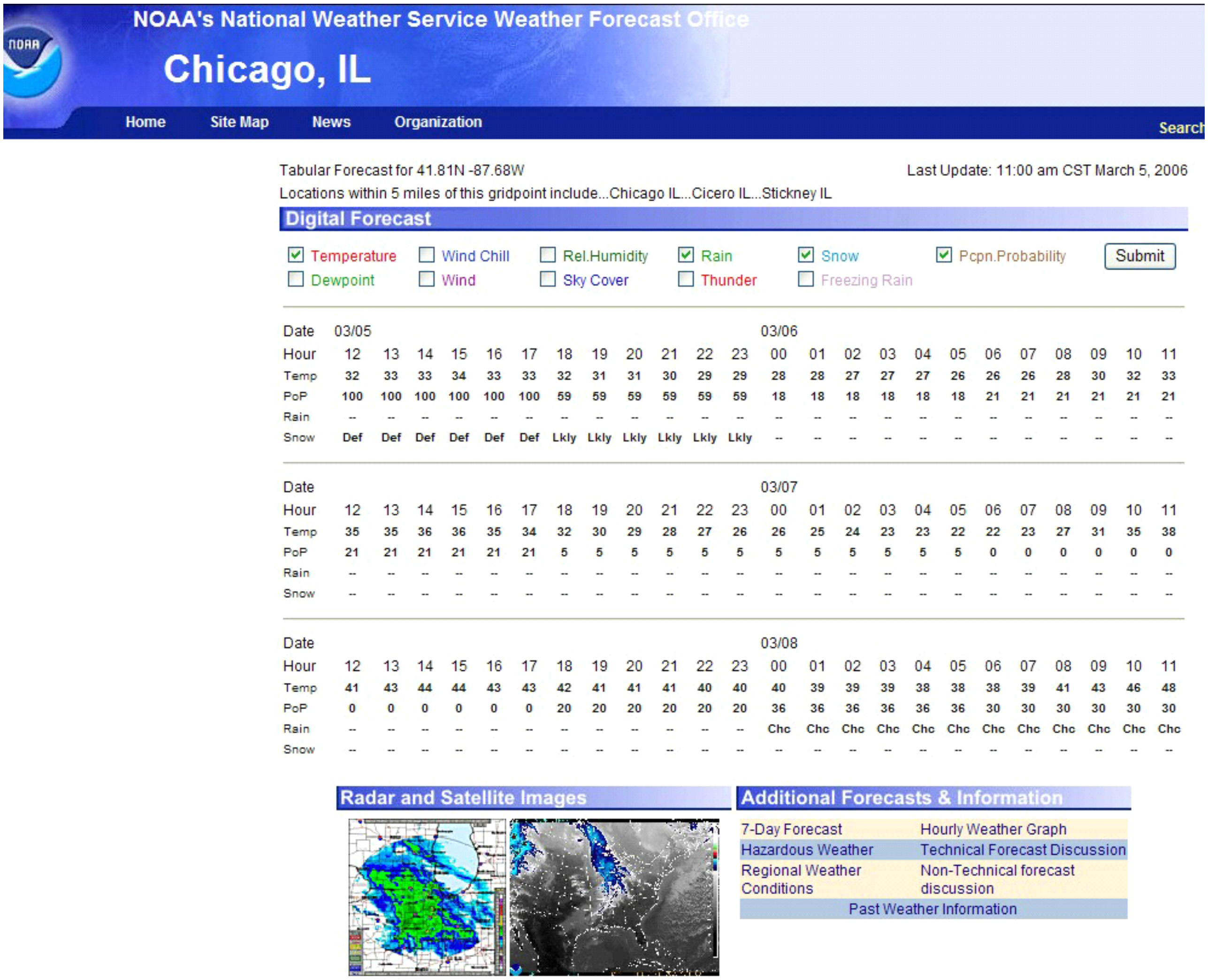
No significant new snowfall expected through the period.

Forecast Information for 10pm
Temperature 45°F
Rain: Chc
Dewpoint 37°F
Snow: ---
Wind NE 13mph
Thunder: Chc
Sky Cover 97%
Freezing Rain: ---
Rel.Humidity 73%
Pcpn Prob 30%

FIGURE 4.13 Hourly weather graph for Friday, March 10 to Saturday, March 11. SOURCE: NWS.

*Continued*

## BOX 4.6 Continued



NOAA's National Weather Service Weather Forecast Office

Chicago, IL

Tabular Forecast for 41.81N -87.68W
Last Update: 11:00 am CST March 5, 2006

Locations within 5 miles of this gridpoint include...Chicago IL...Cicero IL...Stickney IL

Digital Forecast

☑ Temperature ☐ Wind Chill ☐ Rel.Humidity ☑ Rain ☑ Snow ☑ Pcpn.Probability Submit
☐ Dewpoint ☐ Wind ☐ Sky Cover ☐ Thunder ☐ Freezing Rain

| Date | 03/05 | | | | | | | | | | | | 03/06 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 |
| Temp | 32 | 33 | 33 | 34 | 33 | 33 | 32 | 31 | 31 | 30 | 29 | 29 | 28 | 28 | 27 | 27 | 27 | 26 | 26 | 26 | 28 | 30 | 32 | 33 |
| PoP | 100 | 100 | 100 | 100 | 100 | 100 | 59 | 59 | 59 | 59 | 59 | 59 | 18 | 18 | 18 | 18 | 18 | 18 | 21 | 21 | 21 | 21 | 21 | 21 |
| Rain | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Snow | Def | Def | Def | Def | Def | Def | Lkly | Lkly | Lkly | Lkly | Lkly | Lkly | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

| Date | | | | | | | | | | | | | 03/07 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 |
| Temp | 35 | 35 | 36 | 36 | 35 | 34 | 32 | 30 | 29 | 28 | 27 | 26 | 26 | 25 | 24 | 23 | 23 | 22 | 22 | 23 | 27 | 31 | 35 | 38 |
| PoP | 21 | 21 | 21 | 21 | 21 | 21 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 0 | 0 | 0 | 0 | 0 | 0 |
| Rain | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| Snow | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

| Date | | | | | | | | | | | | | 03/08 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hour | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 |
| Temp | 41 | 43 | 44 | 44 | 43 | 43 | 42 | 41 | 41 | 41 | 40 | 40 | 40 | 39 | 39 | 39 | 38 | 38 | 38 | 39 | 41 | 43 | 46 | 48 |
| PoP | 0 | 0 | 0 | 0 | 0 | 0 | 20 | 20 | 20 | 20 | 20 | 20 | 36 | 36 | 36 | 36 | 36 | 36 | 30 | 30 | 30 | 30 | 30 | 30 |
| Rain | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | Chc | Chc | Chc | Chc | Chc | Chc | Chc | Chc | Chc | Chc | Chc | Chc |
| Snow | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |

Radar and Satellite Images

Additional Forecasts & Information

| | |
|---|---|
| 7-Day Forecast | Hourly Weather Graph |
| Hazardous Weather | Technical Forecast Discussion |
| Regional Weather Conditions | Non-Technical forecast discussion |
| Past Weather Information | |

FIGURE 4.14 Digital IFPS forecast product for Sunday, March 5 to Wednesday, March 8. SOURCE: NWS.

## BOX 4.6 Continued

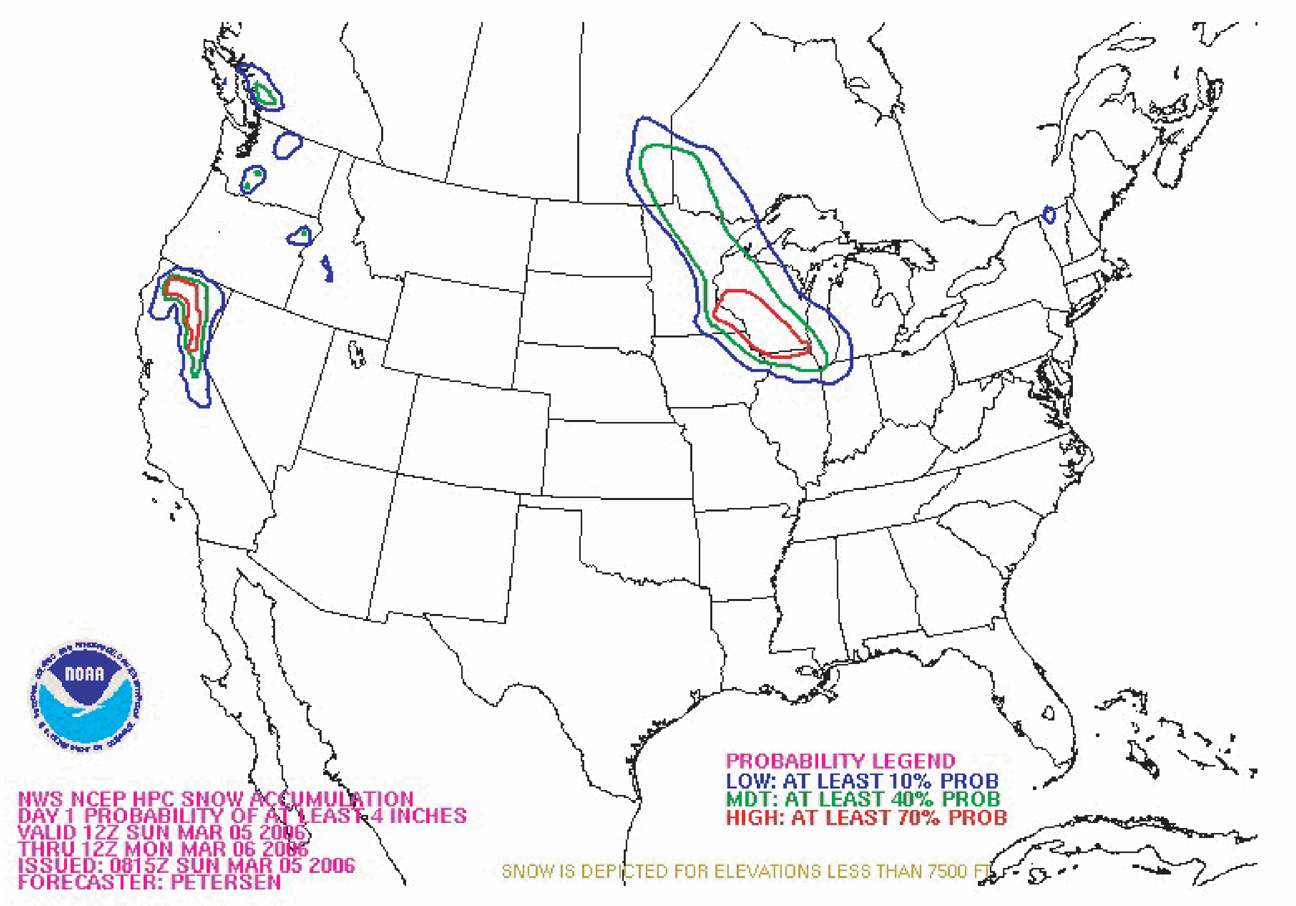
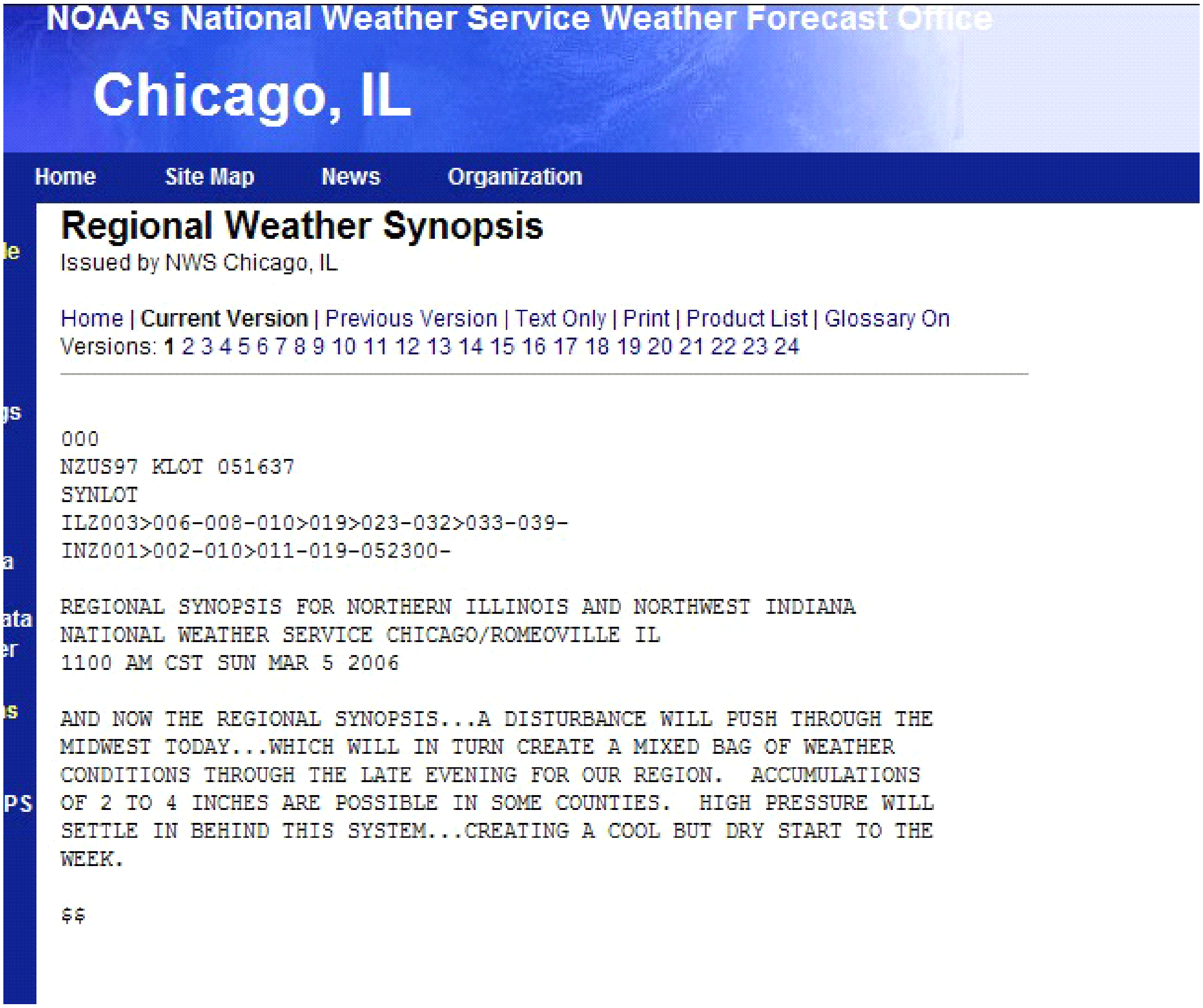


FIGURE 4.15 Probability of snow accumulation. SOURCE: NWS Hydrometeorological Prediction Center.

*Continued*

## BOX 4.6 Continued



**Regional Weather Synopsis**

Issued by NWS Chicago, IL

```
000
NZUS97 KLOT 051637
SYNLOT
ILZ003>006-008-010>019>023-032>033-039-
INZ001>002-010>011-019-052300-

REGIONAL SYNOPSIS FOR NORTHERN ILLINOIS AND NORTHWEST INDIANA
NATIONAL WEATHER SERVICE CHICAGO/ROMEOVILLE IL
1100 AM CST SUN MAR 5 2006

AND NOW THE REGIONAL SYNOPSIS...A DISTURBANCE WILL PUSH THROUGH THE
MIDWEST TODAY...WHICH WILL IN TURN CREATE A MIXED BAG OF WEATHER
CONDITIONS THROUGH THE LATE EVENING FOR OUR REGION.  ACCUMULATIONS
OF 2 TO 4 INCHES ARE POSSIBLE IN SOME COUNTIES.  HIGH PRESSURE WILL
SETTLE IN BEHIND THIS SYSTEM...CREATING A COOL BUT DRY START TO THE
WEEK.

$$
```

FIGURE 4.16  Regional synopsis for northern Illinois and northwest Indiana, Sunday, March 5. SOURCE: NWS.

and weaknesses of each new communications platform, with respect to conveying uncertainty information, and to optimize the strengths and minimize the weaknesses. For example, cell phones and PDAs have a limited capacity for receiving and conveying information; nonetheless, their usage continues to expand and bandwidth limitations will be reduced. Thus, a strategic approach to utilizing these and other evolving technologies is to recognize the current limitations, track the actual and potential evolution of these technologies, and, most importantly, identify and tailor communications products for them because they enable broad and rapid dissemination of uncertainty information. As the Enterprise considers the incorporation of uncertainty information into products, these opportunities and challenges will have to be understood and incorporated into the product development processes. Finally, even as more—and soon the majority of—forecast uncertainty information is provided to users through "new" media, NWS and the Enterprise will still need to serve users who receive their forecasts through long-standing "traditional" media including television, newspapers, and radio.

The dramatic recent increase in Internet usage has also changed how NWS and Enterprise disseminate forecast information. For example, the Enterprise now routinely conveys complex forecasts and supporting information, including graphical and visual information, through the Internet (e.g., Box 4.5). Indeed, NOAA and NWS home pages and information sites are already the most frequently visited government sites on the Internet.[4] Looking ahead, Internet technology could help NWS meet the needs of both specialist and nonspecialist users alike by allowing individual users to select the format and detail of uncertainty information most appropriate for them. Such technology could also help disseminate the increased amount of forecast uncertainty information. For example, the NWS home page could present limited, relatively simple uncertainty information, such as forecaster confidence, high/low temperature ranges, and PoP and precipitation type, with a one-sentence summary of the weather situation. Visitors to the site could have the option to click on the basic information to view graphics that give more detailed uncertainty information about different aspects of the forecast situation, a text discussion of the uncertainty in the forecast situation, and so on. In addition, the information could be viewed in different presentations (e.g., as a map, as a graph of temporal evolution at one location, or as a pdf at one location and time). Additional "clicks" would allow specialist visitors to drill down to obtain more detailed uncertainty information or to download digital information that they could incorporate into their own analyses or value-added products. Such a capability would be facilitated by the development of a database of uncertainty information, such as the National Digital Guidance Database (Chapter 3) and the modifications to IFPS proposed in recommendation 4.1.

### 4.3.4 The Role of the Traditional Media

The majority of weather information in the United States is communicated to users through intermediaries, particularly the media industry. This industry is composed of two parts—the new media (e.g., Internet, cell phones, pagers, bugs) and the traditional media (e.g., television, radio, newspapers). Weather forecasts and products are one of the primary sources of "hits" and "page views" on the Internet, and although weather information on the Internet and other new media continues to rapidly expand, television (including cable) is still the public's primary source of weather information.

The media industry as a whole can be considered both "gatekeeper" and a principal partner with NWS in the communication of forecasts, warnings, and uncertainty information. As such, intermediaries, and specifically the media, play a critical role in communicating forecast uncertainty and addressing the challenges presented in doing this effectively. To fully understand the implications of this situation, it is helpful to understand the business fundamentals of the media industry.

The vast majority of the revenue generated in media comes from advertising. Advertisers pay to have their message seen by as many potential customers as possible. Advertisers also pay a premium to have their message delivered to certain "target" customers. When the media communicates hydrometeorological information, the quality of the information content itself is only one of several factors affecting the recipient's overall perception of quality of the product. Other environmental components that directly affect audience attraction and retention include the personalities presenting the information, the aesthetics of the visuals, and the effectiveness of promotion.

The media industry is also highly competitive. Advertising budgets are limited and any advantage can make a critical difference in where those dollars are spent and the profitability of media entities. Similarly, any disadvantage is often very costly. Including uncertainty information in a forecast may be viewed by some media industry managers and advertisers as a demonstration of weakness, hedging, lack of credibility, or lack of skill instead of as providing a better, scientifically sound, and more useful product. In fact, this is probably one of the main drivers of what might be called the "pretend determinism" that exists in many media presentations today. On the other hand, savvy media entities could regard the inclusion of uncertainty information in forecasts as a competitive advantage.

Changing this deeply embedded legacy will be difficult and require significant time and determination. Nonetheless, there is basis for hope. For example, the news media adopted the hurricane cone of uncertainty (Figure 1.6), which dramatically illustrates uncertainty in the hurricane track forecast, not long after NWS's Tropical Prediction Center developed it. Similarly, many media presentations now include the

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[4] Jack Kelly, NOAA, in presentation at AMS Annual Conference, 2006.

### BOX 4.7
### Probability of Precipitation

PoP forecasts have been provided for several decades and are an example of uncertainty forecasts that the public and other users have accepted and used. The public's understanding of the technical meaning of the forecasts has been debated for years, yet the public does appear to understand PoP sufficiently well to find it useful (Murphy et al., 1980; Gigerenzer et al., 2005; NOAA Technical Memorandum NWS AR-44). Numerous presenters of forecasts to the public have found that whereas news management may want simple deterministic pronouncements, the public does use the PoP in their decision-making process.

PoP (Box 4.7) within text or graphics as they have found users find the probability useful to their decision making even though they may not understand exactly the correct definition of "PoP." Products that effectively communicate uncertainty will be adopted by the media and advance the public understanding of uncertainty and utility in decision making. Effective and ongoing partnerships between the media and other parts of the Enterprise, along with education of the public and the media, will be critical for acceptance of uncertainty by the user community. NWS is positioned to catalyze this process.

## 4.4 ROLE OF USERS IN THE PRODUCT DEVELOPMENT PROCESS

The shift from a deterministic to a probabilistic approach to communicating forecasts represents such a fundamental change in the presentation of information that user perceptions and opinions will be needed throughout the product development process. Thus, it is important to consider venues for user consultation by NWS, the approach to product development at NWS, and ways in which collaboration with users could be improved.

The need for attention to user interaction on product development is recognized in several earlier NRC reports. In *A Vision for the National Weather Service: Road Map for the Future* (1999b), the NRC recommended that NWS "routinely examine and anticipate the needs of primary customers and ultimate users." In *Making Climate Forecasts Matter* (1999c), the NRC emphasized that there was a need "to bring scientific outputs and users' needs together," specifically through the use of surveys and structured discussions. In *Fair Weather: Effective Partnerships in Weather and Climate Services* (2003a), NRC recommended that NWS establish an independent advisory committee to gather feedback from users, representing all sectors, on weather and climate matters. Discussions within NOAA on this option are under way.

NWS uses a variety of mechanisms for interacting with users and getting feedback on its products. These include formalized workshops and local meetings with public officials, emergency managers, the media, and other weather-sensitive groups. In addition, and usually at the local level, direct informal one-on-one communications take place. For example, NWS staff at the Weather Forecast Offices or Regional Forecast Centers (RFCs) work regularly and directly with users, especially larger customers.

Other venues for user interaction are national meetings of professional organizations (e.g., the American Meteorological Society), annual NWS partner meetings, NOAA data and information user workshops, and annual meetings of target user communities (e.g., the space weather community[5]). Such interactions can also lead to new forecast uncertainty products; for example, a new probabilistic seasonal forecast product originated from six user workshops held at the RFCs during 1994.[6]

In addition, NWS gathers user feedback through its Web pages and through Customer Satisfaction Surveys. Although such feedback does provide a snapshot of user issues, such surveys may be insufficient to fully understand and address user needs because they may lack detail, may not be a representative sample, and may not be designed to develop a thorough understanding of how to more effectively communicate uncertainty information. Such surveys are not a substitute for formal research or for effectively collaborating with users (Chapter 2).

Last, NWS has stated[7] that it can collect user advice through the NOAA Science Advisory Board (SAB) and the NRC (e.g., this committee). However, neither SAB nor NRC can provide the dedicated, continuous, and long-term forum that user interaction deserves. In addition, SAB may not be the appropriate venue for dealing with the details and nuances of forecast uncertainty information and how it is presented and disseminated.

Although NWS uses a range of mechanisms for gathering user perspectives, these perspectives are not formally or consistently sought throughout the product development process. New products can appear to users to be more technologically driven than scientifically or user driven. NWS's policy for developing new and enhanced products and services is given by NWS Directive 10-102 (approved August 28, 2002; Box 4.8).[8] The NOAA Partnership Policy (Box 1.3) also bears directly on the product development process.

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[5] Kent Doggett presentation, September 21, 2005.

[6] Ed O'Lenic presentation, August 4, 2005.

[7] In its response to a set of questions from the committee.

[8] Of note, NWS exempts numerical prediction guidance products from Directive 10-102.

Although Directive 10-102 discusses user needs and requires user feedback, it does not require or discuss sustained feedback from the broader Enterprise from the earliest stage of the product development process. In the first stage, new or amended NWS products can be proposed at any level within NWS. These products must solely meet a requirement of mission connection to NWS. The subsequent experimental phase involves customer feedback and comment on preferences, but does not include objective evaluation of how the product will be interpreted by different users, or how users might make better decisions using the product. Evaluation of NWS products is largely conducted by outside survey organizations that seek to measure customer satisfaction (which may not necessarily mean understanding of or best decision making with the product, especially with respect to communicating uncertainty; Chapter 2). In addition, and with the recent exception of a product developed in the Hydrologic Services Division,[9] products are rarely scientific evaluated from perspectives outside the atmospheric and related physical sciences (e.g., by social scientists) prior to product implementation. In fact, social science expertise within NOAA is presently underutilized.[10]

**Finding:** The official NWS process for developing new products does not formally engage the user throughout the product development process. Rather, it seeks feedback when the product already has gained significant momentum. Moreover, the feedback obtained often fails to rigorously and comprehensively evaluate the product's effectiveness.

**Recommendation 4.5: NWS should extend NWS Directive 10-102 to require collaboration with users on product development throughout the development process. Moreover, users' comprehension and interpretation of products should be formally evaluated at several stages during the product development process.**

Processes for collaborating with users throughout the product development process will need to accommodate the complexities involved in disseminating and communicating forecasts to a wide variety of users, and how those users incorporate forecasts into their decision making. Such complexities highlight the need for a rigorous and sustained effort that draws on a broad range of expertise, including from the social sciences. These complexities, for example, include users being reached directly or through intermediaries who add value to NWS products; the diversity in technical sophistication and ability to utilize products among users; and the constant evolution of technology and user needs, as well as the user population itself.

## BOX 4.8
## NWS Directive 10-102

NWS Directive 10-102 describes in detail the process of, and framework for, developing a new product or service or changing an existing one, including the development of an internal Product/Service Description Document (PDD). The directive requires internal sponsors of a new product to discuss its intended use and audience; its Appendix B states that "[n]ew products should be developed to satisfy valid user needs/requirements." The directive also discusses seeking external review and comment upon proposed products and services, stating that "NWS will seek ongoing user feedback on official [operational] products." Moreover, the directive dictates that NWS will include a feedback statement with each product (one that identifies an actual person responsible for collecting feedback) or otherwise provide a feedback notice to the public.[a] Feedback must be reviewed at least annually.

The procedures outlined in Directive 10-102 clearly mandate the involvement of users in *product* development, depending, of course, on how well this directive is actually implemented in practice. It does not, however, require or even mention the involvement of users in *concept* development; rather, users are not formally involved in new product development until the experimental stage, when a product is nearly complete. Further, the PDD itself, the key document that initiates the product development process within NWS, does not require any user input or external review.

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[a] Feedback can also be collected via an Office of Management and Budget-approved customer survey included as an appendix to Directive 10-102.

Fortunately, there are several examples where units of NWS have worked, or are working, effectively with users. These efforts could serve as models as NWS refines its product development process. Possible case studies include the development of the AHPS, the NWS Regional Climate Services (for example, in the Central Region), and the Regional Integrated Sciences and Assessment (RISA) program (e.g., the RISA in Arizona). There are also many models to draw from outside NWS—at public institutions (e.g., the NCAR-RAL partnerships with the Federal Aviation Administration and Federal Highway Administration) and in the private sector.

## 4.5 RESEARCH AND DEVELOPMENT PROGRAM TO IMPROVE COMMUNICATION OF FORECAST UNCERTAINTY

Without a stronger knowledge base, NWS and broader Enterprise efforts to improve communication of forecast

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[9] Information provided to the committee by NOAA describes recent efforts by the NWS Hydrologic Services Division to engage users, communicators, and outside expertise at the initial stage of product development.

[10] Presentation by Rodney Weiher to the NOAA SAB, March 2006.

uncertainty will be inefficient and perhaps ineffective. A sustained research and development program to improve communication of uncertainty in hydrometeorological forecasts is therefore needed (see also recommendation 4.4). Research on communicating uncertainty is ongoing in many disciplines and sectors outside NWS. For example, there is a body of knowledge about communication of uncertainty and risk in weather, climate, and hydrology, as well as in areas such as medicine and natural and technological hazards (see Chapter 2). Much of the existing research identifies "don'ts" and important factors to consider when communicating uncertainty. Yet many questions remain unanswered, particularly about how to better communicate uncertainty ("dos"), how to do so in the hydrometeorological forecasting arena, and how to do so in ways that meet different users' needs.

The topic of communicating uncertainty is broad, including all sectors of the Enterprise, and there are many important research questions to be addressed. Moreover, the forecast and communication environments are continuously evolving. Thus, rather than identify specific prioritized research questions, the committee recommends a process for NWS, in partnership with the Enterprise and others, to identify and address key research questions. Examples of possible initial directions include understanding (1) the needs of users for uncertainty information and incorporating these needs into communication techniques; (2) how to effectively partner with the media and other intermediaries to improve uncertainty communication; (3) whether, when, and how to communicate uncertainty in short-term warnings for hazardous weather-related events; (4) what is the relative effectiveness of communicating uncertainty in different ways to users (e.g., as forecast confidence versus different forms of probabilistic forecasts); and (5) how to effectively design icons and other visual tools.

To select research directions and develop them into focused research and development efforts, NWS will need to partner with members of the academic, public, and private sectors on a regular basis to survey existing knowledge, specify priority areas, and develop implementation strategies. One mechanism for doing so is through testbeds (see Chapter 3). To gather a full picture of existing knowledge and needs within NWS, the process of selecting and developing research directions will benefit from communication between NWS headquarters, national centers, and regional and local offices.

A key component of this broad program is for NWS to acquire core in-house expertise in relevant social sciences (recommendation 2.4). This in-house expertise is needed to (1) conduct research, particularly in response to short-term needs; (2) help NWS identify priority research questions and appropriate methods for answering them; (3) help NWS identify and engage relevant external social science or other expertise; and (4) assist with product development. In addition, there is a large external community, particularly in academia, with relevant expertise that could significantly advance this effort. Because most of these researchers rely on funding support, they tend to focus on topics for which more funding is available. One way, then, to engage the academic research community in helping NWS and the Enterprise as a whole improve communication of uncertainty is to draft Requests for Proposals (RFPs) on questions of overlapping interest. These RFPs could be developed and put out by NWS/NOAA on its own, or to leverage additional funding to address research questions of mutual interest, through NWS/NOAA partnerships with other entities. For example, questions that have fundamental as well as applied aspects might be addressed through joint efforts with the National Science Foundation (in addition to linking with the private sector), whereas questions that focus on communication with specific user groups served by NWS might best be addressed through joint efforts with other federal mission agencies, also in partnership with the private sector as appropriate. Other mechanisms for NWS and the Enterprise to put relevant questions about uncertainty communication on the national and international social science agendas include funding visiting scientist programs, student internships, and dissertation and post-doctoral fellowships. Such programs can also train future researchers in this area and train future forecasters and users in key aspects of uncertainty communication. In all, because of the complex, interdisciplinary nature of the topic, this research and development effort will need to employ a mix of strategies to be successful and enduring.

Questions on communication of uncertainty in areas beyond hydrometeorological forecasting are of critical interest to a variety of communities, both within the Enterprise and more broadly. Thus, NWS interests in this area have significant overlap with a number of other entities across society. This has several implications. First, there are groups already studying and implementing more effective communication of uncertainty that NWS will benefit from engaging. Second, there are ample opportunities for NWS to partner with other groups in developing and implementing joint initiatives, leveraging available funding. Third, the results of a program on communication of forecast uncertainty can be used in other areas of risk communication such as medicine, terrorism, and other disasters.

Last, methods of communicating hydrometeorological uncertainty are being explored or implemented in several other countries (see examples in Annex 4). In developing and testing methods for uncertainty communication, NWS will benefit from regular consultation with foreign hydrometeorological services to share experiences and lessons learned. From a global perspective, the World Meteorological Organization (WMO) can be a useful venue for international dialog on experiences with communication of uncertainty, research initiatives, and "best practices." In addition, WMO has training programs for weather presenters and communicators in many developing countries. Effective communication of forecast uncertainty, built on international dialog on such matters (perhaps led by NWS and the U.S. permanent representative to WMO), could help regions with weather risks worldwide.

## 4.6 EDUCATION AND TRAINING NEEDS

The research and development aspects of communicating uncertainty will include and lead to education and training of all parties participating in generating, communicating, and using hydrometeorological forecasts. Here "education" is used in a broad sense and involves communication, understanding, and learning.

Implementation of this report's recommendations will change how the Enterprise operates and will lead to adoption of new forecast techniques, products, and communication tools by all sectors. But this will only happen if all Enterprise partners are actively involved in "turning the ship" and are working in a mutually supportive framework. Education initiatives will need a strong commitment by all sectors of the Enterprise and include a wide variety of participants—from elementary school teachers and students to emergency managers, media managers, and communicators. Such initiatives include undergraduate education of future hydrometeorological professionals and continuing education and training of all who communicate hydrometeorological information and forecasts (especially those working in the media). And these initiatives will rely on a two-way interaction that involves effectively communicating new information while also soliciting feedback to further improve communication and understanding.

Most forecasters begin their education in an undergraduate program such as a meteorology program. Current standards for undergraduate meteorology programs established by the federal government and the American Meteorological Society (Smith and Snow, 1997) have no requirement to cover uncertainty, use of probabilistic information, and how forecast-related information is used in decisions. Without this material in their curriculum, many meteorology students are not adequately prepared for future careers in generating, communicating, or using hydrometeorological foreasts that include uncertainty information.

Training courses are a critical vehicle for forecasters' continuing education, once they have graduated. These courses convey the latest insights and techniques that enhance forecast generation and communication. Such courses could deliver relevant information and training on communicating uncertainty information. With respect to the training component, academia and government laboratories could partner on developing coursework that addresses forecast uncertainty.

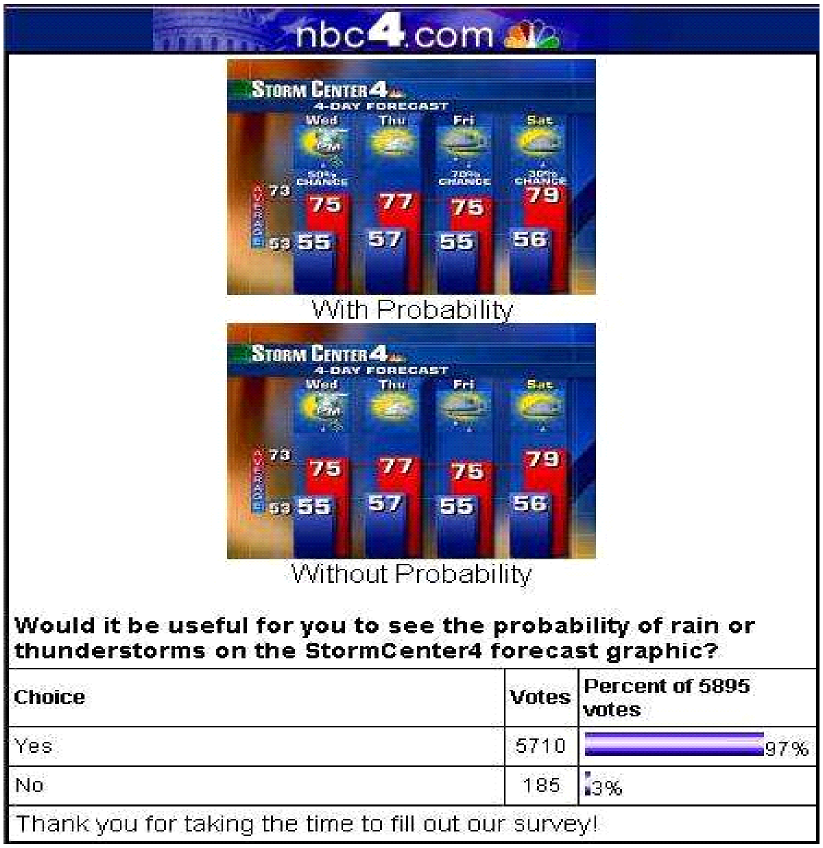
A hydrometeorological forecast is often only one piece of a broader spectrum of information being integrated into a decision (Chapter 2). As the human role in conveying probabilistic forecast information becomes increasingly focused at the interface between forecast systems and user decisions (e.g., functioning as the "science integrator" who takes what is known about the science and communicates it to decision makers), academic and other training programs will need to adjust their content accordingly. This adjustment may entail adding material into existing courses or by offering elective courses that focus on communication, probability, and decision issues facing weather- or climate-sensitive decision makers.

Because members of the public receive most of their forecasts from the media, the media will play a critical role in helping the public understand and use new uncertainty products. Take, for example, PoP forecasts (Box 4.7). The value derived from PoP forecasts is in no small part due to the long-term efforts of the Enterprise, especially media meteorologists and weathercasters, in educating users about PoP. Even if many members of the public do not know the exact meteorological definition of PoP, many still consider this uncertainty information useful (e.g., Figure 4.17). The broad familiarity with the hurricane track probability forecast (Section 4.3.4) is another case in which the media played a critical role in facilitating acceptance of an uncertainty product and educating the public about its meaning. Including probabilities within the cone presents an opportunity for improving public understanding of uncertainty forecasts.

## SUMMARY

Even the "best" uncertainty information will not serve its ultimate purpose—helping users make better decisions that enhance socioeconomic value—unless that information is effectively communicated. Although a variety of forecast uncertainty products are available from NWS and others in the Enterprise, some of these products do not communicate uncertainty as effectively as they could. Moreover, most publicly available forecast products often communicate little or no uncertainty information. Changing from the current paradigm of primarily deterministic forecast communication will be a major shift, requiring a concerted, coordinated effort by NWS in partnership with others in the Enterprise.

The use of uncertainty information in decision making is complex. Learning to communicate uncertainty effectively will therefore require consideration of three factors. First, effective communication must incorporate an understanding of user needs for uncertainty information and how users will apply it. Such understanding must be based on social science research and close interactions with users starting early in the product development process. Second, effective communication requires considering and preventing potential user misunderstanding and confusion that can result from inconsistent communication and ineffective use of uncertainty language and graphics. Third, effective communication of uncertainty requires understanding the key roles that dissemination mechanisms and technologies and the media play in conveying forecasts. This chapter provides several recommendations to help NWS and the Enterprise shift to a new paradigm of clear, effective communication of forecast uncertainty that is consistent with scientific understanding



**Would it be useful for you to see the probability of rain or thunderstorms on the StormCenter4 forecast graphic?**

| **Choice** | **Votes** | **Percent of 5895 votes** |
|---|---|---|
| Yes | 5710 | 97% |
| No | 185 | 3% |

Thank you for taking the time to fill out our survey!

FIGURE 4.17 TV/Internet survey results of the user utility of PoP in graphic forecasts. SOURCE: Courtesy of NBC Universal. Any reuse of this material requires the express written consent of NBC Universal.

of the atmosphere and hydrosphere and knowledge of how uncertain information is used in decision making. These include developing comprehensive education and training efforts and a dedicated, long-term research and development program to improve uncertainty communication in hydrometeorological forecasts.

## ANNEX 4
## EXAMPLES OF UNCERTAINTY COMMUNICATION APPROACHES AND PRODUCTS

This Annex presents examples of the range of uncertainty communication approaches and products. The committee sought examples from a variety of sources, including NWS management and individuals from NWS, other government agencies, the private sector, and academia. These examples included operational, experimental, and proposed products, primarily from weather, climate, and hydrological forecasting, but also from other fields.

Maps are useful for communicating spatial distributions of forecasted variables and their uncertainty. They can represent forecasts at a specific time, over a specific period, or as a coherent weather feature (such as a hurricane or winter storm) evolves and moves. One way of using maps to communicate forecast uncertainty is to portray the spatial distribution of the likelihood of an event (e.g., tornado) or of a parameter exceeding a specified threshold (e.g., precipitation greater than one inch). Figure 4A.1 shows two examples, one containing numerical probabilities and the other containing qualitative likelihoods.

A second way of using maps to communicate forecast uncertainty is to portray the spatial distribution of minimum/mean/maximum expected (or 10/50/90 percent exceedance) values of a parameter (Figure 4A.2). Maps can also be used to portray the likelihoods of different scenarios in different regions (Figure 4A.3). Another method of communicating uncertainty using maps is to overlay a map of mean or expected values with a map of uncertainty or confidence (Figure 4A.4).

The example maps above primarily use contours to represent values. When values are depicted using numbers or other symbols, uncertainty can be portrayed using different symbol sizes or colors (Figure 4A.5).

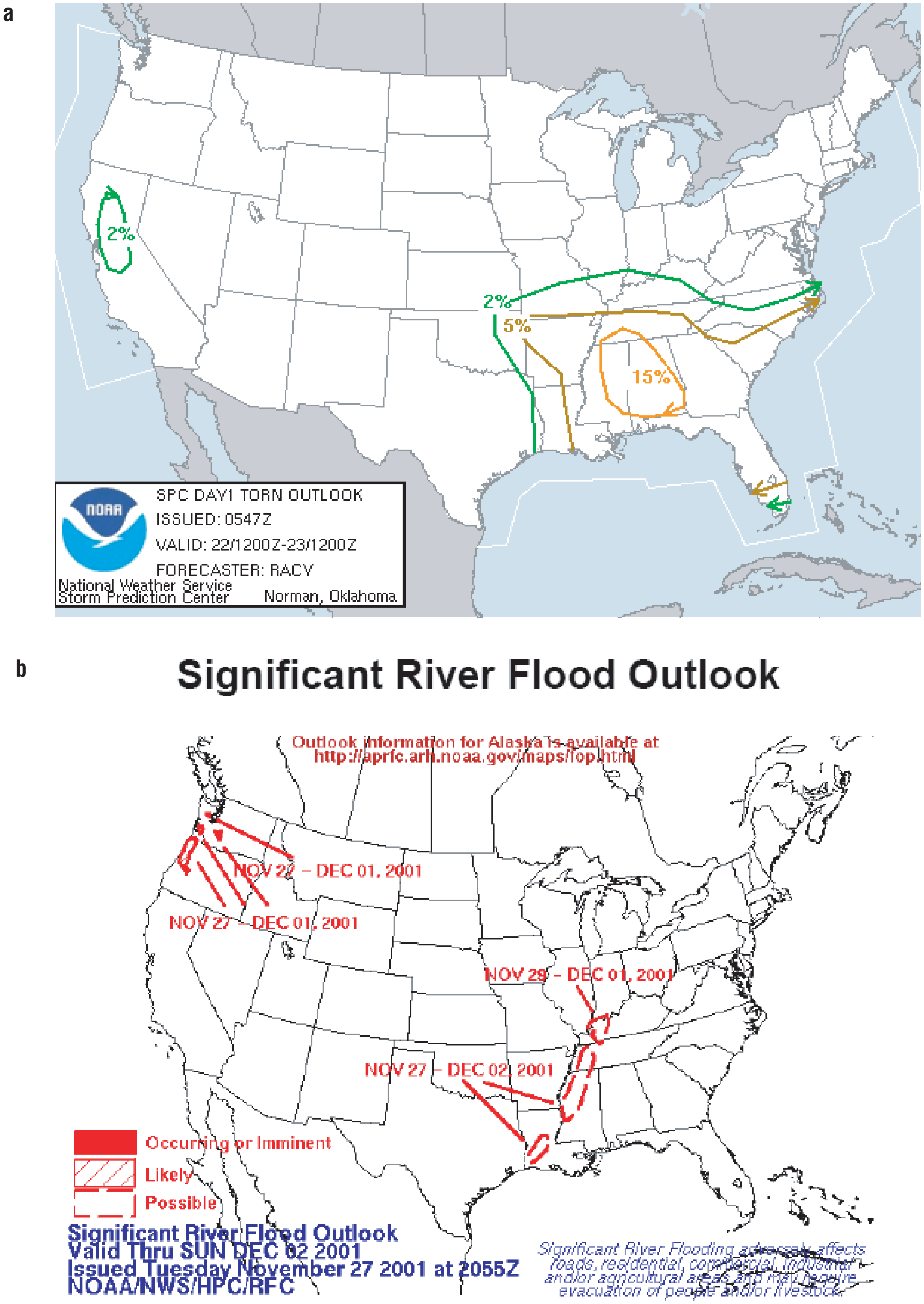


FIGURE 4A.1 (a) Forecast of tornado probabilities at different locations (SOURCE: Operational NWS product generated by SPC). 4A.1 (b) Forecast of likelihood of significant river flooding at different locations. SOURCE: Operational NWS product generated by HPC.

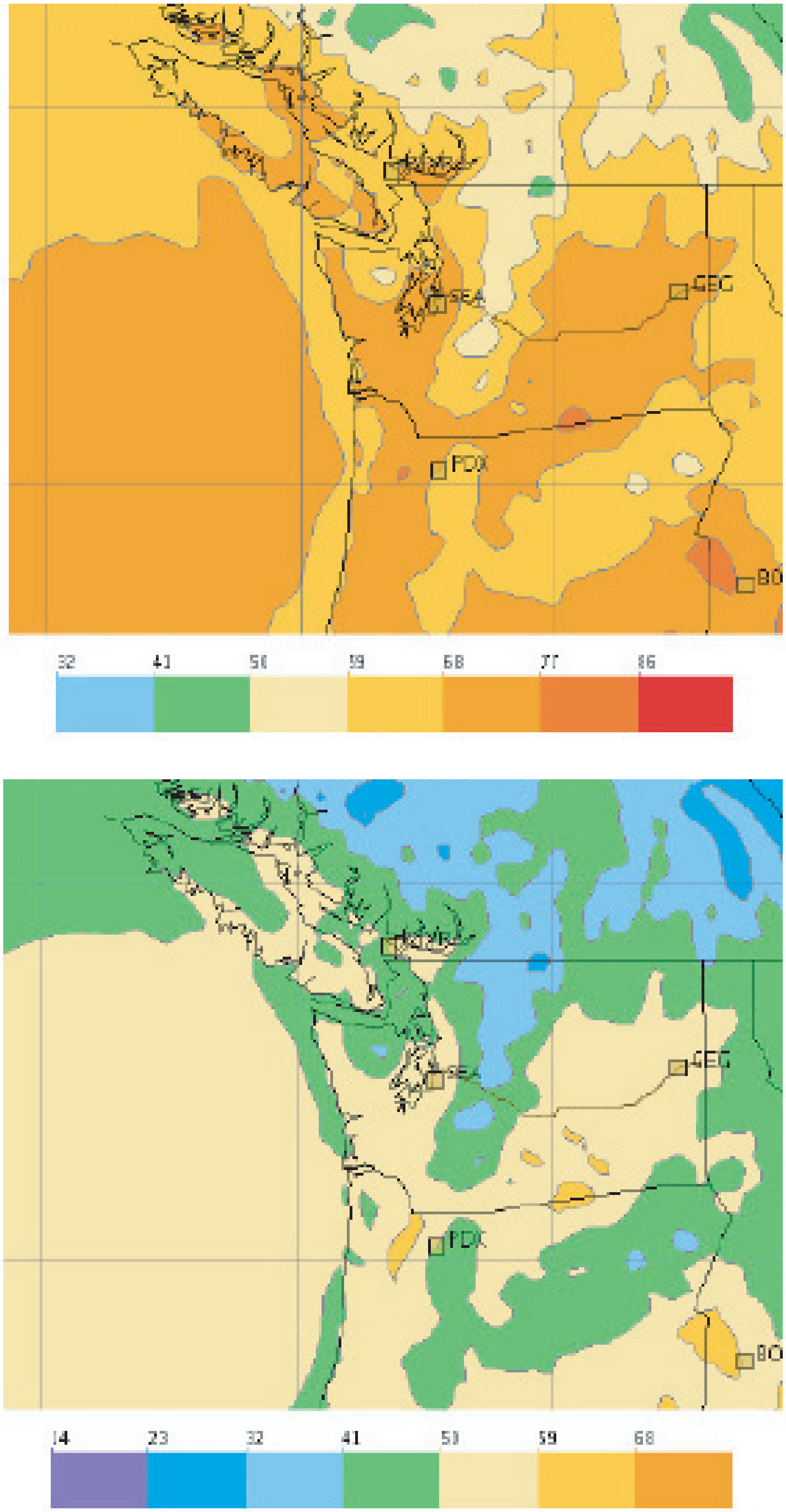


FIGURE 4A.2 Upper bound (90 percent exceedance) and lower bound (10 percent exceedance) 48-hour forecasts of temperature at 2 m in the northwestern United States. SOURCE: MURI research group at University of Washington, http://www.stat.washington.edu/MURI/.

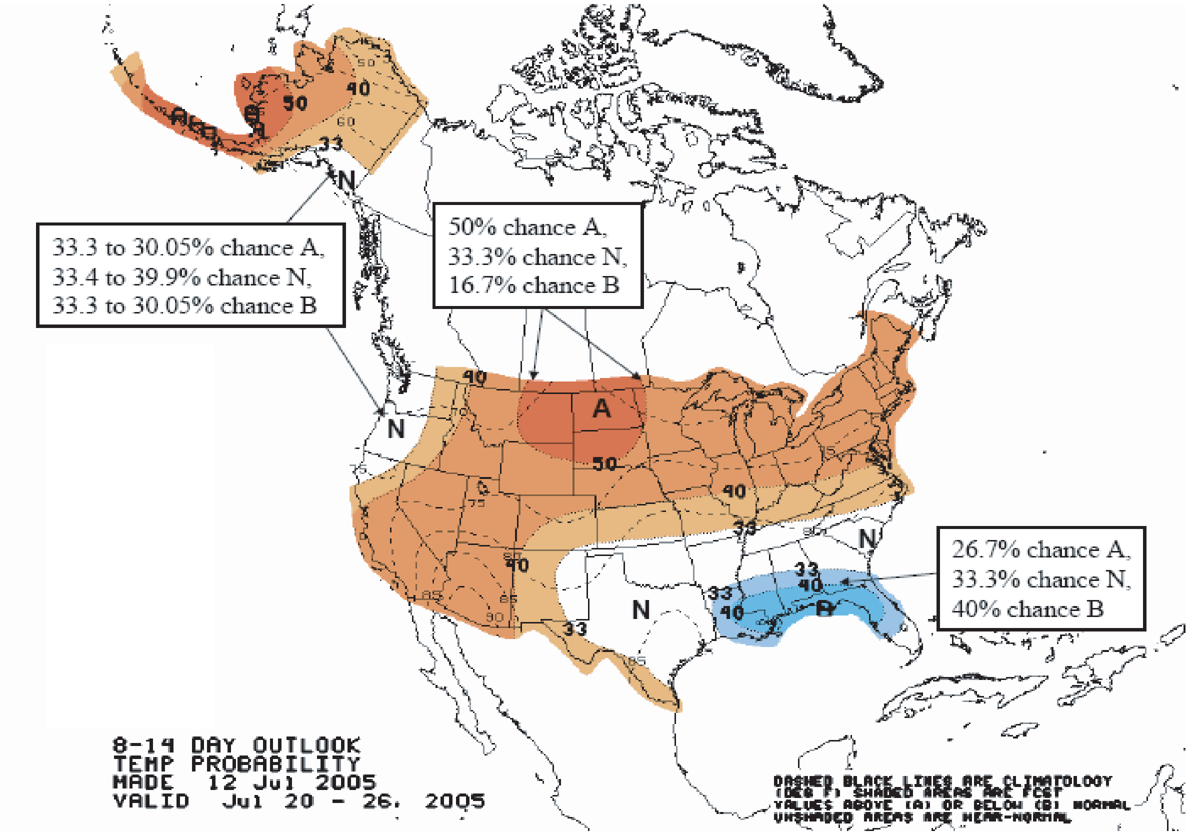


FIGURE 4A.3 8- to 14-day temperature outlook. SOURCE: Operational product generated by NOAA CPC.

Maps can also be used to communicate how uncertainty associated with a moving feature, such as a hurricane or winter storm, evolves with time. One such type of map depicts uncertainty in a feature's location along its track; an example for hurricane track forecasts was shown in Figure 1.5, whereas Figure 4A.6 shows an example for midlatitude low-pressure systems. Uncertainty in the weather associated with a feature (e.g., wind) at different times along its track can also be depicted (Figure 4.1).

Graphs communicating uncertainty can take many forms. One type of forecast uncertainty graph depicts the temporal evolution of a quantity of interest, with uncertainty represented using an ensemble of multiple temporal trajectories, box and whisker plots at each time, or probabilities of exceedance of one or more thresholds at each time. The example shown in Figure 4A.7 uses box and whisker plots to communicate how uncertainty in two forecast parameters increases and evolves with time.

A related type of graph is the temporal evolution of the probability of a certain event (such as precipitation) or multiple events (rain, snow, and ice; Figure 4A.8). Another type of graph, commonly used by scientists but probably less easily understood by many members of the public, is a probability density function (PDF) of a variable at a specific location and time (Figure 4A.9). As noted in Section 4.3.3, with Internet technology and in sophisticated decision-support systems, these types of maps and graphs can be combined. For example, a general map or graph can be presented first, allowing users to click on a location or time of interest and obtain a more specific graph or PDF.

Most maps and graphs used to communicate uncertainty in hydrometeorological forecasts are two-dimensional. However, three-dimensional representations can also be used (see, e.g., the NRC's Board on Mathematical Sciences and their applications workshop "Toward Improved Visualization of Uncertain Information"), as well as movies.

Tables and charts can communicate uncertainty using numbers, words, icons (symbols), or a combination. Two examples are shown in Figures 4A.10 and 4A.11 (see also Figure 1.4).

Narratives can be used to communicate uncertainty orally or through written text. Three examples of narrative forecasts are the NWS forecast discussions written by WFO, HPC, TPC, CPC, and other NWS/NOAA forecasters;

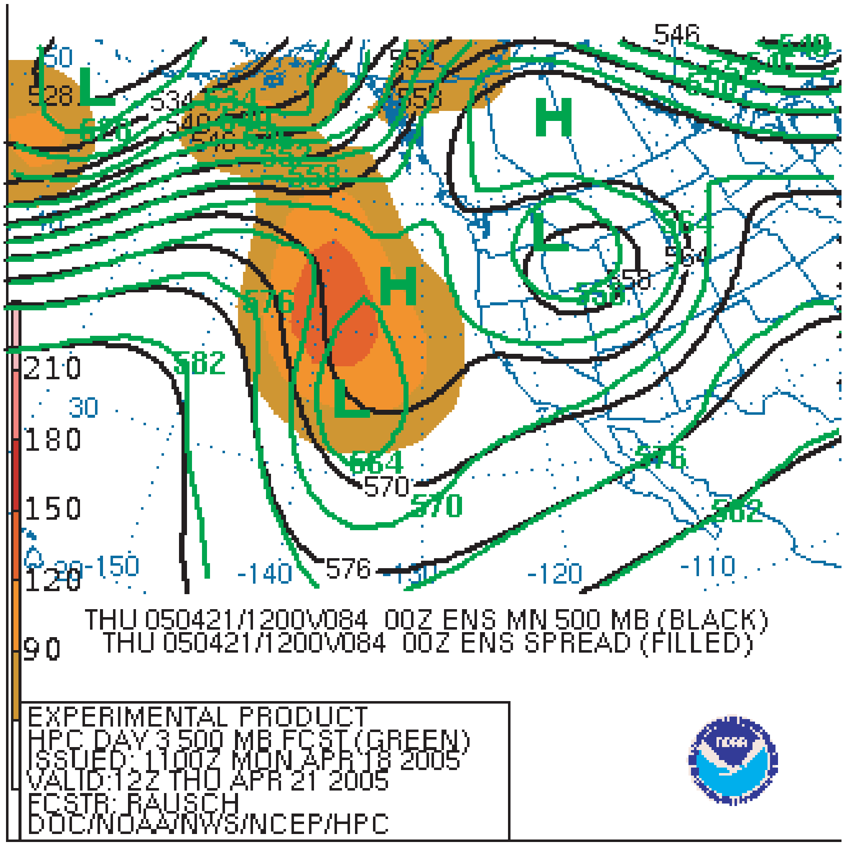
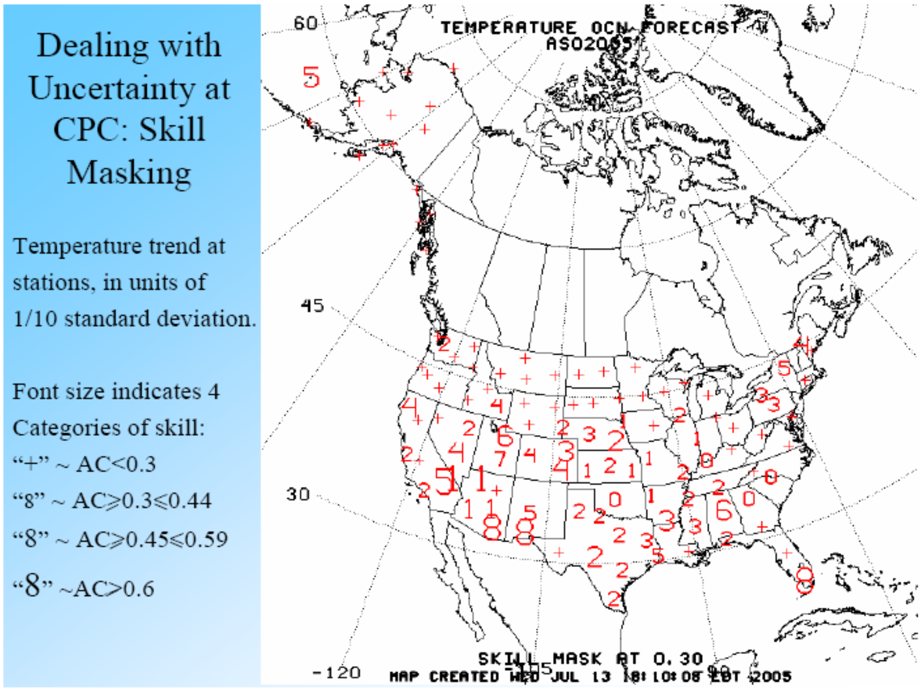


FIGURE 4A.4 500-mb day 3 forecasts generated by HPC (green lines) and NCEP ensemble mean (black lines), overlaid with NCEP ensemble spread (filled contours). SOURCE: Experimental NWS product generated by HPC.



Dealing with Uncertainty at CPC: Skill Masking

Temperature trend at stations, in units of 1/10 standard deviation.

Font size indicates 4 Categories of skill:
"+" ~ AC<0.3
"8" ~ AC⩾0.3⩽0.44
"8" ~ AC⩾0.45⩽0.59
"8" ~AC>0.6

FIGURE 4A.5 Example of how symbol size can be used to communicate level of uncertainty. SOURCE: Presentation to the committee by Ed O'Lenic, NWS.

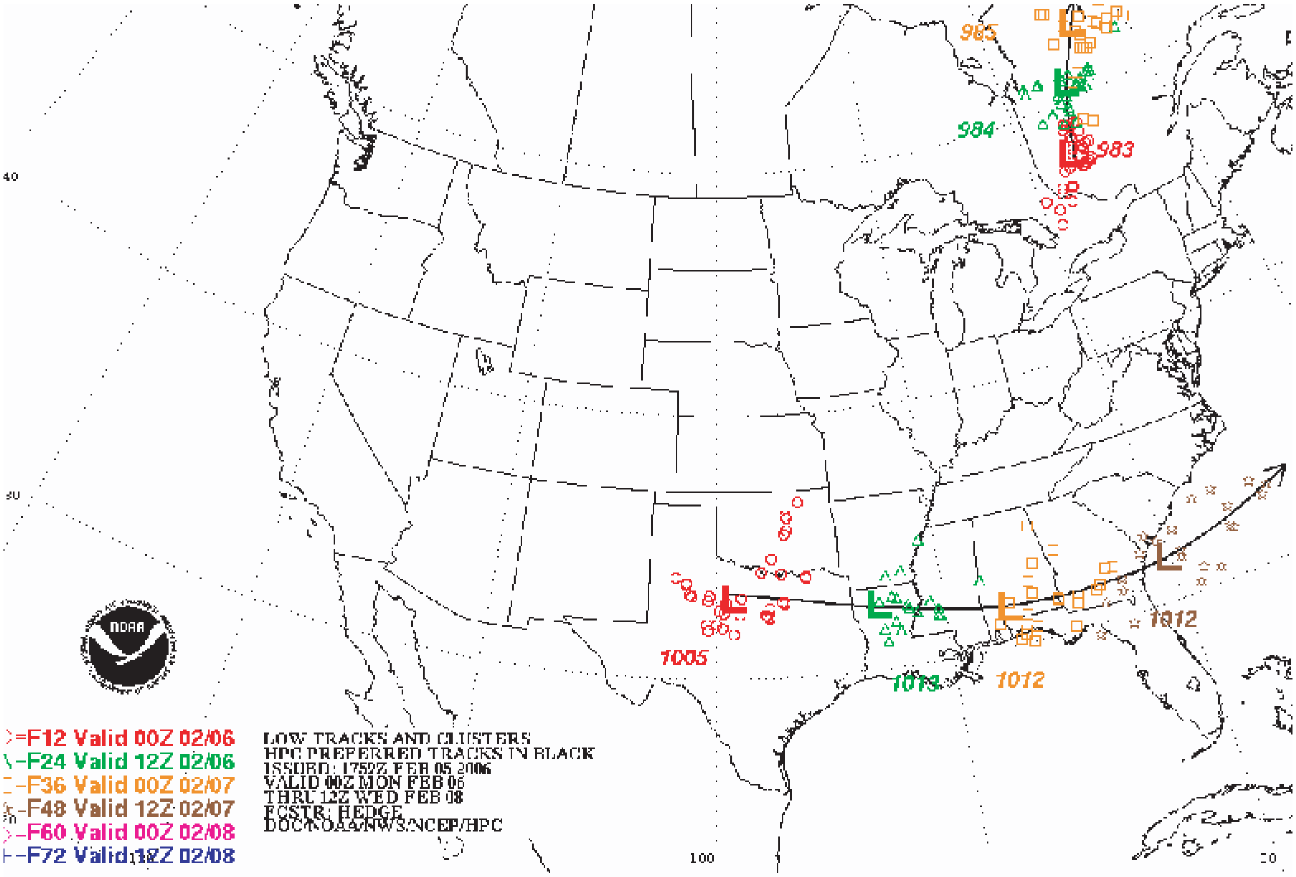
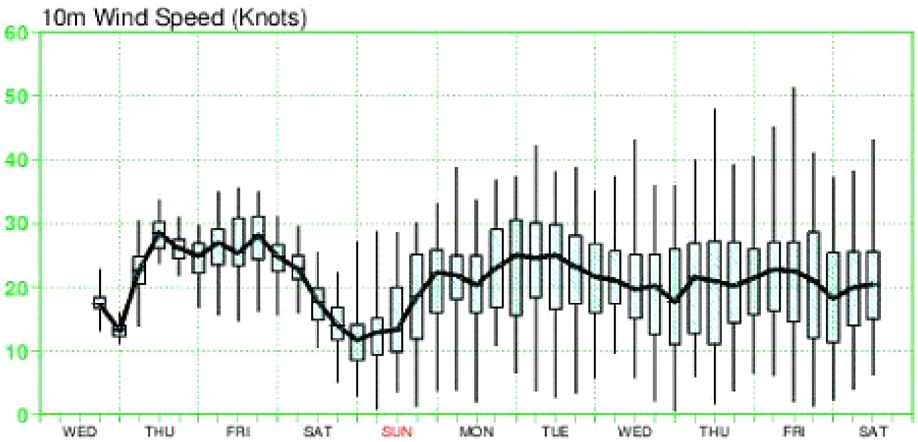


FIGURE 4A.6 Low-pressure system forecast tracks: preferred tracks and track uncertainty. SOURCE: Experimental NWS product generated by HPC.

NWR; and TV forecasters presenting a forecast. Figure 4.4 shows an example of the NWS AFD. Often, but not always, narratives accompany one or more maps, graphs, or tables/charts. Narratives are versatile; they can be used to describe uncertainty in ways ranging from indications of forecaster confidence to scenarios of different ways that weather events might evolve. As noted in Chapter 2, however, uncertainty words are often ambiguous, meaning that using words to convey uncertainty can result in ineffective communication or even miscommunication.

As illustrated above, NWS and other members of the Enterprise issue a number of forecasts that include uncertainty information. Nevertheless, as discussed in Chapter 1, most forecasts received by the public and many users still contain little or no information about uncertainty. A prime example is NWS's public weather forecasts produced by the IFPS and distributed as NDFD (Chapter 3). The only element within the IPFS and NDFD operational system that provides uncertainty information is the PoP. Variables such as temperature, dew point, and sky cover are generated as single (deterministic) values out to 7 days, with no change in format as lead time (and thus uncertainty) increases (Figure 4A.12). The basic suite of NWS public forecasts are now automatically generated from NDFD by IFPS, with limited time for forecaster editing. Thus, these forecasts, too, contain no information about uncertainty other than PoP.

Another example of an NWS product that does not convey uncertainty is the quantitative precipitation forecast (QPF) forecast issued by the HPC (Figure 4A.13). This product is accompanied by a forecast discussion that often discusses forecast uncertainty. This uncertainty information is not integrated into the QPF product, however, and thus is likely not seen by many users. Many other products issued publicly by NWS and others in the Enterprise are similar, with limited communication of uncertainty information in ways accessible to those outside the hydrometeorological community.



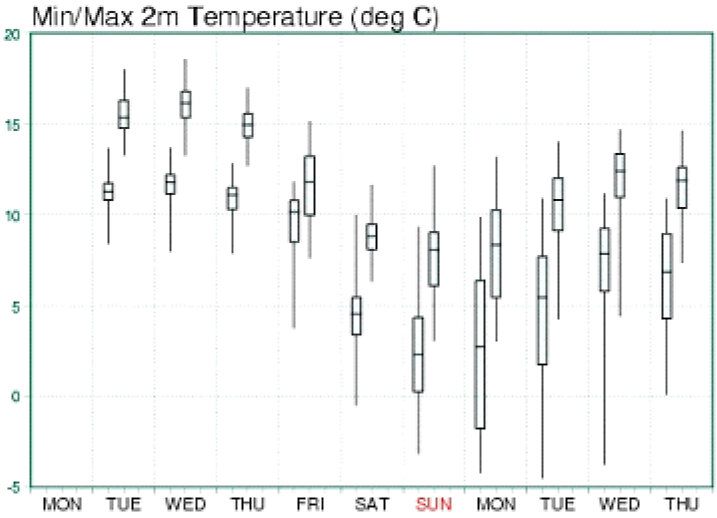


FIGURE 4A.7 Wind and temperature forecast for days 1-10, including forecast uncertainty. For box-and-whisker plots, the top and bottom of the box represent the 75th and 25th percentile, respectively, while the top and bottom of the lines represent the maximum and minimum. SOURCE: UK Meteorological Office.

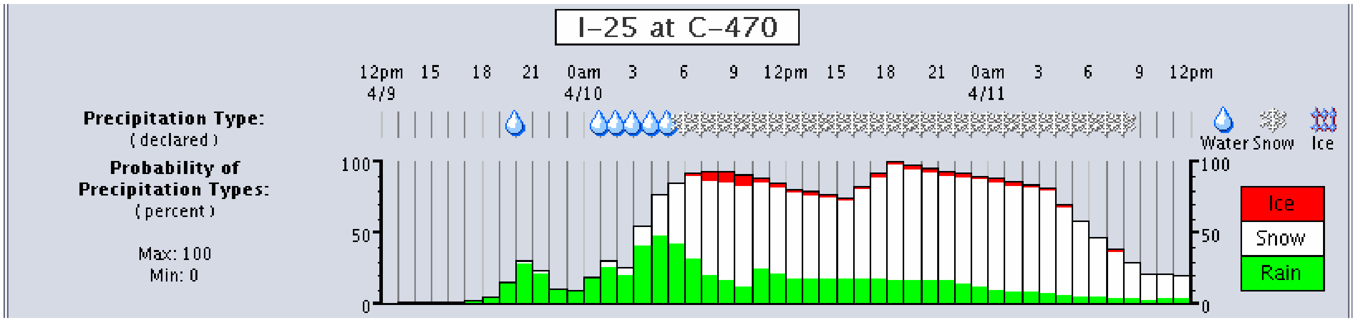


FIGURE 4A.8 Conditional probability of precipitation forecast type product, from Maintenance Decision Support System. SOURCE: Federal Highway Administration/NCAR.

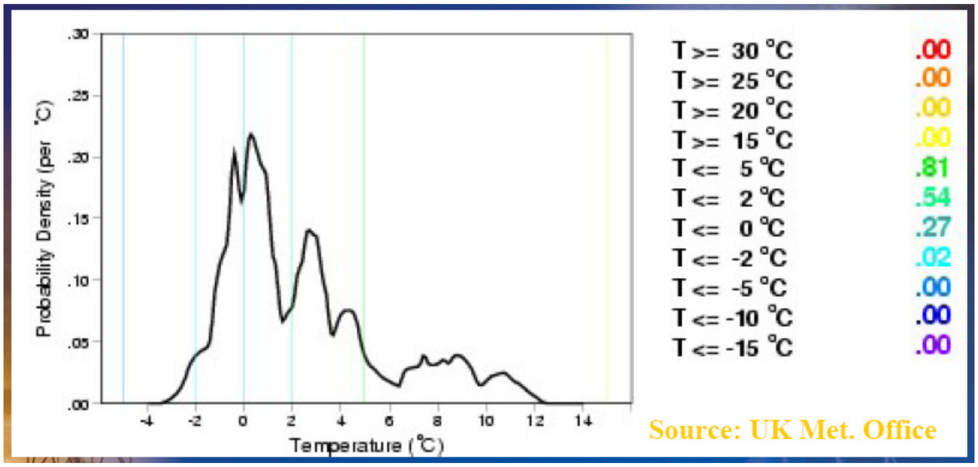
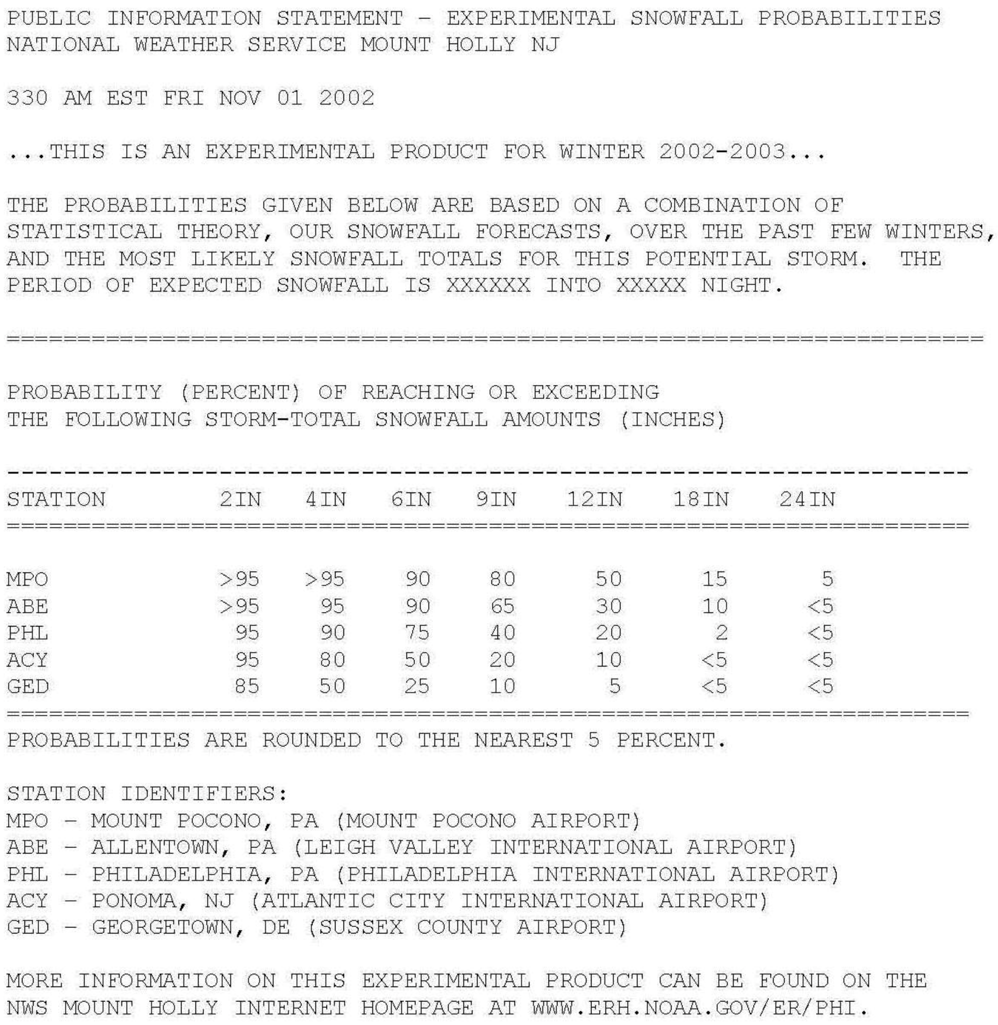


FIGURE 4A.9 PDF for the temperature forecast for a specific time and location, summarized into a table of categorical exceedances on right-hand side. SOURCE: UK Meteorological Office.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PUBLIC INFORMATION STATEMENT - EXPERIMENTAL SNOWFALL PROBABILITIES
NATIONAL WEATHER SERVICE MOUNT HOLLY NJ

330 AM EST FRI NOV 01 2002

...THIS IS AN EXPERIMENTAL PRODUCT FOR WINTER 2002-2003...

THE PROBABILITIES GIVEN BELOW ARE BASED ON A COMBINATION OF
STATISTICAL THEORY, OUR SNOWFALL FORECASTS, OVER THE PAST FEW WINTERS,
AND THE MOST LIKELY SNOWFALL TOTALS FOR THIS POTENTIAL STORM.  THE
PERIOD OF EXPECTED SNOWFALL IS XXXXXX INTO XXXXX NIGHT.

=====================================================================

PROBABILITY (PERCENT) OF REACHING OR EXCEEDING
THE FOLLOWING STORM-TOTAL SNOWFALL AMOUNTS (INCHES)

--------------------------------------------------------------------
STATION         2IN    4IN    6IN    9IN    12IN    18IN    24IN
====================================================================

MPO             >95    >95     90     80      50      15       5
ABE             >95     95     90     65      30      10      <5
PHL              95     90     75     40      20       2      <5
ACY              95     80     50     20      10      <5      <5
GED              85     50     25     10       5      <5      <5
====================================================================
PROBABILITIES ARE ROUNDED TO THE NEAREST 5 PERCENT.

STATION IDENTIFIERS:
MPO - MOUNT POCONO, PA (MOUNT POCONO AIRPORT)
ABE - ALLENTOWN, PA (LEIGH VALLEY INTERNATIONAL AIRPORT)
PHL - PHILADELPHIA, PA (PHILADELPHIA INTERNATIONAL AIRPORT)
ACY - PONOMA, NJ (ATLANTIC CITY INTERNATIONAL AIRPORT)
GED - GEORGETOWN, DE (SUSSEX COUNTY AIRPORT)

MORE INFORMATION ON THIS EXPERIMENTAL PRODUCT CAN BE FOUND ON THE
NWS MOUNT HOLLY INTERNET HOMEPAGE AT WWW.ERH.NOAA.GOV/ER/PHI.
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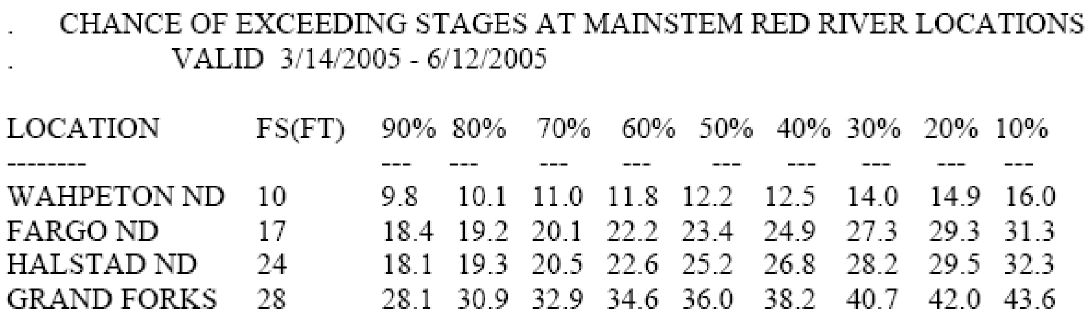
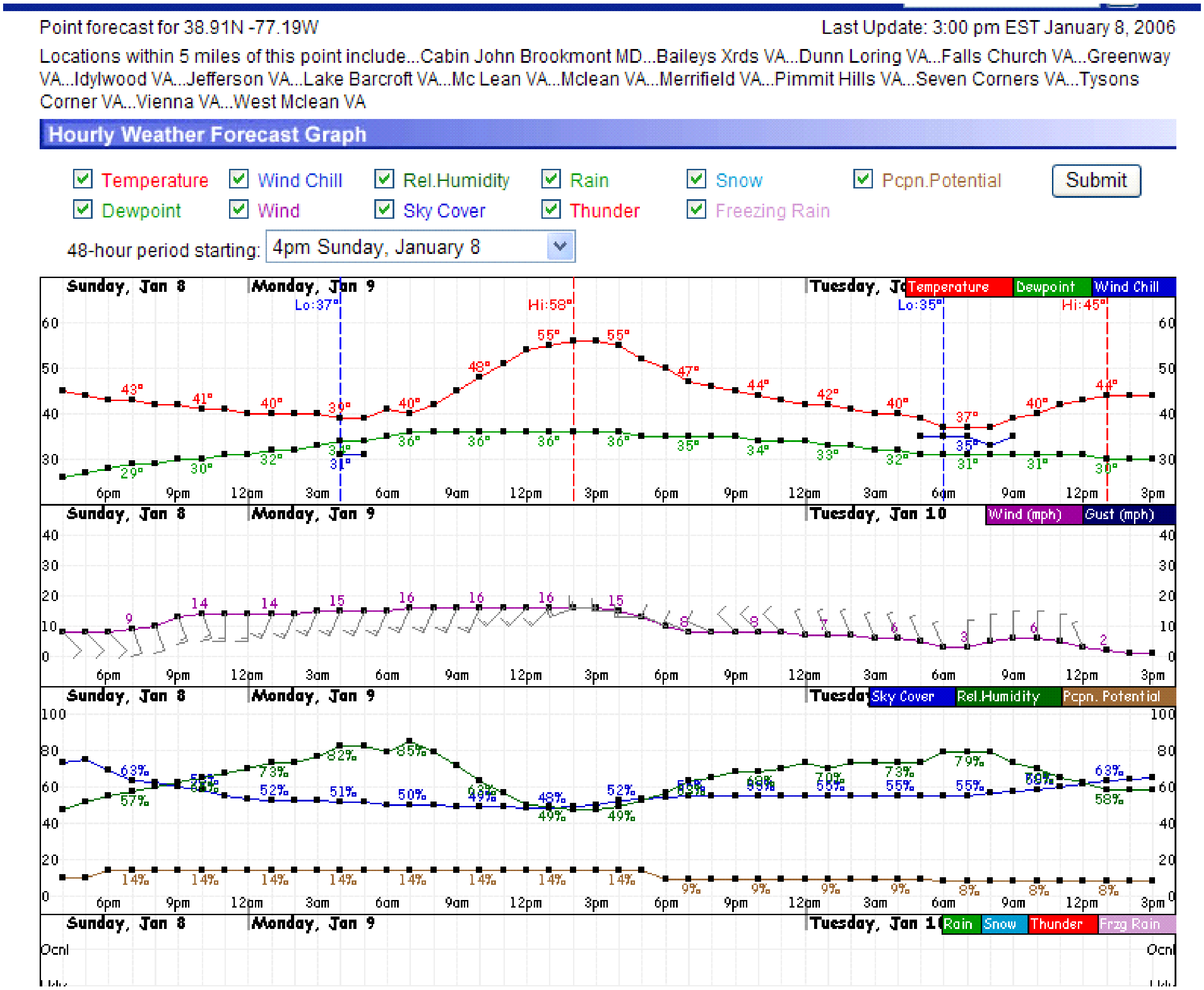
FIGURE 4A.10 Experimental probability of snowfall amount product. SOURCE: Mount Holly, NJ (Philadelphia area) NWS forecast office.



. CHANCE OF EXCEEDING STAGES AT MAINSTEM RED RIVER LOCATIONS
. VALID 3/14/2005 - 6/12/2005

| LOCATION | FS(FT) | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| -------- | | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| WAHPETON ND | 10 | 9.8 | 10.1 | 11.0 | 11.8 | 12.2 | 12.5 | 14.0 | 14.9 | 16.0 |
| FARGO ND | 17 | 18.4 | 19.2 | 20.1 | 22.2 | 23.4 | 24.9 | 27.3 | 29.3 | 31.3 |
| HALSTAD ND | 24 | 18.1 | 19.3 | 20.5 | 22.6 | 25.2 | 26.8 | 28.2 | 29.5 | 32.3 |
| GRAND FORKS | 28 | 28.1 | 30.9 | 32.9 | 34.6 | 36.0 | 38.2 | 40.7 | 42.0 | 43.6 |

FIGURE 4A.11 Flood stage forecast for different locations along the Red River. SOURCE: AHPS, NWS Grand Forks office.



Point forecast for 38.91N -77.19W

Last Update: 3:00 pm EST January 8, 2006

Locations within 5 miles of this point include...Cabin John Brookmont MD...Baileys Xrds VA...Dunn Loring VA...Falls Church VA...Greenway VA...Idylwood VA...Jefferson VA...Lake Barcroft VA...Mc Lean VA...Mclean VA...Merrifield VA...Pimmit Hills VA...Seven Corners VA...Tysons Corner VA...Vienna VA...West Mclean VA

Hourly Weather Forecast Graph

☑ Temperature ☑ Wind Chill ☑ Rel.Humidity ☑ Rain ☑ Snow ☑ Pcpn.Potential

☑ Dewpoint ☑ Wind ☑ Sky Cover ☑ Thunder ☑ Freezing Rain

48-hour period starting: 4pm Sunday, January 8

FIGURE 4A.12 Public weather forecast generated by IFPS from NDFD. SOURCE: Operational NWS product generated by forecast offices.

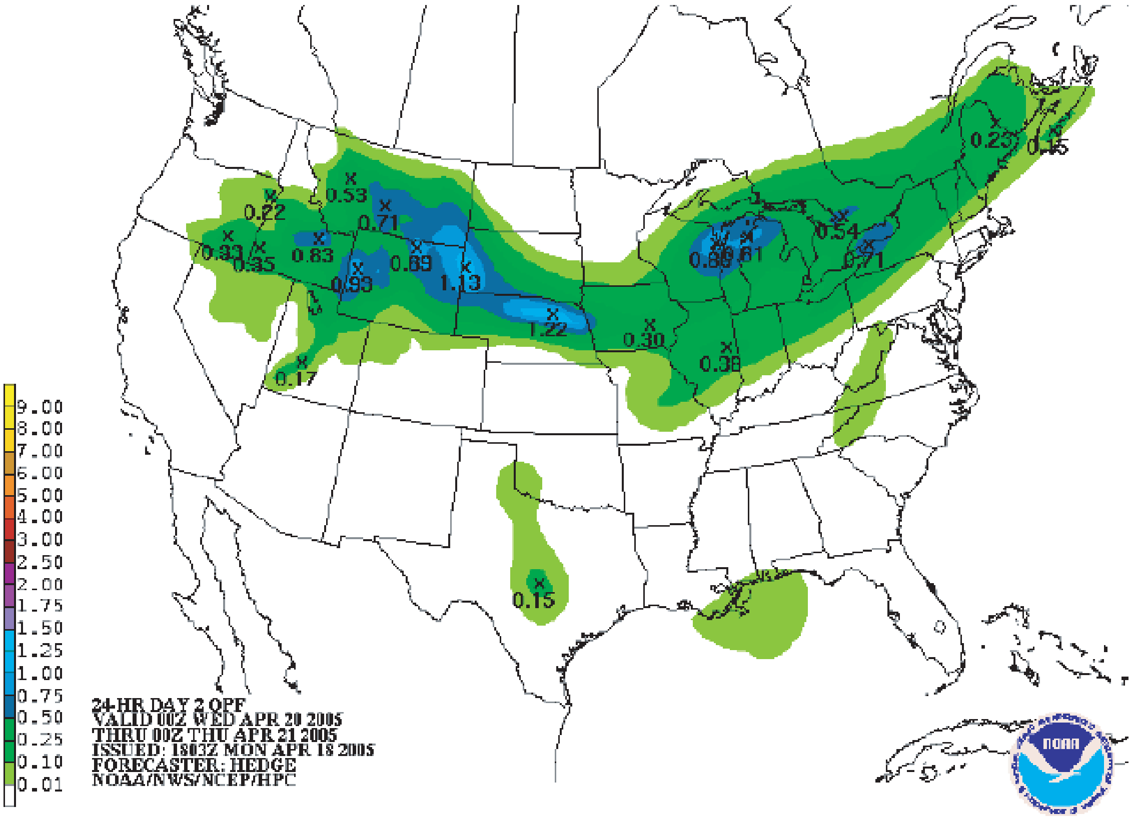


FIGURE 4A.13 Day 2 quantitative precipitation forecast. SOURCE: Operational NWS product, generated by HPC.

# 5

# Overarching Recommendations

Moving toward effective estimation and communication of uncertainty information has broad and deep implications for the Enterprise and the community it serves. Because of the immense breadth and depth of this challenge, detailed solutions are beyond the reach of a single committee. Consequently, this report provides general ideas for consideration by the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) and the entire Enterprise.

The committee presents nine overarching recommendations in this final chapter, all with equal priority. In addition, detailed recommendations appear in the preceding three chapters that add further specificity and breadth. All recommendations should be considered in the context of NOAA's Policy on Partnerships in the Provision of Environmental Information. In cases where a recommendation states that "NWS should . . ." it is the committee's intention that the recommendation also applies to any relevant group or activity within NOAA, such as the Office of Oceanic and Atmospheric Research (OAR).

## CONTEXT

All prediction is inherently uncertain and effective communication of uncertainty information benefits users' decisions (e.g., AMS, 2002; NRC, 2003b). The chaotic character of the atmosphere, coupled with inevitable inadequacies in observations and computer models, results in forecasts that always contain uncertainties. These uncertainties generally increase with forecast lead time and vary with weather situation and location. *Uncertainty is thus a fundamental characteristic of weather, seasonal climate, and hydrological prediction, and no forecast is complete without a description of its uncertainty.*

Nonetheless, many products from the Enterprise do not include uncertainty information, or they include it ineffectively. The deterministic forecasts that dominate the offerings from the Enterprise are often truncated representations of much richer information. Moreover, the information in deterministic forecasts is sometimes confusing or misleading, which can lead to poor decisions and undesirable consequences (NRC, 2003b). Decisions by users at all levels, perhaps most critically those associated directly with protection of life and property, are being made without the benefit of knowing the uncertainties of the forecasts upon which they rely.

Albert Einstein wrote, "[the right to search for truth] implies also a duty; one must not conceal any part of what one has recognized to be true."[1] Because the Enterprise has increasing capability to estimate forecast uncertainty and the ability to provide products that communicate this knowledge, it has the duty to do so in a way that is valuable to the users it serves.

## NEXT STEPS

### Enterprise-wide Involvement

**Finding 1:**[2] Hydrometeorological services in the United States are an Enterprise effort. Therefore, effective incorporation of uncertainty information will require a fundamental and coordinated shift by all sectors of the Enterprise. Furthermore, it will take time and perseverance to successfully make this shift. As the nation's public weather service, NWS has the responsibility to take a leading role in the transition to widespread, effective incorporation of uncertainty information into hydrometeorological prediction.

**Recommendation 1: The entire Enterprise should take responsibility for providing products that effectively communicate forecast uncertainty information. NWS should take a leadership role in this effort.**

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[1] Letter, March 14, 1954.

[2] See Section 1.5 for further discussion on this topic.

### Product Development Incorporating Broad Expertise and Knowledge from the Outset

**Finding 2:**[3] Understanding user needs and effectively communicating the value of uncertainty information for addressing those needs are perhaps the largest and most important tasks for the Enterprise. Yet, forecast information is often provided without full understanding of user needs or how to develop products that best support user decisions.

Parts of the Enterprise (e.g., within the private sector and academia) have developed a sophisticated understanding of user needs. In addition, there is a wealth of relevant knowledge in the social and behavioral sciences that could be more effectively incorporated into product research and development. Currently, this variety of resources is not being fully tapped by NOAA,[4] and user perspectives are not incorporated from the outset of the product development process.

**Recommendation 2: NOAA should improve its product development process by collaborating with users and partners in the Enterprise from the outset and engaging and using social and behavioral science expertise.**

### Education on Uncertainty and Risk Communication

**Finding 3:**[5] Enhanced Enterprise-wide educational initiatives will underpin efforts to improve communication and use of uncertainty information. There are three critical areas of focus: (1) undergraduate and graduate education; (2) recurrent forecaster training, and (3) user outreach and education.

**Recommendation 3: All sectors and professional organizations of the Enterprise should cooperate in educational initiatives that will improve communication and use of uncertainty information. In particular, (1) hydrometeorological curricula should include understanding and communication of risk and uncertainty, (2) ongoing training of forecasters should expose them to the latest tools in these areas, and (3) forecast providers should help users, especially members of the public, understand the value of uncertainty information and work with users to help them effectively incorporate this information into their decisions.**

### Ensembles

**Finding 4:**[6] The ability of NOAA to distribute and communicate uncertainty information is predicated on the capacity to produce post-processed probabilistic model guidance on a variety of spatial scales. Currently, NOAA maintains long-range (global) and short-range ensemble prediction systems. However, the short-range system undergoes no post-processing and uses an ensemble generation method (breeding) that may not be appropriate for short-range prediction. In addition, the short-range model has insufficient resolution to generate useful uncertainty information at the regional level. For forecasts at all scales, comprehensive post-processing is needed to produce reliable (or calibrated) uncertainty information.

**Recommendation 4: NOAA should develop and maintain the ability to produce objective uncertainty information from the global to the regional scale.**

### Ensuring Widespread Availability of Uncertainty Information

**Finding 5:**[7] NWS, through the National Centers for Environmental Prediction (NCEP), produces a large amount of model output from its deterministic and ensemble numerical weather prediction models. The ensemble forecasts and output from statistical post-processing (i.e., Model Output Statistics) already produce a wide variety of uncertainty information. However, both the model output and statistical information regarding its skill are difficult to access from outside NCEP. Thus, NWS is missing an opportunity to provide the underlying datasets that can drive improved uncertainty estimation and communication across the Enterprise.

**Recommendation 5: To ensure widespread use of uncertainty information, NWS should make all raw and post-processed probabilistic products easily accessible to the Enterprise at full spatial and temporal resolution. Sufficient computer and communications resources should be acquired to ensure effective access by external users and NWS personnel.**

### Broad Access to Comprehensive Verification Information

**Finding 6:**[8] To make effective use of uncertainty products, users need complete forecast verification information that measures all aspects of forecast performance. In addition, comprehensive verification information is needed to improve forecasting systems. Such information includes previous numerical forecasts, observations, post-processed uncer-

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[3] See Sections 2.4, 4.2.6, 4.2.7.

[4] Recognizing that private-sector entities gain a competitive advantage through knowledge of user needs, there is, nonetheless, some opportunity for information sharing that could significantly improve the effectiveness and efficiency of product development.

[5] See Section 4.2.8.

[6] See Chapter 3. Production of objective uncertainty information is covered in Sections 3.1 through 3.3.

[7] See Sections 3.1.4, 3.1.5, 3.3.1.

[8] See Section 3.5.

tainty information, and detailed verification statistics (for raw and post-processed probabilistic forecasts).

Verification measures and statistics need to evaluate all aspects of forecast performance that are relevant for use or improvement of the forecasts. Single scalar measures of forecast performance—commonly presented on NWS Web sites—are not adequate to meet these requirements. In many cases, the verification statistics that are provided by NWS are difficult to obtain, overly aggregated, or inappropriate for probabilistic forecasts. Thus, only a small fraction of the information needed by users and model developers is available to them.

**Recommendation 6: NWS should expand verification of its uncertainty products and make this information easily available to all users in near real time. A variety of verification measures and approaches (measuring multiple aspects of forecast quality that are relevant for users) should be used to appropriately represent the complexity and dimensionality of the verification problem. Verification statistics should be computed for meaningful subsets of the forecasts (e.g., by season, region) and should be presented in formats that are understandable by forecast users. Archival verification information on probabilistic forecasts, including model-generated and objectively generated forecasts and verifying observations, should be accessible so users can produce their own evaluation of the forecasts.**

### Effective Use of Testbeds

**Finding 7:**[9] Testbeds are emerging as a useful mechanism for developing and testing new approaches and methodologies in estimating and communicating uncertainty.[10] The effectiveness of testbeds is limited when all appropriate sectors of the Enterprise are not included.

Testbeds are multipartner collaborations that create prototypical environments where innovative approaches can be tested before being applied more generally. They allow the community to evaluate new modes of cooperative research, development, training, and operations. Testbeds allow (1) the operational community to benefit from strengthened connections to academia (including decision and social sciences) and the private sector; (2) academia to benefit from exploring new research areas at the interfaces of physical, social, and decision sciences, and from hands-on student training; and (3) the private sector to provide input on science and technology development and ensure that new approaches are responsive to private-sector requirements. In moving toward improved characterization and communication of forecast uncertainty information, testbeds can, for example, play a critical role in developing the technology of probabilistic prediction, evaluating ways to communicate such information and garnering active input and interactions with user communities. Although NOAA has successfully participated in testbeds in areas such as hurricane prediction and hydrology, no testbed activity currently exists in the critical area of probabilistic prediction using ensemble techniques.

**Recommendation 7: To enhance development of new methods in estimation, communication, and use of forecast uncertainty information throughout the Enterprise, and to foster and maintain collaboration, confidence, and goodwill with Enterprise partners, NOAA should more effectively use testbeds by involving all sectors of the Enterprise.**

### Enterprise Advisory Committee

**Finding 8:**[11] Only through comprehensive interaction with the Enterprise will NWS be able to move toward effective and widespread estimation and communication of uncertainty information. One mechanism for engaging the entire Enterprise on this and other Enterprise-related topics is an independent NWS advisory committee with broad representation. Such a committee is under consideration by NOAA in response to a recommendation in the *Fair Weather* report (NRC, 2003a).

In 2003, the National Research Council recommended that "NWS should establish an independent advisory committee to provide ongoing advice to it on weather and climate matters. The committee should be composed of users of weather and climate data and representatives of the public, private and academic sectors, and it should consider issues relevant to each sector as well as to the set of players as a group, such as (but not limited to)

- improving communication among the sectors,
- creating or discontinuing products,
- enhancing scientific and technical capabilities that support the NWS mission,
- improving data quality and timeliness, and
- disseminating data and information."

**Recommendation 8: The committee endorses the recommendation by the *Fair Weather* report to establish an independent advisory committee and encourages NOAA**

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[9] See Sections 3.1.1, 3.1.6, 3.2.4, 3.3.2.

[10] See, for example, Joint Hurricane Testbed (http://www.nhc.noaa.gov/jht/), Weather Research and Forecasting (WRF) Developmental Testbed Center (http://www.dtcenter.org/index.php), NOAA Climate Testbed (http://www.cpc.ncep.noaa.gov/products/ctb/), NOAA Hydrometeorology Testbed Program (http://hmt.noaa.gov/).

[11] See Section 4.2.6 and overarching recommendation 2.

**to bring its evaluation of the recommendation to a speedy and positive conclusion.**

### Uncertainty Champion

**Finding 9:**[12] Incorporating uncertainty in forecasts will require not only the attention, but also the advocacy of NWS management. Given the scope of this challenge, the level of effort involved will demand a "champion" within the NWS leadership—an individual who can effectively organize and motivate NWS resources and engage the resources and expertise of the entire Enterprise.

There is recent precedent for such an approach at NWS, admittedly at a more technical level: the NWS WRF model coordinator is to implement the WRF program.

**Recommendation 9: NWS should dedicate executive attention to coordinating the estimation and communication of uncertainty information within NWS and with Enterprise partners.**

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[12] See Section 1.5.

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# Appendix A

# Acronyms and Initialisms

| | |
|---|---|
| 3d-Var | three-dimensional variational assimilation |
| 4d-Var | four-dimensional variational assimilation |
| ACE | Advanced Composition Explorer |
| AFD | Area Forecast Discussion |
| AHPS | Advanced Hydrologic Prediction Service |
| AMS | American Meteorological Society |
| ASC | ACE Science Center |
| AWC | Aviation Weather Center |
| BMA | Bayesian model averaging |
| BSE | bovine spongiform encephalitis |
| CAS | Constructed Analog on Soil moisture |
| CCA | canonical correlation analysis |
| CCFP | Collaborative Convective Forecast Product |
| CCMC | Community Coordinated Modeling Center |
| CDC | Climate Diagnostic Center |
| CFS | Climate Forecast System |
| CISM | Center for Integrated Space Weather Modeling |
| CMC | Canadian Meteorological Centre |
| CNRFC | California Nevada River Forecast Center |
| COLA | Center for Ocean-Land-Atmosphere Studies |
| CONUS | Continental United States |
| CPC | Climate Prediction Center |
| CRPS | Continuous Ranked Probability Score |
| CTB | Climate Test Bed |
| DA | data assimilation |
| DART | Data Assimilation Research Testbed |
| DTaP | diphtheria, tetanus, and pertussis |
| DTC | Developmental Testbed Center |
| EC | Equal Chances |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| EMC | Environmental Modeling Center |
| EMWIN | Emergency Managers Weather Information Network |
| EnKF | ensemble Kalman filters |
| EnKS | ensemble Kalman smoothers |
| ENSO | El Niño/Southern Oscillation |
| EPA | U.S. Environmental Protection Agency |
| ESP | ensemble streamflow prediction |
| ESRL | Earth System Research Laboratory |
| FNMOC | Fleet Numerical Meteorology and Oceanography Center |
| FOS | Family of Services |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GMB | EMC Global Climate and Weather Modeling Branch |
| GODAS | Global Ocean Data Assimilation System |
| GSI | Gridpoint Statistical Interpolation |
| HPC | Hydrometeorological Prediction Center |
| HSS | Heidke skill score |
| IFPS | Interactive Forecast Preparation System |
| IPCC | Intergovernmental Panel on Climate Change |
| IRI | International Research Institute |
| IWIN | Interactive Weather Information Network |
| LAF | Lagged Average Forecast |
| MDL | Meteorological Development Laboratory |
| MMB | EMC Mesoscale Modeling Branch |
| MOS | Model Output Statistics |
| MST | Minimum Spanning Tree |
| NAEFS | North American Ensemble Forecasting System |
| NCAR | National Center for Atmospheric Research |
| NCDC | National Climatic Data Center |

| | |
|---|---|
| NCEP | National Centers for Environmental Prediction |
| NDFD | National Digital Forecast Database |
| NDGD | National Digital Guidance Database |
| NGDC | National Geophysical Data Center |
| NHC | National Hurricane Center |
| NOAA | National Oceanic and Atmospheric Administration |
| NOMADS | National Operational Model Archive and Distribution System |
| NSSL | National Severe Storms Lab |
| NWP | numerical weather prediction |
| NWS | National Weather Service |
| NWR | NOAA Weather Radio |
| NWWS | NOAA Weather Wire Service |
| | |
| OAR | Oceanic and Atmospheric Research |
| OCN | Optimal Climate Normals |
| OHD | Office of Hydrologic Development |
| | |
| PDA | personal digital assistant |
| PDD | Product/Service Description Document |
| PDF | probability density function |
| PoP | Probability of Precipitation |
| | |
| QPF | quantitative precipitation forecast |
| | |
| RAL | NCAR Research Applications Laboratory |
| RFC | River Forecast Center |
| RFC | Regional Forecast Center |
| RFP | Request for Proposals |
| RISA | Regional Integrated Sciences and Assessment |
| ROC | Relative Operating Characteristic |
| RPC | Rapid Prototyping Center |
| RPS | Ranked Probability Score |
| RSM | Regional Spectral Model |
| | |
| SAB | Science Advisory Board |
| SEC | Space Environment Center |
| SLP | sea level pressure |
| SMLR | Screening Multiple Linear Regression |
| SPC | Storm Prediction Center |
| SREF | short-range ensemble forecast |
| SSI | NCEP Spectral Statistical Interpolation |
| SST | sea surface temperature |
| | |
| TAF | Terminal Aerodrome Forecast |
| TAR | IPCC Third Assessment Report |
| THORPEX | The Observing System Research and Predictability Experiment |
| TIGGE | THORPEX Interactive Grand Global Ensemble |
| TPC | Tropical Prediction Center |
| | |
| USACE | U.S. Army Corps of Engineers |
| USDA | U.S. Department of Agriculture |
| USGS | U.S. Geological Survey |
| | |
| WFO | Weather Forecast Office |
| WGNE | Working Group on Numerical Experimentation |
| WMO | World Meteorological Organization |
| WRF-AR | Weather Research and Forecasting Advanced Research |
| WRF-NMM | Weather Research and Forecasting Nonhydrostatic Mesoscale Model |
| WWRP | World Weather Research Programme |

# Appendix B

# List of Presenters and Other Contributors to the Study Process

**Lee Anderson,** NOAA Headquarters
**Lisa Bee,** National Airspace System Weather Office
**Jim Block,** Meteorlogix, Inc.
**Harold Brooks,** NOAA National Severe Storms Laboratory
**Brad Colman,** NOAA National Weather Service
**Paul Dallavale,** NOAA Meteorological Development Lab
**Kent Doggett,** NOAA/NCEP Solar Environment Center
**Jun Du,** NOAA National Centers for Environmental Prediction
**Beth Faber,** U.S. Army Corps of Engineers, Hydrologic Engineering Center
**J. Michael Fritsch,** Pennsylvania State University
**Aris Georgakakos,** Georgia Institute of Technology
**Eve Gruntfest,** University of Colorado
**Tom Hamill,** NOAA Earth System Research Laboratory
**Kathy Jacobs,** University of Arizona
**Dale Jamieson,** New York University
**Ed Johnson,** NOAA Headquarters
**D.L. Johnson,** NOAA Headquarters
**Susan Joslyn,** University of Washington
**Scott Kiser,** NOAA/NWS Office of Climate, Water and Weather
**Roman Krzysztofowicz,** University of Virginia
**Jeff Lazo,** National Center for Atmospheric Research
**Robert Livezey,** NOAA NWS Climate Services
**Alexander MacDonald,** NOAA Earth System Research Laboratory
**Bill Mahoney,** National Center for Atmospheric Research
**Max Mayfield,** NOAA Tropical Prediction Center
**Jacqueline Meszaros,** University of Washington, Bothell
**Joel Myers,** AccuWeather
**Edward O'Lenic,** NOAA Climate Prediction Center
**Tom Pagano,** USDA Natural Resources Conservation Service
**Roger Pielke, Jr.,** University of Colorado
**Roger Pulwarty,** University of Colorado
**Warren Qualley,** Weathernews Americas, Inc.
**Adrian Raftery,** University of Washington
**Frank Richards,** NOAA Office of Hydrologic Development
**David Ruth,** NOAA/NWS Office of Science and Technology
**Hyam Singer,** Next Century Corporation
**Leonard Smith,** London School of Economics
**John Sokich,** NOAA Headquarters
**Ellis M. Stanley, Sr.,** City of Los Angeles, Emergency Preparedness Department
**Tom Stewart,** State University of New York at Albany, Center for Policy Research
**Gary Szatkowski,** NOAA NWS
**Zoltan Toth,** NOAA National Centers for Environmental Prediction
**Jerry Wegiel,** Air Force Weather Agency
**Steve Zubrick,** NOAA NWS Baltimore-Washington Forecast Office

# Appendix C

# Biographical Sketches of Committee Members and Staff

**Raymond J. Ban** (*Chair*) is Executive Vice President of Meteorology Science and Strategy at The Weather Channel, Inc. (TWC). He is responsible for the meteorological quality and integrity of all TWC's products and services, and for growing TWC's relationships with the weather community across the entire weather climate enterprise. Prior to joining TWC in 1982, he worked as an operational weather forecaster at AccuWeather, Inc. from 1973 to 1982. He graduated from Pennsylvania State University with a degree in meteorology. He has been an active member of the AMS for over 30 years. He holds both the Television and Radio Seal of Approval from the Society. Previously Ray was the Commissioner on Professional Affairs for the AMS for 6 years and is now serving on the Steering Committee of the AMS Commission on The Weather and Climate Enterprise. He was named a Centennial Fellow of Penn State's College of Earth and Mineral Sciences, an Alumni Fellow of Penn State University, has served on the Board of Atmospheric Science and Climate of the National Academy of Sciences and has also served as President of the Alumni Board of the College of Earth and Mineral Sciences at Penn State. Additionally, Mr. Ban is currently a member of the advisory board to NCAR and the NCAR Societal Impacts Program and serves on the Board of Visitors of The College of Geosciences at the University of Oklahoma. Mr. Ban is Co-Chair of The Weather Coalition and sits on the Board of Directors of the National Environmental Education and Training Foundation. He is a past member of the Cooperative Program for Operational Meteorology, Education and Training (COMET) Advisory Panel and the research and Technical Committee of the Southeast Region Climate Center.

**John T. Andrew** is Chief of Special Planning Projects for the California Department of Water Resources (DWR), where his current projects focus primarily on various aspects of California's hydrology. Prior to his current position with DWR, Mr. Andrew was the water quality manager and Southern California regional coordinator for the California Bay-Delta Authority, and before that he served as Chief of Fish Facilities for DWR's Environmental Services Office. He has also worked for the California Department of Health Services, the U.S. Environmental Protection Agency, and Lawrence Berkeley National Laboratory. Mr. Andrew holds a bachelor's degree in civil engineering and a master's degree in public policy, both from the University of California at Berkeley.

**Barbara G. Brown** is project scientist in the Research Applications Laboratory of the National Center for Atmospheric Research. Her research interests include weather and climate applications of statistics, including forecast verification and development of new verification approaches; probability forecasts and forecast uncertainty; measuring user needs and forecast value; forecast communication; statistical forecasting methods; and weather and climate extremes. She is chair of the World Meteorological Organization's Joint Working Group on Verification and Associate Editor of *Weather and Forecasting*. Ms. Brown has a bachelor's degree in statistics from Colorado State University and master's degrees in environmental sciences and statistics from the University of Virginia and Oregon State University, respectively.

**David Changnon** is an associate professor in the Meteorology Program of the Department of Geography, Northern Illinois University. Dr. Changnon's research activities involve applied climatology, hydroclimatic variability, and synoptic climatology. He examines climate variability and extremes and their impacts in the United States, assesses the use of climate information by weather-sensitive decision makers, and develops climate-related decision-support tools for users in climate-sensitive areas such as utilities, agribusiness, recreation, transportation, and water resources. Dr. Changnon has a bachelor's degree in engineering from the University of Illinois and master's and doctoral degrees in atmospheric sciences from Colorado State University.

**Konstantine Georgakakos** is the Managing Director of the Hydrologic Research Center in San Diego, California. He is also an Adjunct Professor with the Scripps Institution of Oceanography of the University of California, San Diego, and with the Department of Civil and Environmental Engineering of the University of Iowa, Iowa City. His research activities have included interfacing ensemble and probabilistic forecasting with decision models for multiobjective reservoir management and agriculture in Northern California. He has also developed measures of utility of uncertain surface meteorological forecasts for hydrologic and water resources applications by propagating uncertainty in coupled systems and in downscaling, and producing probabilistic diagnostic indices for utilizing climate and weather ensemble model forecasts. He has led the development of operational forecast and management systems in Northern California, at the Panama Canal, over the Nile River basin, in Korea, and in Central America as part of the technology transfer programs of the Hydrologic Research Center. Dr. Georgakakos holds a degree in civil engineering from the National Technical University of Athens, and master's and doctoral degrees in civil engineering from the Massachusetts Institute of Technology.

**James Hansen** is an assistant professor in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology. His research interests include nonlinear dynamics, prediction, predictability, data assimilation, targeted observations, probabilistic forecasting, ensemble assessment, and the impact of model inadequacies. He is a member of the American Geophysical Union, European Geophysical Society, and Royal Meteorological Society. Dr. Hansen holds bachelor's and master's degrees in aerospace engineering from the University of Colorado and a doctoral degree in atmospheric physics from Oxford University.

**Ronald N. Keener, Jr.,** is Meteorology Manager at Duke Energy in Charlotte, North Carolina. He provides weather forecast and climate support services in support of generation load forecasting, energy trading and marketing, hydroelectric operation and planning, emergency response organizations, and project planning and development. Previously he was an Engineering Specialist at the U.S. Environmental Protection Agency, where he participated in fluid modeling studies that supported boundary-layer model development for air quality modeling. He is a member of the American Meteorological Society (AMS), the Nuclear Meteorology Users Group, and the Planetary Society. He is also a member of the Board of Certified Consulting Meteorologists and the U.S. Weather Research Program. He additionally served as Program Chair for the 2001 AMS Annual Meeting and Symposium Chair for the 2000 AMS Meeting on Environmental Applications, and is a past member of the AMS Private Sector Board.

**Upmanu Lall** is Professor and Chair of Earth and Environmental Engineering at Columbia University. His principal areas of expertise are statistical and numerical modeling of hydrologic and climatic systems and water resource systems planning and management. He has over 25 years of experience as a hydrologist. He has been the principal investigator on a number of research projects funded by the U.S. Geological Survey, the National Science Foundation (NSF), the U.S. Air Force, the National Oceanic and Atmospheric Administration (NOAA), U.S. Bureau of Reclamation, Department of Energy, and Utah and Florida state agencies. These projects have covered water quantity and quality and energy resource management, flood analysis, groundwater modeling and subsurface characterization, climate modeling and the development of statistical and mathematical modeling methods. He has been involved as a consultant with specialization in groundwater flow and contaminant transport modeling covering mining operations, streamflow modeling and water balance, risk and environmental impact assessment, site hydrologic evaluation and as a reviewer and as an expert on a number of other hydrologic problems. He has also taught over 20 distinct university courses.

**Clifford F. Mass** is a professor in the Department of Atmospheric Sciences at the University of Washington. He received his B.S. in 1974 in physics at Cornell and his Ph.D. in atmospheric sciences at the University of Washington in 1978. He has been a faculty member at the University of Washington since 1981. His research interests include synoptic and mesoscale forecasting techniques, regional weather phenomena, and mesoscale modeling using the Penn State-NCAR MM5 modeling system. He works with ensemble prediction, including maintaining a real-time mesoscale ensemble system and involvement with the Multidisciplinary University Research Initiative on predictability, and has collaborated for many years with the National Weather Service (NWS) on regional forecasting problems. He currently leads a research group that has studied a wide variety of topics, including heavy precipitation and flooding, wind and snow storms, numerical forecasting strategies, as well as weather phenomena unique to western North America. Dr. Mass also leads the real-time MM5 forecasting effort at the University of Washington.

**Rebecca E. Morss** is a scientist at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, with a joint appointment in the Mesoscale and Microscale Meteorology Division and the Institute for the Study of Society and Environment. Her research interests include atmospheric science, socioeconomic, and public policy aspects of observing network design for weather and El Niño prediction; atmospheric predictability; and improving weather information to meet diverse societal needs. Dr. Morss is also involved in building a collaborative program based at NCAR to understand the use and value of weather forecasts and connect weather forecasts with user needs, and in developing the Societal and Economic Applications component of the international THORPEX program (under the auspices of the World Meteorological Organization). She received a B.A. from the University of Chicago and a Ph.D. in atmospheric science from the Massachusetts Institute of Technology.

**Robert T. Ryan** has been chief meteorologist at NBC4 in Washington, D.C., since 1980. Before joining NBC4 he was a research meteorologist with Arthur D. Little Inc. in Cambridge and worked as a broadcast meteorologist in Providence, Boston, and on the *Today* show. He has served as the American Meteorological Society (AMS) Chair of the Committee of Broadcast Meteorology, Commissioner of Professional Affairs, Member of the Council of the Society, and in 1996 was elected President of the AMS. Additionally, Mr. Ryan has been called to testify before various committees of Congress and recently served on the National Academies' Board on Atmospheric Sciences and Climate and on its Committee on Partnerships in Weather and Climate Services and the NSF Advisory Committee for Geosciences. He has also served as executive editor of *Weatherwise* magazine for many years. Mr. Ryan holds a bachelor's degree in physics and a master's degree in atmospheric sciences from the State University of New York at Albany.

**Elke U. Weber** is the Jerome A. Chazen Professor of International Business in the Management Division of Columbia Business School and Professor of Psychology at Columbia University. Dr. Weber's M.A. and Ph.D. in Behavior and Decision Analysis are from Harvard University. Over the past 20 years, she has held academic positions in the United States (University of Chicago, University of Illinois, Ohio State University) and Europe (Otto Beisheim Graduate School of Corporate Management). Dr. Weber spent a year (1992/1993) at the Center for Advanced Studies in the Behavioral Sciences at Stanford and half a year (2002) at the Wissenschaftskolleg (Center for Advanced Study) in Berlin. She is an expert on behavioral models of judgment and decision making under risk and uncertainty. Recently Dr. Weber has been investigating psychologically appropriate ways to measure and model individual and cultural differences in risk taking, specifically in risky financial situations and environmental decision making and policy. She is past president of the Society for Mathematical Psychology and the Society for Judgment and Decision Making and served on two committees of the National Academies. Dr. Weber has edited two major decision journals and currently serves or has served on the editorial boards of eight other psychology and policy journals. At Columbia, she founded and codirects the Center for the Decision Sciences, which fosters and facilitates cross-disciplinary research and graduate training in the basic and applied decision sciences, and recently founded the Center for Research on Environmental Decisions, which investigates ways of facilitating human adaptation to climate change and climate variability and is financed by the National Science Foundation.

## NRC Staff

**Paul Cutler** (Study Director) is a senior program officer for the Polar Research Board of the National Academies. He directs studies in the areas of polar science and atmospheric science. Before joining the Polar Research Board staff, Dr. Cutler was a senior program officer in the Academies' Board on Earth Sciences and Resources, where he directed the Mapping Science Committee and studies in Earth science and geographic information science. Before joining the Academies, he was an assistant scientist and lecturer in the Department of Geology and Geophysics at the University of Wisconsin, Madison. His research is in glaciology, hydrology, meteorology, and quaternary science, and he has conducted fieldwork in Alaska, Antarctica, arctic Sweden, the Swiss Alps, Pakistan's Karakoram mountains, the midwestern United States, and the Canadian Rockies. Dr. Cutler received an M.Sc. in geography from the University of Toronto and a Ph.D. in geology from the University of Minnesota.

**Leah Probst** is a research associate with the NRC's Board on Atmospheric Sciences and Climate. She works on a wide variety of studies, including issues such as air quality, climate, ecology, and wildlife management. A former resident of Alaska, Ms. Probst has returned to Alaska many times through her work at the NRC, visiting numerous regions of the state and learning about environmental issues unique to Alaska. She earned her bachelor's degree in biology from the George Washington University in Washington, D.C.

**Rob Greenway** has been a program assistant at the National Academies since 1998. He has worked on NRC studies that produced the reports *Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities*, *Review of NOAA's Plan for the Scientific Stewardship Program*, and *Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services*, among others. He received his A.B. in English and his M.Ed. in English education from the University of Georgia.