PREDICTION

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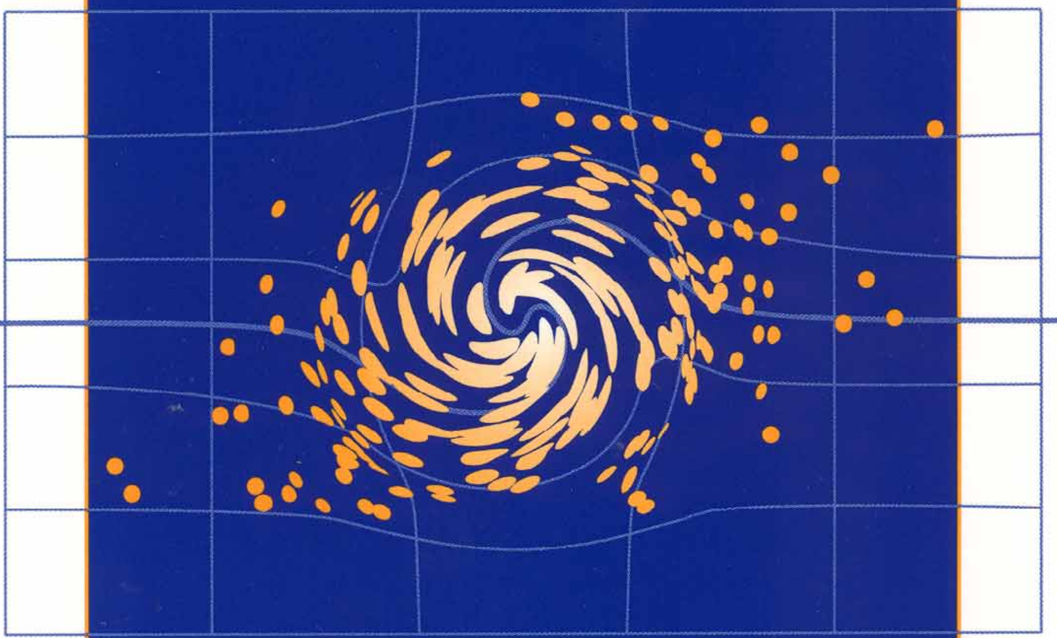

and the Future of Nature

Edited by
Daniel Sarewitz, Roger A. Pielke, Jr.,
and Radford Byerly, Jr.

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Short-Term Weather Prediction: An Orchestra in Need of a Conductor

William H. Hooke and Roger A. Pielke, Jr.

In 1863, in the midst of the Civil War, an aspiring weather forecaster, Francis Capen, approached President Lincoln proposing to supply weather forecasts to the Union Army. President Lincoln was not convinced:

> It seems to me that Mr. Capen knows nothing about the weather, in advance. He told me three days ago that it would not rain again till the 30th of April or 1st of May. It is raining now [April 28th] and has been for ten hours. I can not spare any more time to Mr. Capen. (Whitnah 1961, pp. 14–15)

Since that time, the role of weather forecasts in the United States, and indeed around the world, has changed dramatically.[1] Weather forecasts are today a fundamental component of modern life. Forecasts of routine weather are used by individuals to plan what to wear and to schedule activities. They are an essential element in daily decisions in a range of sectors that span the economy: from electric utilities to aviation to insurance (Pielke 1997). Forecasts, and related warnings, of pending extreme weather, like tornadoes or floods, are a centerpiece of emergency response. Weather forecasting has been shown to have predictive "skill" and in many cases provides great benefits to users (Katz and Murphy 1997).[2] Indeed, by way of contrast with other predictive sciences discussed in this volume, the ability of scientists and policy makers to document long-term improvements in skill and related value of weather predictions is unique. At the end of the twentieth century, the greatest challenge facing the weather forecasting community, and those who depend on its products, is to improve the linkage of advances in predictive knowledge with the decision needs of users.[3]

The exchange between Capen and Lincoln well captures the relationship of meteorologists, the public, and the federal government. Meteorologists have sought federal support of their science, promising in exchange benefits to society. For its part, the public, and its elected representatives, have evaluated weather forecasts based on their vast experience with them. For the most part, in recent decades the outcome has been more favorable for the weather community than it was for Mr. Capen. In recent decades the U.S. government has spent tens of billions of dollars on the nation's forecasting enterprise. This includes support for research in federal agencies, operational forecasting, and data gathering (e.g., with radars and satellites) and processing. At the same time, the private sector has developed a robust industry that distributes weather information. Weather predictions are provided to a wide range of interested parties that includes individuals, the media, government agencies, and private corporations. These various players and perspectives have come together in the modern weather prediction system that we see today.[4]

This chapter has three purposes. First, it provides an overview of weather prediction in the United States. Second, it uses three cases—hurricane, tornado, and flood forecasting—to illustrate the challenges to achieving greater benefits from weather forecasts. Third, it discusses at a general level steps needed to overcome those challenges and concludes with a vision for the future of weather services as the nation enters the twenty-first century.

Weather Prediction in the United States

Weather forecasts are the result of measurements and other kinds of information that characterize the state of the atmosphere; computer models based on scientific understanding and statistical relationships; and human judgment. Weather forecasts have been produced for many decades, and thus a considerable body of theory and experience can be used to assess their accuracy. In the early development of chaos theory, Lorenz showed in the 1960s that weather prediction is inherently limited because small errors in knowledge of the current state of the atmosphere propagate into large differences in future states, a phenomenon popularly called the butterfly effect. Because of this inherent uncertainty, scientists estimate that the fundamental limit of weather prediction is about two weeks. Because of the uncertainties associated with predicting the weather, forecasts are inherently *probabilistic*, meaning that numerous events could occur, given a particular forecast. Forecasts are sometimes, but not always, expressed probabilistically (e.g., 70 percent chance of rain).

Institutional Bases

Weather prediction is characterized by some interesting and unique attributes. First, there is the sheer number of short-term weather predictions issued. Within the United States every day, over one hundred National Weather Service (NWS) local forecast offices produce for public consumption a wide range of products, totaling some *24,000 predictions per day or ten million predictions each year*. Second, the historical improvement in short-term weather prediction has been directly related to supporting research (AMS 1991). There is a long track record of forecast improvements, and there is a high degree of community consensus on how to achieve continuing forecast improvements in the near term (NRC 1998). By contrast, examples such as earthquake prediction or beach erosion modeling show that the historical relationship between research and forecast skill is not always obvious, nor is there necessarily agreement among researchers on how best to proceed (see chapters 7 and 8).

Given the large number of short-term predictions and societal contexts available for study, a third attribute of weather prediction is that the opportunities for *evaluating* the societal benefits of improved forecasts are diverse, plentiful, and often very public (e.g., Katz and Murphy 1997). By contrast, the decades or more that it takes for events such as major asteroid impacts and global change to occur make evaluation of the forecasts, much less their actual value, impossible (see chapter 16). Fourth, decision makers find weather information addictive; i.e., as the quality of weather forecasts and their utility have advanced, user demands for information have expanded commensurately (NRC 1999). This in part results from a well-understood tendency of organizations to "systematically gather more information than they use" (Feldman and March 1981). But another reason for this addiction is that, historically, those making weather-sensitive decisions have not had reliable forecasts. As a result they've tended to make decisions that minimize the maximum losses they could face should the weather prove unfavorable, rather than seek to optimize their decisions to take advantage of favorable opportunities. As the accuracy of forecasts has improved, and the time horizon has lengthened, it has been gradually possible to shift to a more aggressive approach to decisions.

Historically, weather prediction has been the province of national governments and international bodies such as the World Meteorological Organization. Modern-day meteorology dates from the invention of the telegraph, which provided the means for scientists to construct a comprehensive "picture" of the weather at regional and global scales. This allowed the tracking of weather systems over time. The modern functional equivalents to the telegraph are technologies such as satellites and radars, which allow for the tracking of weather by synoptic observation. High-speed computing in the second half of the twentieth century has enabled the prediction of the evolution of weather patterns and specific phenomena from hours to days in advance.

The federal government has organized the nation's weather prediction responsibilities into two related areas. First, "operations" are the basis for production and dissemination of official forecasts and warnings. (Operational services are also divided between public-sector predictions, both civilian and military, and private-sector, value-added dissemination and prediction services.) Annually, federal operational weather services in 1999 spent more than $2.2 billion (table 4.1). Related technological development activities—radars, satellites, etc.—account for another $500 million a year (NRC 1998). Private-sector expenditures, including those for the operations of broadcast meteorologists, total more than $1 billion annually (Hererra 1999). Second, research, systems development, and technology development and implementation are supported to improve the skill of predictions. These activities are in some cases tightly coupled to operational efforts, while others have a weaker connection. Research is carried out within both federal laboratories and universities. Research and development, whether in federal laboratories or universities, are largely supported by the federal government and amount to about $500 million each year (OFCM 1998). Thus, on an annual basis resources devoted to the nation's weather forecasting system total more than $4 billion dollars.[5] This system supports many weather-related decisions. Estimates suggest that $1 trillion of the nation's $7 trillion economy is weather sensitive (NRC 1998).

TABLE 4.1
Federal budget for meteorological operations and supporting research, FY 1999 (in thousands of dollars).

Agency	Operations	% of Total	Supporting Research	% of Total	Total	% of Total
Agriculture	$ 12,600	0.6	$ 15,500	4.0	$ 28,100	1.1
Commerce	$1,303,450	59.0	$ 70,768	18.1	$1,374,218	52.9
Defense	$ 438,228	19.9	$ 87,013	22.3	$ 525,241	20.2
Interior	$ 800	0.0	0	0.0	$ 800	0.0
Transportation	$ 448,648	20.4	$ 13,955	3.6	$ 462,603	17.9
EPA	0	0.0	$ 5,700	1.5	$ 5,700	0.2
NASA	$ 2,963	0.1	$197,095	50.5	$ 200,058	7.7
NRC	$ 110	0.0	0	0.0	$ 110	0.0
TOTAL	$2,206,799	100.0	$390,031	100.0	$2,596,830	100.0

As weather prediction capabilities have matured in recent years, a broader spectrum of weather-sensitive industrial sectors has increasingly incorporated weather forecasts on all time scales into its decision making (Pielke 1997). Box 4.1 shows examples of weather impacts on some industries and how improving forecasts could reduce those impacts. In response, the value-added private sector has also matured, building on the government's provision of observations and global models to create specialized weather services for different business interests and other uses. Because of the changing nature of technology and user demands, public and private responsibilities are frequently debated, leading to an uneasy relationship (see e.g., Leavitt 1997).

For many decision makers, alternatives to weather prediction (see, e.g., chapter 14) include a wide variety of practices to make human activities as robust as possible with respect to the variability of weather conditions. For example, South Florida has adopted a building code for wind that is among the strongest in the nation. It has arguably limited that region's total hurricane impacts (Pielke and Pielke 1997). Farmers have the option of planting a mix of crops to ensure some production, whether the summer growing season proves hot or cold, dry or wet, or somewhere in between. More recently, agribusiness, utilities, the recreation sector, and other weather-sensitive industries have turned to weather derivatives and other financial instruments to hedge their seasonal and longer-term weather risks (Salpukas 1999).

The federal role in weather prediction is well codified and clearly stated (for an overview, see U.S. Congress 1979). The nation's policy goals for weather prediction are captured in the 1890 law creating the National Weather Service, which assigned to the NWS responsibility for:[6]

> forecasting of the weather, the issue of storm warnings, the display of weather and flood signals for the benefit of agriculture, commerce, and navigation, the gauging and reporting of rivers, . . . the reporting of temperature and rainfall conditions, . . . the distribution of meteorological information. (15 USC Sec. 313)

Subsequent laws direct the NWS to:

> furnish such weather reports, forecasts, warnings, and advices as may be required to promote the safety and efficiency of air navigation in the United States and above the high seas . . . [and] study fully and thoroughly the internal structure of thunderstorms, hurricanes, cyclones, and other severe atmospheric disturbances . . . with a view to establishing methods by which the characteristics of particular thunderstorms may be forecast.

BOX 4.1

The effects of weather and the potential value of improved weather information for different industrial sectors:

Oil and gas exploration and production

Improved forecasts of tropical weather conditions (wind, waves) could reduce delays in drilling operations at a cost of up to $250,000 per rig per day (there are several thousand rigs in the Gulf of Mexico).

Improved hurricane track predictions could reduce days of production shutdown, each day of which costs the industry and the U.S. Treasury a combined $15,000,000.

Vegetable processing

Improved temperature and precipitation forecasts could lead to greater efficiency in chemical spraying (e.g., pesticides), which costs $10–$15 per acre per application for hundreds of thousands of acres.

On a national scale the annual cost of lost production to the vegetable processing industry, primarily due to weather, is $42,500,000.

Insurance

A single hurricane can lead to more than $80,000,000,000 in damages.

Weather-related catastrophes have led to more than $48,000,000,000 in property insurance claims over the period 1989–93.

Rail transportation

It costs $2,000 per hour to stop a train; a single tornado warning covering fifteen miles of track for fifteen minutes can lead to seven stopped trains.

Most weather-related derailments cost between $1,000,000 and $5,000,000.

Electric power

Improved thunderstorm forecasts could save a single utility $200,000 annually in reduced outage time.

"Good quantitative precipitation forecasts" could save a single utility $2,000,000 over five years.

Improved temperature forecasts could save "hundreds of millions annually nationwide for the utility sector."

Aviation

Every avoided cancellation saves $40,000; every avoided diverted flight saves $150,000.

For the sixteen members of the Air Transport Association, delays and cancellations cost $269,000,000 annually.

The federal government has also expressed its sense that:

> a reliable and comprehensive national weather information system responsive to the needs of national security; agriculture, transportation, and other affected sectors; and individual citizens must be maintained through a strong central National Weather Service that can work closely with the private sector, other Federal and State government agencies, and the weather services of other nations.

In short, weather predictions, and improved use of weather predictions, directly support the following policy goals: safer communities in which to live and work; job growth and economic prosperity; and protection of national security. The clarity, strength, and consistency of this mission is arguably a critical factor in the successes of the weather prediction system.

The Forecast System as a Symphony Orchestra

One of the most important criteria for evaluating weather forecast products is accuracy, defined as the difference between what is forecast and what actually occurs. The more accurate a forecast is, the greater its potential value to a decision maker. Scientists have invested considerable effort in evaluating the accuracy of forecasts, although some have suggested that additional efforts are needed (Doswell and Brooks 1998). The results have shown a long-term improvement in the ability of forecasters to predict the weather, as measured by objective criteria (e.g., NRC 1999). According to the American Meteorological Society (AMS 1991, p. 1273):

> The notable improvement in forecast accuracy that has been achieved since the 1950s is a direct outgrowth of technological developments, basic and applied research, and the application of new knowledge and methods by weather forecasters. High-speed computers, meteorological satellites, and weather radars are tools that have played major roles in improving weather forecasts.

Of course, weather forecasts are far from perfect, but their accuracy (or relative inaccuracy) can be quantified reliably. This track record sets weather forecasting apart from all other predictive earth sciences.

Predictions are produced in the environment of a broader *prediction process,* which includes the production of forecasts, but also communication of forecast information and the incorporation of that information *in user decisions. The process might be thought of as a symphony orchestra in which the different sections must work together harmoniously to produce music (Drucker 1993). The analogue to music in the forecast process is effective decision making with respect to weather.* Often, some mistakenly ascribe a linear relation to the three subprocesses, i.e.:

predict → communicate → use

These three subprocesses are instead better thought of as occurring in parallel, with significant feedbacks and interrelations between them. Table 4.2 illustrates the elements of the forecast process and the outcomes associated with each element.

An accurate forecast is insufficient for effective decision making (Katz and Murphy 1997).[7] More generally, success in any one of the three subprocesses does not necessarily result in benefits to society (e.g., Pielke, 1999, 2000; Doswell and Brooks 1998; Roebber and Bosart 1996; Vislocky, Fritsch, and DiRienzo 1995). A technically skillful forecast that is miscommunicated or misused can actually result in costs to society. Similarly, effective communication and use of a misleading forecast can lead to decisions with undesirable outcomes. For the process to work effectively, success is necessary in all three elements of the forecast process: prediction, communication, and use. Further, success requires healthy connections between the elements; they cannot be considered in isolation, i.e., with the tasks of prediction, communication, and use delegated to isolated or poorly connected parties. Integration of evaluation methods is a necessity. At the interfaces of the elements lie several questions that ought to be asked and answered in a healthy forecast process:

TABLE 4.2

Evaluation methods for elements of the prediction process.

Element of prediction process	Outcome	Criteria of evaluation	Methods of evaluation (example reference)
Prediction	Forecast products	Skill, quality, etc. (Murphy 1997)	Verification
Communication	Guidance	Information transfer (Sorensen 1993)	Survey, interview, etc.
Use	Decisions	Value	Prescriptive/descriptive decision studies, etc. (Stewart 1997; Wilks 1997; Changnon 1997)

Between Prediction and Use

- What ought to be predicted?
- How are predictions actually used?

Between Prediction and Communication

- What does the prediction mean in operational terms?
- How reliable is the prediction, and how is uncertainty conveyed?

Between Use and Communication

- What information is needed by the decision maker?
- What content or form of communication leads to the desired response?

Because the forecast process is composed of multiple elements, no single measure captures the societal "goodness" of a forecast process. Instead, multiple measures are needed to evaluate the technical, communication, and decision dimensions of forecasts. Table 4.2 also summarizes some of those measures. Typically, policy makers have focused attention on the economics of forecasts in order to determine a bottom-line assessment of value, while social scientists have studied the communication process (e.g., warnings) and physical scientists have evaluated forecasts according to technical criteria like skill scores and "critical success indexes." These different foci are clearly important and necessary; however, the segregation of evaluation tasks has meant that no one is responsible for evaluation of the entire forecast process. The result is that we try to improve the system by working on its components while ignoring critical interactions visible only from a more comprehensive perspective.

Consequently, when policy makers or other users of weather forecasts ask the general question "What is the value of an improved forecast?" and expect to get an aggregate answer in dollars or lives, they ask the wrong question. They ought instead to ask "What changes to the existing forecast process (predict, communicate, use) can we expect to lead to better outcomes?" and expect the answer to be contextual, multidimensional, and subjective. Consider the following examples in hurricane, tornado, and flood forecasting.[8]

Case: Hurricane Forecast Improvements

Forecasts of hurricane motion have become increasingly accurate in recent decades, but it is not clear how those improvements have led to improved decision making. Figure 4.1 shows the improvement in hurricane track predictions for 24-, 48-, and 72-hour forecasts. But at the same time, the actual length of coastline warned per storm by the

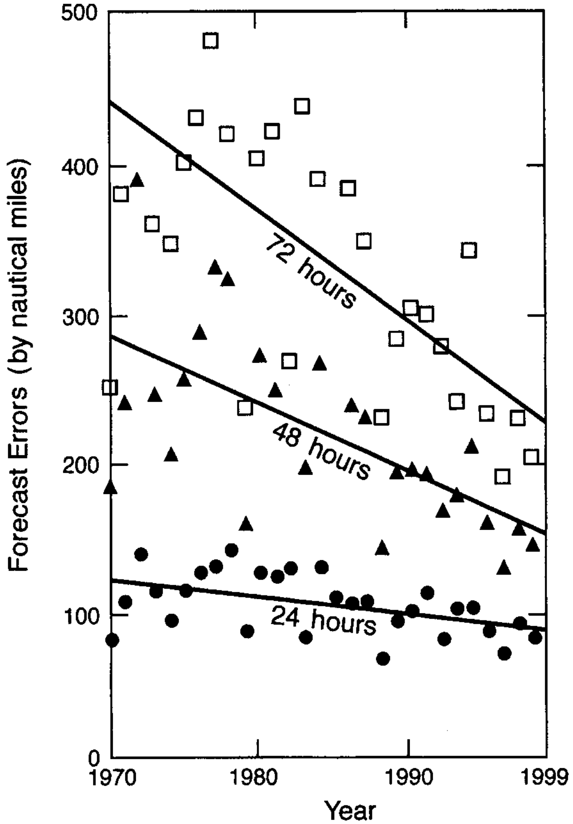

Fig. 4.1 Improvement in accuracy of hurricane track forecasts, 1970–98. Circles are 24-hour forecasts, triangles are 48-hour forecasts, and squares are 72-hour forecasts. (Data courtesy of Tropical Prediction Center and National Hurricane Center)

National Hurricane Center (NHC) has increased from less than 300 nautical miles (nm) in the late 1960s to about 400 nm over the past ten years, as shown in figure 4.2. This at first seems counterintuitive because if the hurricane track is better known, it would seem that areas believed not to be at risk (because of improved track predictions) would not need to be warned. The length of coastline warned is important because it dictates how many people will be ordered to evacuate and will otherwise choose to prepare for the storm.

According to Jarrell and DeMaria (1999), "The increase is somewhat surprising, because, since 1970 . . . [errors in] official NHC track fore-

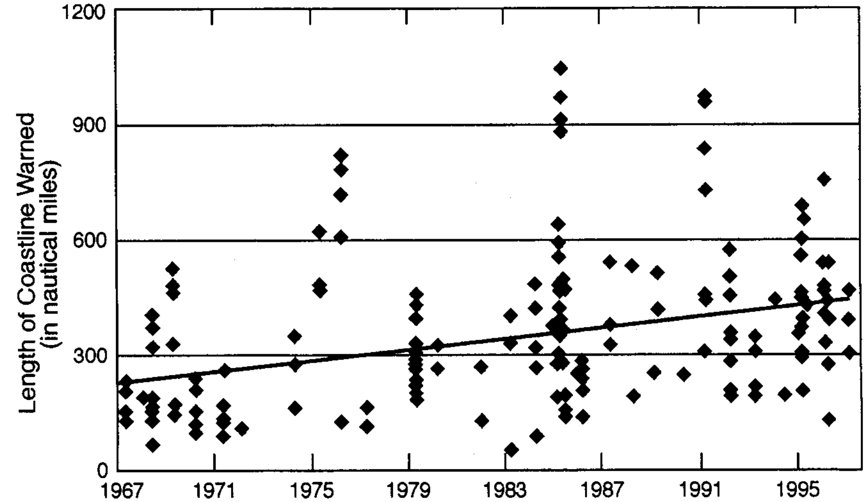

Fig. 4.2 Scattergram and linear trend line of the length of the U.S. coastline included in hurricane warnings 1967–97. (Data courtesy of Tropical Prediction Center, National Hurricane Center, and NESDIS/CIRA, as shown in Jarrell and DeMaria 1999)

casts have been decreasing at about 1% per year." Jarrell and DeMaria speculate that the improvement in track forecasts has translated into longer lead times for evacuation decisions. Lead time, from the time the first warning is issued to the time that the storm's center crosses the coast, has increased from about 18 hours to 24 hours. Increased lead time results in more miles of coastline warned because of the larger uncertainty associated with predictions made for longer periods, as shown in figure 4.1. This could be an example of the forecast process working in a healthy manner—i.e., for many decision makers an increase in lead time could be a worthwhile tradeoff with miles of coastline warned.

But there are other possible explanations for the upward trend in miles of coastline warned, including (a) the desire of emergency managers (and elected officials) to shift accountability to other sources by requesting that NHC warnings be extended to cover their communities; (b) a desire throughout the evacuation decision process to avoid the error of a strike on an unwarned population (thus, translating the forecast improvement into lower risk); and (c) the fact that more and more people inhabit the coast, meaning that evacuation times are much greater, making necessary longer lead times and lengths of coastline warned. Unfortunately, despite these hypotheses, it has not been convincingly demonstrated why the length of coastline warned per storm has increased during a period of decreasing forecast errors and whether this increase confers a net benefit or cost on society. In this instance, no one has assessed whether the orchestra is in fact making music.

Given the large costs involved with overwarning, both in unnecessary preparations including evacuations and in potential public disgust with false alarms, causing them to ignore subsequent warnings (see Dow and Cutter 1998), it would seem to be in the best interests of forecasters, policy officials, and the general public to obtain a greater understanding of the use of hurricane forecasts. The hurricane research community has made a convincing case that it is well positioned to make dramatic advances in the science of forecasting (Marks, Shay, and Prospectus Development Team #5 1996)—but for forecasts to be effectively used by decision makers, and thus to be of significant benefit to society, there must at the same time be advances in the scientific understanding of how hurricane forecasts are used in the decision-making process.

Case: Tornado Verification Statistics

On Monday, May 3, 1999, more than seventy tornadoes tore through Oklahoma and Kansas, killing forty-six people, injuring scores more, and resulting in more than $1 billion in damage. The National Weather Service called the outbreak one of the most severe in this country in the past fifty years. According to Doswell (1999), one of the nation's experts on tornadoes, two important factors kept loss of life from being even higher. One was luck—in that the storm did not strike in the middle of the night or cross a busy interstate crowded with rush-hour traffic. The second was that the nation's severe-weather infrastructure performed admirably in a region where people take official warnings seriously and are prepared to respond to them. The event was but one of many that recently have underscored the importance of the nation's forecasting system.

But with increasing importance to the nation comes more visibility and responsibilities, and ultimately greater demands from the public to improve the forecast process. Future improvements in the forecast process, perhaps defined in this case by some measure of lives lost related to tornadoes, depend on knowing the reasons behind past successes and failures.

Figure 4.3 shows that the nation has gone from an average annual loss of life to tornadoes of more than 300 per year in the 1920s to less than 100 per year in the 1990s (Brooks 1999). The data are even more striking when considered in the context of the nation's population

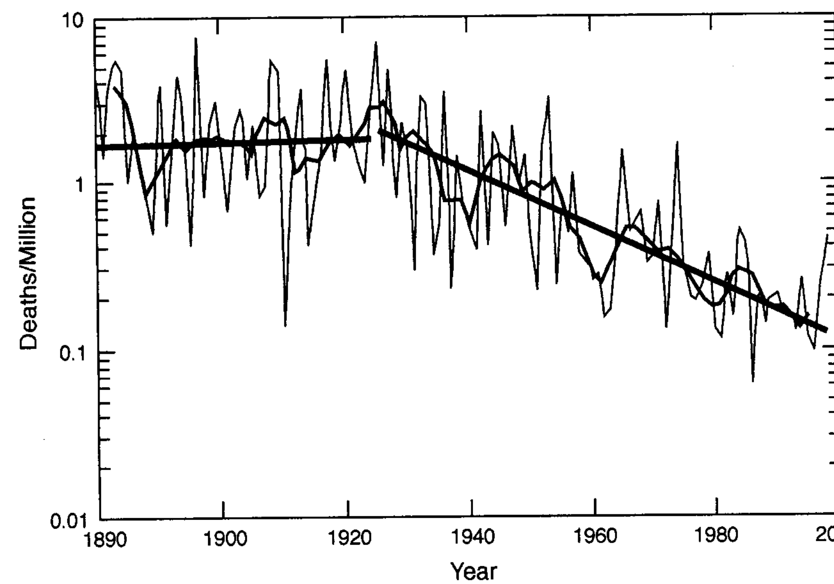

Fig. 4.3 Decrease in incidence of tornado deaths per unit of population, 1880–1998. (Source: Doswell and Brooks 1998)

growth. From 1880 to 1924 the death rate from tornados was about 1.8 per million; by 1997 it had declined to 0.14 per million. Considering that losses have decreased steadily since the 1920s, yet official tornado warnings date only to 1948, Brooks admits:

> I cannot explain the decrease. Lots of things contribute—improved forecasts and warnings, communication of warnings, better housing, the movement of people from rural areas to urban areas, less time being spent outdoors, etc. Before we, in the meteorological and preparedness communities pat ourselves on the back, it is important to note that lightning deaths also show a decreasing trend over this time period, but we do little forecasting or preparedness work on that problem, in comparison to tornadoes.

Others have criticized how the National Weather Service evaluates its severe weather forecasts. (See, for example, Pettit 1999, Brooks 1999.)

If the economic and other impacts associated with tornadoes increase in absolute terms, demands from the public and policy makers for the weather community to do something will also increase. In fact, impacts associated with most types of extreme weather are expected to increase, simply because of the growing population of the nation (see

Kunkel, Pielke, and Changnon 1999). The weather prediction system will be able to respond to such demands more effectively if the people who manage it better understand the relationship between its products and societal outcomes. The National Weather Service could conduct research needed to gain that understanding, or, perhaps more appropriately, an independent entity could oversee the needed studies (cf. chapter 12). The bottom line is that if the nation expects decreased impacts from tornadoes, then it must better understand the relationship of weather forecasts and societal outcomes. Once again we see that little attention has been paid to the overall performance of the "orchestra."

Case: Red River Floods

In April 1997, the Red River of the North, which flows north along the North Dakota–Minnesota border, experienced extreme flooding (this event is also discussed in chapter 5). Damages related to the event have been estimated at $1–2 billion, with most damage occurring in Grand Forks, North Dakota, and East Grand Forks, Minnesota. Through the spring the NWS had been predicting a flood crest (i.e., a maximum river level) of forty-nine feet at East Grand Forks, which would have been a record, but the actual crest was fifty-four feet. This discrepancy contributed to decisions that arguably exacerbated the damages, such as failure to remove personal property from the areas at risk or "sacrificing" parts of the community to allow more water to pass through the town. In the aftermath of the event, considerable attention was focused by policy makers on flood predictions and their role in decisions that preceded the peak flooding (see Pielke 1999 for an in-depth discussion of this case).

Figure 4.4 shows historical overestimates and underestimates of recent Red River flood crests. By historical standards, the forecast of the 1997 flood crest was not unusually inaccurate. Given that the forecast was for a record event, i.e., one for which there was no experience, the forecast was arguably much better than many issued in previous years. In interviews conducted in May 1997 with various decision makers in the Red River of the North basin, it is clear that different people interpreted the NWS prediction in different ways. Some viewed the flood crest forecasts as a maximum, i.e., a value that would not be exceeded. For example, on April 8, 1997, the *Grand Forks Herald* reported that "[NWS] experts are still forecasting a maximum 49-foot crest for the Red at East Grand Forks." Others viewed the prediction as exact, i.e., that the crest would be forty-nine feet. Still others viewed the outlook as somewhat uncertain; examples of the degree of uncertainty ascribed to the prediction by various decision makers ranged from one to six feet.

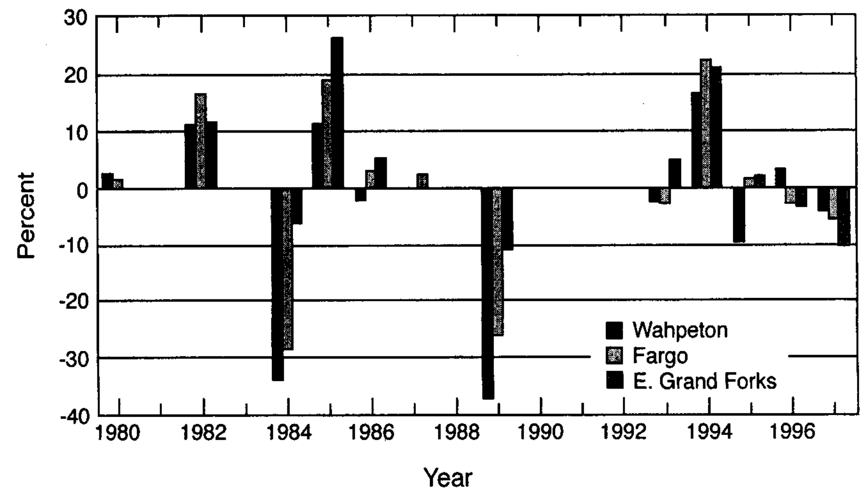

Fig. 4.4 Prediction error at Wahpeton, Fargo, and East Grand Forks, North Dakota, as a percentage. (Source: North Central River Forecast Center)

While scholars have long recognized that communication involves both *sending* and *receiving* information, little attention has been paid to the manner in which flood forecasts are interpreted by decision makers, and subsequently, to the role of this information in the forecast process. In short, it is apparent that the use and value of existing flood forecasts are not well understood, much less the potential usefulness and value that might be attained through "improving" the overall forecast process. Other recent experience suggests that this circumstance may be fairly common in flood forecasting in general (e.g., see chapter 5) and in other areas of prediction as well (e.g., see chapters 6, 8, and 12).

All three of these cases show that the challenge of more effective use of forecasts cannot be solved by simply providing more information, such as by improving the accuracy of existing products or developing new products, e.g., probabilistic forecasts. If decision makers have difficulty using existing products, these difficulties will not go away simply through providing more or "better" information. Indeed, several recent studies of judgment suggest that as the amount of information available increases, the judgment process may actually become less reliable due to information overload, especially in contexts of high uncertainty and high risk such as the forecasting of extreme events like hurricanes, tornadoes, and floods (e.g., see Stewart et al. 1992). More attention must be paid to how forecasts are issued, who actually receives what information, and with what effect.

From Research to Societal Benefit

What stands in the way of achieving improvements in the overall forecast process? The most common answer is that improvements are constrained by limited resources—resources for research, for computers, for forecasters, for training and education, and so on. More research, faster computers, more (and better trained) forecasters can demonstrably lead to better predictive capabilities (e.g., NRC 1999), but better predictive capabilities are at best a necessary but insufficient condition for improving the overall process. It is as if an orchestra's conductor were to focus only on the string section to the exclusion of the horns and percussion. The situation was aptly summarized by a colleague who said, "As forecasters, the gap between what we know and what we communicate to the public has never been larger." But if that view is correct, and society is not fully making use of the knowledge and resources that it already has, policy makers may rightly ask what would be the point of adding more resources to the system, unless at the same time we improve the forecasting process itself.

Twenty years ago, the administrator of the National Oceanic and Atmospheric Administration (NOAA) wrote to the president of the National Academy of Sciences to ask that the academy conduct a study to assess how advances in science and technology could best lead to an improved forecasting system for the nation. In its report (NRC 1980), the academy concluded that there was a need for new observing systems, improved computer systems, and better communication systems. But the report also noted, "The rate of progress toward better services is not limited by technology"—and, by extension, not by resources for technology. Instead, the constraint was an "inadequate mechanism for transferring weather and hydrological information and knowledge of applications to specific users." That statement clearly went beyond matters of *forecast production* to the broader issue of the *forecast process*. It seems clear that—even twenty years after the academy report—the weather community has yet to fully and systematically address the challenge of understanding the factors necessary and sufficient for advances in science and technology to most effectively contribute benefits to society.

The nation has invested considerable resources in the development of understanding and technologies to meet the expected demands of its citizens for improved forecasts. These include the modernization of the National Weather Service and the U.S. Weather Research Program. Regrettably, many of the fruits of those investments have not been transferred via an effective forecast process into useful products for decision makers; hence, benefits to the nation are much less than they might be. Examples include data from satellites and radars that are not fully or effectively used (Dabberdt and Hales 1998), techniques for the manipulation of data that are understood but not used (Schlatter et al. 1999), and knowledge of human judgment that is not incorporated into the development of useful products (Pielke 1997). At the core of such problems is a mismatch between the weather forecasting system's capability of producing scientific and technological advances and of translating those advances into useful information. A challenge facing the nation is thus to implement an improved forecasting process that takes full advantage of our continuing national investment in observations, research, and technology. Without enabling an improved forecast process—spanning research to societal benefit—the nation will not fully benefit from its ongoing investments, and may thus fail to meet society's growing expectations of weather prediction.

As the United States moves into the twenty-first century, the nation expects greater accuracy, timeliness, and reliability in weather forecasts, as well as an increased number of useful products (NRC 1998). In an improved forecasting process, such products could play an increasingly important role in both public- and private-sector decision making. Furthermore, an improved forecast process could provide expanding opportunities to better protect life and property, stimulate economic activity, enhance national competitiveness, and contribute to environmental management (NRC 1998).

Because the nation has not fully benefited from its weather investments, many scientists are concerned that funders will react by reducing support for research. But this would be a mistake and would run contrary to the need to view weather forecasting as a prediction process. It would be much as if the owner of a grocery store with a backlog of bread on its shelves were to address the problem by telling farmers to stop planting wheat. The issue is not like regulating flow through a pipeline, but rather like managing numerous parallel processes to form a coherent whole—like trying to get a symphony orchestra to produce music. Thus, a central challenge facing the community is to identify opportunities to improve the existing forecast process and to recommend alternative courses of action necessary and sufficient to open the way to more effective and efficient capitalization of the ongoing investment in weather forecast research and technology.

A limitation more fundamental than that of resources is that of leadership. If the forecast process is indeed like a symphony orchestra, then it suffers from the lack of a conductor. No one has assumed responsibility for the task of improving the forecast process. A committee of the National Academy of Sciences has arrived at a consistent conclusion in a broad review of atmospheric research: "No one sets the priorities; no one fashions the agenda" (NRC 1998, p. 58). While many participants in the nation's forecasting system agree that the process *should* be improved (by someone), the community has not organized itself to systematically evaluate the existing process and implement improvements. There are candidate conductors, such as the National Weather Service, which issues forecasts, and the U.S. Weather Research Program, which seeks to better understand the science of weather, including impacts, forecasts, and use. But until responsibility to improve the process is assumed, it is likely that a gap will continue to exist, if not broaden, between knowledge of weather forecasting and its effective use. The recommendation of specific steps to improve the forecast process goes beyond the scope of this chapter, but some steps are being taken. The National Research Council, for instance, has begun to study the issue, which marks a significant departure from its traditional focus on natural science research isolated from societal application. However, without recognition that it is the process that needs attention, not simply improvement in forecast products, even the best-intentioned advice is likely to fall short of achieving the nation's potential in outcomes related to weather prediction.

The Future of Weather Services

The following exchange on the subject of hurricane forecasts took place between a member of Congress and a National Weather Service official during a 1993 congressional hearing on the performance of the agency in several instances: Hurricane Andrew in 1992, the 1993 "Superstorm" East Coast blizzard, and the Midwest floods of 1993 (U.S. Congress 1993):

> Member of Congress: Have we ever undertaken a study that . . . would try to analyze . . . a cost benefit analysis of whether we . . . are actually dollars ahead in terms of the ability to predict whether or not hurricanes are going to hit, when they are going to hit, where they are going to hit, how they are going to hit, how hard they are going to hit? . . . Has it been worth [the investment in prediction]?
>
> NWS Official: Okay. First, you respond for protection of life . . . second, with a warning, you can indeed protect your property so you have much less loss . . .
>
> Member of Congress: I understand that. But have we ever done an analysis that would compare the amount of money

> that has been spent preparing for hurricanes that have not occurred against the amount of money that would be saved or that is saved in preparing for the one that does occur? . . .
>
> NWS Official: . . . Okay. It's a tremendous savings there . . .
>
> Member of Congress: Wait, excuse me. I am sorry, but my question is: Has that sort of analysis ever been attempted or performed?
>
> NWS Official: I don't think it has been done in detail.

The exchange between the member of Congress and the NWS official illustrates the significance of understanding the weather forecast process. The member of Congress wanted to know the relationship between funds appropriated to hurricane forecasting and the outcomes that result, with outcomes defined societally, not technically. Presumably, such information could be used by Congress to help set priorities for weather spending versus the myriad other items on its agenda. Knowledge of the effectiveness of the forecasting process is thus squarely in the public interest.

But the answer of the NWS official is representative of the broader circumstance: policy makers lack information that would allow for systematic, comprehensive answers to questions about the forecast process: "Somewhat surprisingly . . . relatively little attention has been devoted to determining the economic [or other societal] benefits of existing weather forecasting systems or the incremental benefits of improvements in such systems" (Katz and Murphy 1997). As a result, all users and potential users of forecast information suffer. Debate and discussion of the health of the weather forecasting process depends more on unverified anecdotes, optimistic assumptions, and simple politics than on reliable information and systematic analysis (cf. GAO 1996, 1997).

If leadership in the weather prediction community comes forward and implements steps to better understand the forecasting process as an integrated system—as compared to a simple understanding of the discrete elements of that process focused on products—then the following sort of exchange might be expected to occur between a member of Congress and an NWS official at some point in the near future, to the benefit of policy makers, the weather community, and an entire nation that has grown dependent on its weather forecast system:

> Member of Congress: Once again, your agency has come before this committee with a request for a budget increase in

order to improve forecasts. Now you realize that each agency under this committee's jurisdiction is asking for an increase. Fiscal realities dictate that budget increases will be difficult. Have you any information that would lead this committee to expect that the increased investment you have requested will yield a societally beneficial outcome?

NWS OFFICIAL: I'm glad you asked that question. In fact, over the past several years we have completed a number of studies on the forecast process that cover the interrelated aspects of prediction, communication, and the use of forecast information in decision making. In addition to these retrospective evaluations, we have conducted several forward-looking analyses that, while preliminary, suggest a number of contexts in which decision making can improve, with the following potential benefits expected from this year's request . . .

Notes

1. This chapter focuses on weather forecasting in the United States. We use the terms *forecast* and *prediction* interchangeably throughout this chapter.
2. *Skill* is defined as a prediction's improvement over a baseline measure of performance.
3. The first of ten recommendations in a 1999 National Research Council report on the future of the National Weather Service was that the organization, and its parent agency, NOAA, "should more aggressively support and capitalize on advances in science and technology to increase the value of weather and related environmental information to society" (NRC 1999, p. 1).
4. Throughout this chapter the term *forecast system* is used to refer to the institutions, infrastructure, and resources that are involved with the production, communication, and use of weather predictions.
5. NASA's Earth Observing System is not usually associated with weather prediction; however, its data products could be used for that purpose (NRC 1999), in which case the total would increase by more than $1 billion.
6. See chapter 5 for a brief history of the National Weather Service. See Whitnah (1961) for an in-depth history.
7. There are also obviously situations in which a forecast is unnecessary for effective decision making. Understanding when and when not to rely on predictions is an essential aspect of the effective use of prediction. See chapter 14.

8. These examples focus on the prediction of extreme weather. A similar case can be made for the importance of prediction of "routinely disruptive" weather, see Pielke 1997 for discussion.

References

AMS (American Meteorological Society). 1991. Weather forecasting: A policy statement of the American Meteorological Society as adopted by the Council on 13 January 1991. *Bulletin of the American Meteorological Society* 72:1273–1276.

Brooks, H.E. 1999. Observed record—All tornados and deaths. In *Tornado-related items,* unpublished document on Internet, www.nssl.noaa.gov/~brooks.

Changnon, S.A. 1997. *Assessment of uses and values of the new climate forecasts.* Boulder, CO: University Corporation for Atmospheric Research.

Dabberdt, W., and J. Hales. 1998. *Nowcasting and predictions for urban zones.* Report of the Prospectus Development Team #10 of the U.S. Weather Research Program. Online at uswrp.mmm.ucar.edu/uswrp/PDT/PDT10.html.

Doswell, C.A., III. 1999. *Tornados: Some hard realities,* unpublished copyrighted manuscript on Internet at www.wildstar.net/~doswell/Tornado_essay.html.

Doswell, C.A., III, and H.E. Brooks. 1998. Budget cutting and the value of weather services. *Weather and Forecasting* 13:206–212.

Dow, K., and S.L. Cutter. 1998. Crying wolf: Repeat responses to hurricane evacuation orders. *Coastal Management* 26:237–252.

Drucker, P.F. 1993. *Post-capitalist society.* New York: HarperCollins.

Emanuel, D., E. Kalnay, and Prospectus Development Team #7. 1996. *Observations in aid of numerical weather prediction for North America.* Report of the Prospectus Development Team #7 of the U.S. Weather Research Program. Online at uswrp.mmm.ucar.edu/uswrp/PDT/PDT7.html.

Feldman, M.S., and J.G. March. 1981. Information in organizations as signal and sign. *Administrative Science Quarterly* 26:171–186.

GAO (General Accounting Office). 1996. *NWS has not demonstrated that new processing system will improve mission effectiveness.* Report no. GAO/AIMD-96-29. Washington, DC: GAO.

GAO (General Accounting Office). 1997. *National Weather Service: Closure of regional offices not supported by risk analysis.* Report no. GAO/AIMD-97-133. Washington, DC: GAO.

Glantz, M.H., and L.F. Tarleton. 1991. *Mesoscale research initiative: Societal aspects.* Report of the workshop December 10–11, 1990. Boulder, CO: Environmental and Societal Impacts Group, National Center for Atmospheric Research.

Grand Forks Herald. 1997. *Come hell and high water: The incredible story of the 1997 Red River flood.* Grand Forks Herald, Box 6008, Grand Forks, ND 58206-6008.

Herrera, S. 1999. Weather wise. *Forbes* (June 14). Online at www.forbes.com/forbes/99/0614/6312090a.htm.

Jarrell, J.D., and M. DeMaria. 1999. An examination of strategies to reduce the size of hurricane warning areas. In *Twenty-third conference on hurricanes and tropical meteorology,* vol. 1. Boston: American Meteorological Society, pp. 50–52.

Katz, R.W., and A.H. Murphy, eds. 1997. *Economic value of weather and climate forecasts.* Cambridge, UK: Cambridge University Press.

Kunkel, K.E., R.A. Pielke, Jr., and S.A. Changnon. 1999. Temporal fluctuations in weather and climate extremes that cause economic and human health impacts: A review. *Bulletin of the American Meteorological Society* 80(6):1077–1098.

Leavitt, M.S. 1997. Testimony of the Commercial Weather Services Association before the Subcommittee on Energy and Environment, U.S. House of Representatives, April 9. Downloaded from www.house.gov/science/leavitt_4-9.html.

Marks, F., L. Shay, and Prospectus Development Team #5. 1996. *Landfalling tropical cyclones: Forecast problems and association research opportunities.* Report of Prospectus Development Team #5 of the U.S. Weather Research Program. Online at uswrp.mmm.ucar.edu/uswrp/PDT/PDT5.html.

Murphy, A.H. 1997. Forecast verification. In *Economic value of weather and climate forecasts*, R.W. Katz and A.H. Murphy, eds. Cambridge, England: Cambridge University Press, pp.19–74.

NRC (National Research Council). 1980. *Technological and scientific opportunities for improved weather and hydrological services in the coming decade.* Washington, D.C.: National Academy Press.

NRC (National Research Council). 1998. *The atmospheric sciences: Entering the twenty-first century.* Washington, DC: National Academy Press.

NRC (National Research Council). 1999. *A vision for the National Weather Service: Road map for the future.* Washington, DC: National Research Council.

OFCM (Office of the Federal Coordinator for Meteorology). 1998. *The federal plan for meteorological services and supporting research for fiscal year 1999.* FCM-P1-1998. Washington, DC: OFCM.

Pettit, P. 1999. *A review of National Weather Service severe weather warning statistics, 1994–1997.* Unpublished document on the Internet, www.weatherconsultant.com/Verification.html.

Pielke, R.A. Jr. 1999. Who decides? Forecasts and responsibilities in the 1997 Red River flood. *Applied Behavioral Science Review* 7:1–19.

Pielke, R.A., Jr. 2000. Policy responses to the 1997/1998 El Niño: Implications for forecast value and the future of climate services. In *The 1997/1998 El Niño in the United States,* S. Changnon, ed. Oxford, England: Oxford University Press.

Pielke, R.A., Jr., ed. 1997. *Workshop on the Social and Economic Impacts of Weather.* Proceedings of workshop held April 2–4, 1997, in Boulder, Colorado. Boulder, CO: Environmental and Societal Impacts Group, National Center for Atmospheric Research.

Pielke, Jr., R.A., and R.A. Pielke, Sr. 1997. *Hurricanes: Their nature and impacts on society.* Chichester, England: John Wiley and Sons.

Roebber, P.J., and L.F. Bosart. 1996. The complex relationship between forecast skill and forecast value: A real-world comparison. *Weather Forecasting* 11: 544–559.

Salpukas, A. 1999. Firing up an idea machine: Enron is encouraging the entrepreneurs within. *New York Times,* Sunday, June 27, Section 3, p.1.

Schlatter, T.W., F.H. Carr, R.H. Langland, R.E. Carbone, N.A. Crook, R.W. Daley, J.C. Derber, and S.L. Mullen. 1999. *A five-year plan for research related to the assimilation of meteorological data.* Report of USWRP Workshop on Data Assimilation, December 9–11, 1998. Internet: uswrp.mmm.ucar.edu/uswrp/reports/five_year_plan/title.html.

Sorenson, J.H. 1993. Warning systems and public warning response. Paper prepared for January workshop *Socioeconomic Aspects of Disaster in Latin America.* Oak Ridge, TN: Oak Ridge National Laboratory, pp. 1–15.

Stewart, T.R. 1997. Forecast value: Descriptive decision studies. In *Economic value of weather and climate forecasts,* R.W. Katz and A.H. Murphy, eds. Cambridge, England: Cambridge University Press, pp. 147–182.

Stewart, T.R., W.R. Moninger, K.F. Keideman, and P. Reagan-Cicerone. 1992. Effects of improved information on the components of skill in weather forecasting. *Organizational Behavior and Human Decision Processes* 53:107–134.

U.S. Congress. 1979. *Atmospheric Services and Research and a NOAA Organic Act.* Report prepared for Subcommittee on Natural Resources and Environment of the Committee on Science and Technology, U.S. House of Representatives, 96th Cxongress.

U.S. Congress. 1993. *NOAA's response to weather hazards—Has nature gone mad?* Hearing before Subcommittee on Space of the Committee on Science, Space, and Technology, 103rd Congress, September 14. Washington, DC: U.S. Government Printing Office.

Vislocky, R.L., J.M. Fritsch, and S.N. DiRienzo. 1995. Operational omission and misuse of numerical precipitation probabilities. *Bulletin of the American Meteoroligical Society* 76:49–52.

Whitnah, D.R. 1961. *A history of the United States Weather Bureau.* Urbana: University of Illinois Press.

Wilks, D.S. 1997. Forecast value: Prescriptive decision studies. In *Economic Value of Weather and Climate Forecasts,* R.W. Katz and A.H. Murphy, eds. Cambridge, England: Cambridge University Press, pp. 109–146.