

SOCIETAL AND ECONOMIC RESEARCH AND APPLICATIONS FOR WEATHER FORECASTS

Priorities for the North American THORPEX Program

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Societal and economic research and applications can significantly improve understanding of weather–society interactions, benefiting the meteorological community and society.

Hazardous weather-related events cause thousands of deaths and billions of U.S. dollars in damage each year worldwide.¹ Weather also affects many socioeconomic activities, ranging from agriculture to transportation to water resource management. Because of weather's significant effects on society and the economy, decision makers have

grown to rely on weather forecasts provided by the meteorological community. Yet significant gaps remain among the weather forecast information available, its use in decisions, and desired societal outcomes such as reduced deaths, reduced damage, and enhanced well-being. These gaps between weather forecasts and their societal benefits can be illustrated by numerous examples, ranging from high-profile cases—such as the 2003 European heat wave and 2005's Hurricane Katrina—to experience with forecasts and outcomes in local weather events. Related gaps are evident in areas such as flood prediction, seasonal climate prediction, and climate change (e.g., Pielke 1999; Sarewitz et al. 2000; Lemos et al. 2002). As these examples indicate, one cannot, a priori, assume that forecasts will be useful and valuable without considering how they interact with societal decisions and outcomes. In order to enhance weather forecast use and help realize the potential value

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The abstract for this article can be found in this issue, following the table of contents.

DOI:10.1175/BAMS-89-3-335

In final form 23 October 2007
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¹ From www.wmo.int/pages/madrid07/, compiled from S. G. Cornford reviews in WMO Bulletin, 1998–2003. Related statistics for the United States can be found in NRC (1998) and Pielke and Carbone (2002).

of forecasts, we as a community must address not only physical science and technology aspects of the weather forecasting system, but also socioeconomic aspects.²

The weather prediction community has recognized the importance of socioeconomic and policy research for decades (e.g., Fleagle and Wolff 1979; Glantz and Tarleton 1991; Pielke and Kimple 1997; NRC 1998, 2003a, 2006; WMO 2003; Gladwin et al. 2007), but despite years of discussion and dispersed effort, research on socioeconomic aspects of weather forecasts has not reached the critical mass required to meet the needs of the weather enterprise (e.g., Pielke and Kimple 1997; Pielke and Carbone 2002; WMO 2003). This article seeks to catalyze interest in societal and economic research and applications (SERA) within the meteorological and social science communities. It does so by exploring key socioeconomic issues related to weather forecasts and proposing SERA priorities for the next decade. A robust SERA effort integrated with other weather activities will improve understanding of socioeconomic aspects of weather forecasts, advance fundamental interdisciplinary knowledge, identify new questions for the meteorological research, and aid development of new and improved forecast applications. The resulting knowledge will help meteorologists provide more useful and more valuable forecast information, benefiting the meteorological community and society.

A robust SERA effort will also help meteorologists explain the societal importance of weather research and forecasting to policy makers and others, motivating current and future investments. Because of budgetary pressure, hydrometeorological services and programs are facing demands to identify, measure, and enhance societal benefits of weather prediction (NRC 1998; Pielke and Carbone 2002; Zillman 2005; Rogers et al. 2007). People involved in advocating meteorological programs to non-meteorologists report that addressing societal aspects cursorily, without sound evidence and concrete

examples, often fails to be convincing. If addressing societal concerns is important to policy makers, funders, and sponsors, we believe the meteorological community will achieve more success by doing so through partnerships among meteorologists, forecast users, and social scientists.

The concepts and priorities we present were articulated largely under the auspices of the North American THORPEX program, with input from meteorologists and social scientists who participated in a North American THORPEX SERA workshop in Boulder, Colorado, in August 2006.³ Participants included more than 40 U.S., Canadian, and Mexican researchers and practitioners from a broad range of disciplines, as well as representatives from the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the North American and International THORPEX programs.⁴ The World Meteorological Organization's (WMO) THORPEX: A Global Atmospheric Programme is an international research and development program that aims to "accelerate improvements in the accuracy of one-day to two-week high-impact weather forecasts for the benefit of society, the economy and the environment" (WMO 2005) in the developed and developing world. THORPEX has explicitly incorporated SERA from the start, as one of four areas of emphasis (Shapiro and Thorpe 2004). While North American THORPEX facilitated the development of the ideas presented here and the resulting priorities are being incorporated into North American and U.S. THORPEX planning (e.g., USTSSC 2007), they are highly relevant to all weather forecasting efforts and are presented here with that perspective in mind.

We start by discussing connections with related efforts and two cross-cutting topics that underlie SERA activities. Next, we present five priority themes for weather-related SERA research:

- understanding the use of forecast information in decision making;
- communicating weather forecast uncertainty;

² Socioeconomic aspects of weather forecasts include non-physical-science aspects of weather forecast generation, provision, communication, interpretation, use, impacts, and value, as well as the societal and policy context in which these activities occur. This includes a broad range of issues from economic, decision making, communication, sociological, political, policy, institutional, cultural, applications, and other perspectives. Examples of socioeconomic issues to be considered are provided throughout the paper and in the references provided here and at www.sip.ucar.edu/thorpex/. Further examples are provided in the bibliographies at <http://sciencepolicy.colorado.edu/biblio/index.html> and www.sip.ucar.edu/wasis/background.jsp.

³ THORPEX formerly stood for The Observing System Research and Predictability Experiment. The international THORPEX program looks to regional efforts by groups of nations, such as North America, to implement and, in some cases, establish research priorities.

⁴ A list of workshop attendees is available at www.sip.ucar.edu/thorpex/participants.jsp.

- developing user-relevant verification methods;
- estimating the economic value of weather forecasts; and
- developing decision-support systems and tools.

These priorities, while not exhaustive, were selected because they simultaneously address critical societal needs for weather forecasts, connect with weather prediction community interests, and are at the intellectual forefront of social science and interdisciplinary research. We then discuss SERA research integrated across the five themes and with other meteorological research. We close by recommending next steps, looking back at previous related efforts, and looking forward to new opportunities. The ideas presented are the authors' collective interpretation of community interests and needs, reflecting contributions from many additional meteorologists and social scientists that resonated at the workshop and in other discussions.

The interdisciplinary and social science research concepts and methods required to examine societal aspects of weather are unfamiliar to many atmospheric scientists. To bridge this gap, one goal of the article is to familiarize nonexperts with key SERA ideas and methods. The discussion of each research priority therefore begins with a brief overview for nonexperts. It then continues by articulating interesting topics for research, highlighting possible foci and methods. Although the article summarizes concepts and priorities briefly without extensively citing previous work, further background knowledge, more detailed discussions of research questions and methods, and additional references can be found in the workshop theme papers, workshop report, and other materials available at www.sip.ucar.edu/thorpex.

If weather prediction and THORPEX are to realize their potential societal benefit, another important issue is collaboration among developed and developing countries. While not addressed in the article, this topic was discussed at the workshop; further information can be found on the workshop web site.

CONNECTIONS WITH RELATED EFFORTS. This article and the THORPEX SERA program build on several previous efforts to motivate weather/society research and develop related research agendas. These include workshops on societal aspects of weather for the Mesoscale Research Initiative (Glantz and Tarleton 1991) and the U.S. Weather Research Program (Pielke and Kimple 1997) and work within the World Weather Research Program

(Anderson-Berry et al. 2004). Our ideas also build on previous work in socioeconomic aspects of weather (e.g., Pielke et al. 2000; Scharff et al. 2004; Katz 2006; NOAA 2006); in related areas such as seasonal-to-interannual climate prediction, climate change, hydrology and water resources, and natural hazards; and in a variety of other fields. Some of the general concepts we discuss—such as the importance of approaching SERA activities from a socioeconomic rather than meteorological perspective—are similar to those articulated in previous efforts. Other ideas—such as understanding and improving uncertainty communication—are revised or new, based on recent developments in meteorology and social science and on input from new participants.

Previous attempts to develop sustainable interdisciplinary efforts in societal aspects of weather have not been as successful as many participants had hoped. We believe now is an opportune time to reinvigorate such activities for several reasons. First, recent developments indicate that interest in SERA within the meteorological community is growing. Examples include the American Meteorological Society (AMS) Policy Program and Summer Policy Colloquium; the Weather and Society*Integrated Studies program (Demuth et al. 2007); efforts to build social science capacity within NOAA (e.g., Anderson et al. 2003; NOAA 2007); the National Research Council study on estimation and communication of forecast uncertainty commissioned by the National Weather Service (NRC 2006); and the increasing emphasis on societal issues at the AMS, Canadian Meteorological and Oceanographic Society, and American Geophysical Union annual meetings and other community gatherings.⁵ Another indication is the strong support for SERA among the international and North American leadership of THORPEX and at the World Meteorological Organization (WMO). SERA issues are also being emphasized in the seasonal-to-interannual climate and climate change communities, through activities such as NOAA's Regional Integrated Sciences and Assessments program and Working Groups II and III in the most recent Intergovernmental Panel on Climate Change assessment (IPCC 2008a,b). These developments are part of a broader trend in science and research, in which many communities are evolving toward more interdisciplinary and society-oriented activities (Lattuca 2001; NRC 2003b). NSF,

⁵ For example, the overall theme for the 2008 AMS annual meeting was "Enhancing the Connectivity between Research and Applications for the Benefit of Society."

for example, has initiatives in areas such as Coupled Human/Natural Systems and mandates that all proposals address a “broad impacts” criterion. As this momentum builds, more social and natural scientists are growing interested in the collaborations necessary for SERA activities.

To develop SERA priorities that both build on existing knowledge and reflect cutting-edge ideas in different disciplines, we reviewed existing work and solicited preworkshop discussion papers on four SERA themes.⁶ We incorporated expertise from a wide variety of fields through the workshop participants, whose background represented natural hazards, climate and water resources, hydrology, engineering applications, economics, psychology, communication, geography, sociology, and other domains. Most of the workshop participants had not previously been involved in THORPEX and many had not previously collaborated extensively with the weather community. Consequently, a range of new perspectives were incorporated in the discussions. The result is a set of SERA concepts and priorities focused around current knowledge, needs, and opportunities, presented here to a new largely new audience.

FRAMING SOCIOECONOMIC RESEARCH AND APPLICATIONS FOR WEATHER PREDICTION. To provide a shared interdisciplinary context for discussing SERA priorities for weather prediction, here we address two topics that motivate and frame SERA activities.

What are high-impact weather forecasts? Many national hydrometeorological services and weather prediction programs, including THORPEX, focus explicitly or implicitly on improving high-impact weather forecasts (e.g., NWS 2001; MSC 2004; SMN 2006; WMO 2006). Despite this shared focus, people interpret “high-impact weather forecasts” in different ways. These different interpretations can strongly influence how individuals frame SERA activities. Common interpretations include the following:

- i) Forecasts of extreme, low-probability, or hazardous weather events (e.g., hurricanes, floods, or heat waves)
- ii) Forecasts of weather conditions that historically have had a major impact on one or more segments of society (e.g., agriculture, energy, or transportation)

- iii) Weather forecasts that have a significant impact (positive or negative) on one or more segments of society

These interpretations range from a meteorological perspective focusing on *weather events* (i), to a focus on the *impacts of events* (ii), to a socioeconomic perspective focusing on the *impacts of forecasts* (iii). They overlap but are not equivalent. *Weather* will have a high impact not simply because meteorological conditions are extreme (beyond climatology), but because someone (or something that someone values) is sensitive to those conditions (Mills and Morss 2004). *Weather forecasts* will have a high impact not simply because weather (extreme or routine) has high impact, but because someone can incorporate predictions of that weather into their decisions.

Because high-impact weather forecasts are a primary point of intersection between SERA and other weather prediction activities, a shared understanding is important. We propose the following working definition: *High-impact forecasts provide information that individuals or organizations can use in making decisions that may significantly mitigate costs or enhance benefits.* This may include forecasts of extreme and routine weather, and of “favorable” and “unfavorable” weather (e.g., Pielke and Carbone 2002), all of which depend on users’ perspective. Costs and benefits may be any outcome of interest to users or society, including personal safety, property damage, health, environmental quality, and economic well-being. The emphasis here is on the *impact of the forecast*, rather than solely on the impact of the weather.

To simplify their focus, meteorologists often emphasize improving forecasts of extreme weather [interpretation (i) above] or high-impact weather [interpretation (ii)]. In many cases, high-impact weather forecasts [interpretation (iii)] are a subset of forecasts of high-impact weather, so such efforts still have societal relevance. However, even accurate, well-communicated forecasts of high-impact weather may not have benefit if potential users do not understand the forecast information or its relevance, perceive no options arising from the forecasts, have insufficient time to take action, or do not act. This distinction is illustrated by Hurricane Katrina in New Orleans. While forecasts of this extreme, high-impact event affected many decisions, much of the property at risk could not be moved out of harm’s way. Moreover, for a variety of reasons, some people did not or could not act on the forecasts, with devastating consequences. Society will reap the greatest

⁶ The four theme papers are available at www.sip.ucar.edu/thorpep/theme.jsp.

benefit not simply from improvements in forecasts of extreme or other high-impact weather, but from improvements in high-impact forecasts—whether of a major hurricane or tomorrow’s temperature. As this discussion suggests, it is important to understand not only which *forecasts* have highest impact, but which types of *forecast improvements* are likely to have highest (positive) impact.

How do forecasts relate to societal outcomes and enhance value? Figure 1 depicts a simple model of the weather forecast—society system and the chain from forecast creation to value realization. The model illustrates how the SERA priorities discussed in this article connect with each other and with other aspects of weather prediction. As we found at the workshop, the model also provides a framework for people with different backgrounds and expertise to discuss views of the weather–society system and SERA knowledge gaps.

The “Weather Forecast System” box at the top of Fig. 1 encompasses meteorological aspects of weather prediction, including observing systems, data assimilation, numerical modeling, forecasting, and related research.⁷ The forecast information produced by this system (including uncertainty) is communicated directly or through intermediaries to users, who combine the forecasts with other information in their decisions, affecting outcomes. In reality, there are a quasi-infinite number of users and decision contexts, represented here in an aggregated fashion. The impacts of current or improved forecasts accrue along the different stages of this chain. Forecast value is determined according to the outcomes of interest from the users’ or society’s point of view and thus has different interpretations in different contexts (e.g., reduced casualties or property damage, resources

saved, avoidance of discomfort or misery, enhanced environmental sustainability). In general, however, value is the net economic benefits and improvements in societal well-being, broadly defined, that are realized from having the weather forecast information.

The first two research priorities represented in the diagram are the use of forecast information in decision making and the communication of forecast uncertainty. A third priority, decision support systems and tools, more formally integrates forecasts with other relevant information to help users make decisions. The final two priorities represented, on the right-hand side of the figure, are two perspectives for evaluating the forecast system: verification and valuation. Although forecast verification often focuses on measures of quality based in the weather forecast system portion of the diagram, more user-relevant verification approaches can help communicate user needs and value back to the weather forecast system and into decision support tools. Forecast value can be added (or lost) at each stage within the chain; these sum to total value, the net benefit obtained by a decision maker, an economic sector, or society.

The diagram is consistent with an end-to-end-to-end weather forecasting system (Morss et al. 2005b) and the interactive forecast system proposed by THORPEX, in which feedback from users, outcomes, and value can flow back to the researchers, developers, and providers that form the weather forecast system. This integrated feedback is represented by the curved

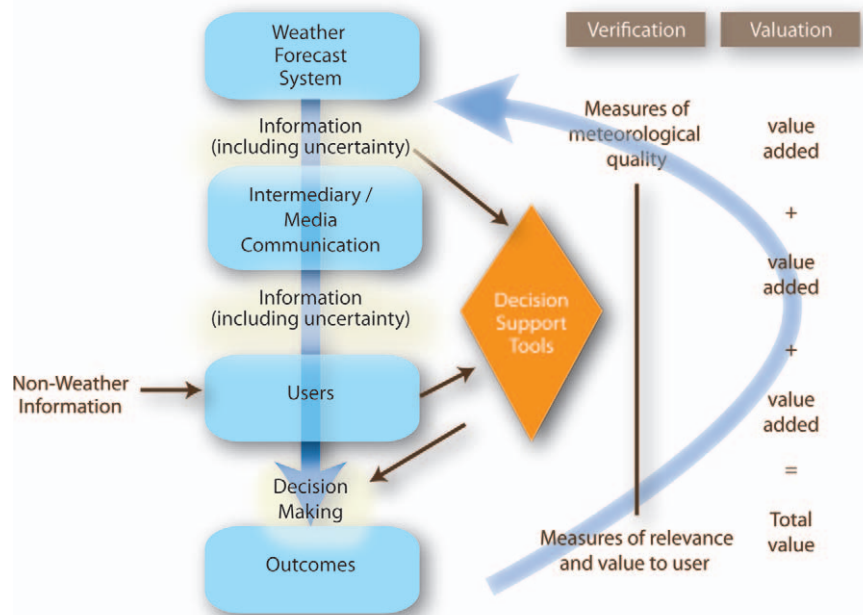


FIG. 1. Simplified model of the chain from forecast creation to value realization and the five SERA priority themes.

⁷ Note that this box also encompasses SERA issues not discussed here, such as use of information by weather forecasters and prioritization of weather forecasting activities within the meteorological community.

blue arrow arching back from users and outcomes to the weather forecast system. The diagram also demonstrates how the research priorities interconnect around central concepts such as the use of forecast information in decisions.

PRIORITIES FOR RESEARCH AND APPLICATIONS. *Understanding the use of forecast information in decision making.* Understanding how users interpret forecast information and apply it in decision making is a research priority for two reasons. First, the knowledge gained can help the meteorological community provide more useful information, benefiting society. Second, this knowledge provides the foundation needed for other SERA activities.

The use of forecast information in decision making involves a complex set of processes (e.g., Hilton 1981; Abelson and Levi 1985; Lawrence 1999; Lindell et al. 2007). For example, how people use forecast information depends on how weather conditions interact with their decision-making context and time line, as well as on characteristics of the specific situation. When making decisions, people also combine forecasts with other information drawn from their observations, experience, preferences, and socioeconomic conditions and constraints. Moreover, decisions interact, decision makers have different perspectives, and people generally do not have the time or ability to use all information that is potentially relevant to a decision. Thus, even with “perfect” forecast information, nonweather factors such as legal or political issues, sociocultural barriers, limited resources, or other concerns may constrain people’s capacity to incorporate forecast information into their decisions (e.g., Morss et al. 2005b; Rayner et al. 2005). For example, water resource managers operate under institutional rules that can constrain their use of forecasts, and members of the public may be aware of a weather-related hazard but not rank the threat as high as their need to get to work or to pick up a child. Understanding such interactions, constraints, and concerns, where they arise, is a prerequisite to understanding how forecasts are and could be used.

Three key research questions are as follows: how do various decision makers interpret weather forecast information, how do they combine forecasts with other information in their decision processes, and what constrains their use of current or improved forecast information? Because forecast users and uses are diverse, research is needed in a variety of specific decision contexts, as well as synthesizing results across contexts to draw broader conclusions. Such studies can draw on a large body of existing

research on the use of other types of information in decision making. Relevant methods include those that assume an optimizing decision maker, such as experiments with cost–loss and more complex prescriptive models, and those that examine decisions under more realistic conditions (e.g., Katz and Murphy 1997). Fields such as decision science, psychology, behavioral economics, sociology, and geography contribute a variety of tools, including ethnographic studies; surveys, interviews, and focus groups; case studies and cross-case experiments; critical incident and decision analysis; verbal protocol analysis; and decision-making experiments.

Communicating weather forecast uncertainty. Because weather forecasts are inherently imperfect, uncertainty is an unavoidable part of weather forecast generation, communication, interpretation, and use. Although substantial evidence indicates that not effectively communicating forecast uncertainty can be misleading and limit the use and value of forecasts, most weather forecasts are currently presented with little, if any, formal information about uncertainty (e.g., NRC 2006). Meanwhile, advances in ensemble and probabilistic forecasting techniques and efforts such as the THORPEX Interactive Grand Global Ensemble (TIGGE)⁸ are improving estimates of forecast uncertainty. For these scientific and technological developments to reach their potential, research is needed to learn how to communicate weather forecast uncertainty in ways that enhance decision making and societal benefit.

All decisions involve multiple sources of information and uncertainty. Thus, many of the factors discussed above on the use of forecasts in decision making are important to communicating uncertainty. Another consideration in weather forecasting is that users often receive forecasts from multiple channels, which may affect their perception of uncertainty. Simply providing more information about forecast uncertainty, without considering these factors, may not benefit many users. Forecast users also have varying preferences, abilities, and information needs. Some users can understand and use relatively complex, quantitative descriptions of forecast uncertainty, while others may be averse to ambiguity (Ellsberg 1961). Furthermore, a given user may have different preferences depending on the time he/she has available and the particular situation. To be effective, the presentation of uncertainty informa-

⁸ For further information about TIGGE, see <http://tigge.ucar.edu/home/home.html>.

tion should therefore be both audience- and context-specific, based on empirical research on how the information is likely to be interpreted and used.

Important research questions include the following: how do forecast users interpret forecast uncertainty information, what uncertainty information would be useful to them, how do they respond to various forms of uncertainty communication, and how can available and potential future forecast uncertainty information be communicated more effectively? Related issues include how thresholds, risk perceptions and preferences, and trust of information sources affect forecast-related decisions. These questions must be addressed for a variety of current and potential forecast users, ranging from businesses to emergency managers to members of the public. Because decision making under uncertainty, in general, is an active area of research, approaches and findings from other areas can also be applied to and tested for weather forecasting. Methods for investigating communication of uncertainty include those discussed previously for research on the use of forecast information in decision making, as well as approaches from risk communication (e.g., mental modeling; Morgan et al. 2002).

Developing user-relevant verification methods. Forecast verification is the process of evaluating forecasts. Although verification can serve “administrative,” “scientific,” and “economic or user” purposes (Brier and Allen 1951; Wilks 2006), most current applications of verification focus primarily on monitoring forecast performance and provide limited information to benefit users’ decisions or estimate forecast value. For example, anomaly correlations of 500-mb height (a common verification measure) are useful from a historical and large-scale numerical modeling perspective but are at best indirectly relevant to most users. Forecasts that are more directly user-relevant, such as quantitative precipitation forecasts, are generally verified on a point-by-point basis that provides limited information about the location, timing, and other types of errors that are of interest to many users.

Some new verification approaches are currently being developed that better serve scientific purposes and have potential to connect with economic- or user-oriented verification. Examples include diagnostic verification (e.g., Casati et al. 2004) and features-based or scale-sensitive approaches (e.g., Ebert and McBride 2000; Davis et al. 2006). Yet despite rapid advances in prediction methods and forecast uses, most currently applied verification methods remain

similar to those developed more than a century ago. Further work is needed to develop methods that evaluate user-relevant forecast attributes in ways that are meaningful given users’ forecast information needs. Verification approaches that are most user-relevant will not only provide users with valuable information about forecast quality but will also feed back into scientific and administrative verification, helping researchers and forecasters generate more user-relevant and hence more beneficial forecasts. For example, employing verification methods relevant for a broad spectrum of users can help administrators allocate resources for forecasting, including model development, in ways that enhance forecast value.

A priority in incorporating more user relevance into verification methods is working with specific user groups to identify meaningful forecast attributes and approaches to forecast evaluation. Other research topics include understanding what types of verification information could benefit users, how to communicate this information to users, and how to incorporate this information into decision making and decision support tools. One mechanism for conducting this research is a set of interdisciplinary case studies to conceptualize, develop, and employ user-relevant verification approaches with different user groups. Each case study would investigate users’ forecast and verification-related needs through methods such as interviews, surveys, and focus groups, combined with expertise in verification techniques. These results can then be synthesized to develop more general approaches to user-relevant verification.

Estimating the economic value of weather forecasts. In economic terms, the value of forecasts is measured by individual or aggregated changes in well-being (utility), broadly defined, associated with changes in forecast information (Letson et al. 2007). Such changes in well-being are often, but not always, monetized and expressed in dollar terms. Estimates of the economic value of forecasts are often sought to aid policy decisions and motivate investments in forecasts. However, economic valuation studies can also contribute to fundamental understanding by illuminating people’s preferences for forecast information.

Although some weather forecasts are developed and sold by the private sector, most weather forecasts, as public goods, are not bought and sold in ordinary markets, and most private-sector forecasts rely on public-good weather data. Because there are no market prices that directly yield information

about the forecasts' value, the value of most weather forecasts must generally be estimated as nonmarket goods (Freebairn and Zillman 2002a,b). In addition to the research that has been performed on the economic value of weather forecasts (e.g., Katz and Murphy 1997; Lazo and Chestnut 2002; Katz 2006), a broad literature exists on the value of other types of information (Lawrence 1999), providing knowledge and tools that can be applied to weather forecasting.

Priority research topics include estimating the value of different changes in forecast information, evaluating users' preferences among forecast changes, and identifying trade-offs among forecast changes. All can be investigated using the well-established tools economists have developed to value other nonmarket goods, such as environmental amenities (Freeman 2003). Nonmarket valuation methods include revealed-preference and stated-preference approaches (e.g., Lazo and Chestnut 2002), which are complementary techniques for eliciting people's willingness to pay for a good or service. Other applicable research methods can be drawn from behavioral economics (Camerer and Loewenstein 1997), laboratory experiments (e.g., Roulston et al. 2006), and decision-making models (Clemen and Reilly 2001).

Using cost-benefit analysis techniques, forecast valuation results can be integrated with cost information and meteorological knowledge to evaluate the societal costs and benefits of different forecasts (e.g., Morss et al. 2005a; Lazo et al. 2007). Such research will address THORPEX resource allocation questions related to observing network design and the proposed interactive adaptive observing system (Shapiro and Thorpe 2004), as well as related policy questions posed by the U.S. atmospheric science community (e.g., Emanuel et al. 1997; NRC 1998).

Developing decision support systems and tools. Decision support serves as a bridge to connect specific users with weather information providers. Decision support systems (DSSs) typically consist of computer-based platforms that integrate relevant data to help decision makers structure problems and objectively identify and evaluate decision alternatives (Eierman et al. 1995; Reich and Kapeliuk 2005). Also relevant are less formal decision support tools that help decision makers use information to address weather-related problems. Currently, weather-related DSSs and tools are most common in aviation, water management, and agriculture, but examples are also found in natural hazard management and the energy, surface transportation, and public health sectors.

DSSs and tools can benefit users by helping them incorporate new types of forecast information into their decision processes or increasing the value of forecast information that they already use. The development of DSSs and tools can also help forecast providers understand users' needs, facilitating forecast product improvements. A key component of developing successful DSSs and tools is a thorough understanding of the targeted users' decision-making contexts. This involves understanding users' weather-related problems and weather-information needs, including their outcomes of concern, the relationship between weather and these outcomes, and the alternatives they can employ to manage outcomes in response to weather-related risks or opportunities. This also involves understanding users' values and beliefs, along with the organizational, technical, political, and other aspects of their environments that may affect their decisions.

DSSs and tools are generally most effective when the targeted users are actively involved in the development process. Engaging users allows them to vet, test, and implement the tool at different stages. Doing so also builds trust, promoting adoption of the tool and use of the information it provides. Moreover, involving users in the development process facilitates mutual learning with researchers, building capacity on both sides. Fully engaging users in the development process requires building substantive relationships over a period of time—often several years or longer. Because this engagement is time-intensive, developers often work closely with one or a few users to develop a prototype tool, then, if appropriate, implement and test the tool more widely.

A major priority in this area is developing systems and tools that help different types of users (current and potential) incorporate existing and improved weather forecasts into decisions—particularly forecasts containing uncertainty information. Such research can both facilitate new uses of forecasts in already-served sectors and benefit our user groups that are currently underserved. Another priority, to help researchers leverage existing knowledge, is synthesizing best-practice guidelines for assessing user needs and building decision support tools.

INTEGRATED RESEARCH. As Fig. 1 and the above discussion illustrates, the five priority areas are interrelated; all are centered on users' forecast-related decisions. There are also synergies among the priority areas. For example, advanced verification methods can help estimate forecast value, and they can help convey complex forecast content (including uncer-

tainty) in formats more readily usable in decision making and decision support. In addition, many of the proposed SERA activities involve bringing meteorologists together with forecast users and researchers from other disciplines. To take advantage of these synergies and promote cross-disciplinary learning, we propose SERA activities that integrate research in all five priority areas, with several interdisciplinary research teams studying different aspects of a single user's or sector's weather-related decisions.

As an example, one integrated research project might focus around a local or regional water resource management organization's forecast-related decisions, including decisions about storing and releasing water, scheduling maintenance, and managing water supply. A set of teams including (at minimum) expertise in meteorology, hydrology, verification, decision sciences, economics, psychology, and software engineering would, along with members of the water management organization and other stakeholders,

- 1) examine users' forecast-related decision processes, current and potential future use of forecast information, and forecast information needs;
- 2) explore how communicating forecast information, including uncertainty, in alternate ways affects users' decisions and societal outcomes;
- 3) develop, test, and implement a decision support tool to help users incorporate forecast information into their decisions;
- 4) develop and test alternate user-relevant verification measures;
- 5) identify and estimate the value of different types of forecast information, with and without the decision support tool.

Together, these interrelated projects would advance knowledge in all of the priority areas discussed earlier, while providing an intellectual hub to address interconnections among the areas and offering an end-product to encourage user buy-in. Over time, the project could expand to incorporate decision makers in related areas such as flood warnings, hydroelectric power production, and environmental management.

A second integrated project might focus on hurricane evacuation decisions. One component could examine how emergency managers, coastal residents, and others use hurricane forecasts in making evacuation-related decisions. Other components could study different aspects of forecast communication (including uncertainty communication and the role of the media), develop and test an emergency management decision support tool, explore user-relevant veri-

fication methods, and estimate the value of different types of forecast information to various users.

Similar integrated research efforts could be developed in other sectors, including energy generation and supply, agriculture, public health, and transportation. Collectively, a series of such projects conducted with consistent research frameworks would yield emerging patterns and generalizations, enhancing overall understanding of weather–society interactions. As the projects progress, they could connect with SERA efforts in intraseasonal and longer-term climate forecasts, to integrate SERA knowledge across time scales. To give projects a presence in the weather community and promote meteorology–SERA integration, each project would also have specific links with non-SERA weather prediction efforts. In THORPEX, for example, this could involve using output from TIGGE, testing experimental observations or forecasts produced by THORPEX researchers, or connecting to a THORPEX field program.

RECOMMENDATIONS FOR NEXT STEPS.

The SERA activities above can both advance our fundamental understanding of how society interacts with weather forecasts and help the meteorological community provide more useful, more valuable forecasts. In doing so, SERA activities can help meteorologists understand and connect with diverse forecast users, benefiting society. This, in turn, can create a stronger public and private-sector funding environment for weather prediction. Yet in many areas, SERA's potential to contribute to the weather prediction community remains largely untapped.

The weather SERA community is currently relatively small and dispersed among disciplines and institutions. Realizing SERA's potential will therefore require building a sustainable interdisciplinary SERA community, in partnership with the meteorological community. The interdisciplinary discussions at the North American THORPEX workshop and similar gatherings provide a good start for such a community. For this community to be successful, however, additional social scientists, meteorologists, and forecast users will need to be entrained. Focal points will also be needed, both to give SERA visibility within the meteorological and social science communities and to provide diverse SERA researchers with an identity. Such focal points might initially be provided by the integrated research efforts discussed above, focused around specific meteorological and societal issues.

Another vital step will be building a sustainable funding environment for weather SERA activities. Without such funding, potential weather SERA

researchers will continue to focus on other topics where more funding is available, as many have done recently. Some resources are currently available through general granting mechanisms, such as NSF social science and interdisciplinary programs. Relying on such opportunities is insufficient, however, because competition is steep for limited funds. Moreover, given the wide range of important societal issues, applicants have little incentive to address issues specifically of interest to the weather prediction community. To fully benefit from SERA activities, the weather community will need to work together with social scientists, forecast users, and potential sponsors (such as NSF and NOAA) to develop coordinated mechanisms for funding weather SERA activities, focused on topics of interest to all parties (such as the priorities discussed earlier). Providing such opportunities will require a real financial commitment since, like most meteorological research and applications, significant SERA activities cannot be performed on a shoestring budget. Yet costs of SERA activities are often small compared to those for, say, a meteorological field experiment or new observing platform.

Despite good intentions, meteorologists sometimes view SERA activities as best performed at the end of scientific studies or programs because they believe the physical science must be complete before social science research is needed. However, with the current pressure from funders and policy makers to articulate and demonstrate societal benefits of science, weather prediction programs cannot succeed if SERA efforts are only paid lip service or incorporated toward the end of programs. This is particularly true for programs such as THORPEX, which includes societal benefits as an integral part of its mission. Moreover, many pressing weather-related socioeconomic research and applications questions (including most of those discussed earlier) do not require meteorological advances to create societal value. SERA activities should therefore be pursued now, regardless of the future path of weather research. To achieve their goal of benefiting society through improved weather forecasts, weather research and prediction efforts require an intellectually robust SERA component integrated into programs early on, planned and implemented by a sustainable, interdisciplinary SERA community.

LOOKING BACK, LOOKING FORWARD.

The weather prediction community has recognized the importance of socioeconomic research for decades but has yet to adequately support it. Without a sustained commitment to societal and economic

research and applications, we will not fulfill the societal promise of the modern observing and numerical weather prediction era, recognized by the global weather prediction community as it developed in the original Global Atmospheric Research Program a generation ago (NRC 1969). Given its strong emphasis on SERA as a partner to meteorological research, THORPEX in particular has an opportunity to provide a much-needed coordinating mechanism for SERA activities, community development, and funding within the weather community.

SERA activities can bring new, valuable perspectives to THORPEX and to the atmospheric sciences. While the research priorities discussed here reflect current needs and opportunities and were developed by a largely new group of contributors, the workshop that motivated this article was not the first of its kind. Previous efforts have brought together researchers interested in societal aspects of weather but have dissipated over time, due in part to lack of funding and lack of long-term commitment both from the weather and social science communities. The challenge, for the authors of this article, the workshop participants, and the meteorological community, is to ensure that in the next decade, we make significant progress and are not simply planning a workshop to identify a new set of research priorities. To meet this challenge, we urge the weather, physical science, and social science funding agencies in North America to join together with the meteorological, social science, THORPEX, and user communities to develop robust societal and economic research and application efforts, focused initially on the areas discussed above. Only with such interdisciplinary, intersectoral collaborations will we be able to look back and see substantial progress in advancing weather–society research and applications and their contributions to knowledge, the meteorological community, and society.

ACKNOWLEDGMENTS. The authors thank David Parsons and Gregory Holland for helping develop the North American THORPEX SERA workshop, and we thank all of the participants in the workshop for their contributions and ideas. We especially acknowledge Chris Davis, Julie Demuth, William Mahoney, Dan O’Hair, David Parsons, Eugene Poolman, Alan Stewart, Steven Stewart, and two anonymous reviewers for their helpful comments on the article. All opinions expressed are those of the authors.

The workshop was funded primarily by an NCAR Opportunity Fund grant and the THORPEX International Program Office. Pam Johnson of the U.S. THORPEX project office provided invaluable workshop support.

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