FLOOD RISK, UNCERTAINTY, AND SCIENTIFIC INFORMATION FOR DECISION MAKING

Lessons from an Interdisciplinary Project

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This essay discusses the complex ways in which scientific information and uncertainty can interact with societal decision making, and proposes a collaborative, integrated approach to societally useful scientific research.

"The great tragedy of science—the slaying of a beautiful hypothesis by an ugly fact."

—THOMAS H. HUXLEY

Between 1983 and 2003, flooding caused an average of 98 deaths and $4.5 billion in property damage per year in the United States (based on National Weather Service estimates, damages adjusted for inflation to 2003 dollars; NWS 2005; Downton et al. 2005a; see information online at www.flooddamagedata.org). The Federal Emergency Management Agency (FEMA) considers flooding "America's Number One natural hazard" (Brown 2005). Despite flood management efforts in many communities, U.S. flood damages remain high, due, in large part, to increasing population and property development in flood-prone areas (e.g. Changnon 1998; Pielke and Downton 2000; Burby 2001). Ongoing property development and potential climate changes threaten to increase flood hazards, particularly in coastal areas (McCarthy et al. 2001; Montz and Gruntfest 2002).

Over the long term, flood damages are mitigated through flood-risk management, which relies on estimates of the risk of flooding (see sidebar). Estimates of flood risk have numerous sources of uncertainty. These include the following: 1) limited hydrometeorological observation records (in space and time); 2) spatiotemporal variability in precipitation and flood potential; 3) nonstationarity of climate, both within the data record and over the future period of interest; 4) approximations in statistical techniques; 5) approximations in hydrologic and hydraulic modeling; 6) neglected contributors to flooding, such as debris, structure failures, and local storm water

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ESTIMATING FLOOD RISK

Flood risk is usually estimated in terms of the magnitude of a "design" flood or rainfall event. Examples include the 100-yr flood, which has a 1% chance of being reached or exceeded in any given year, and the probable maximum precipitation event. Such estimates are widely used by federal, state, and local agencies in U.S. flood-risk management, for purposes such as setting flood insurance rates and regulating flood zones, designing dams and flood control structures, developing flood warning systems, and planning community development.

Estimating flood risk combines statistics, climatology, meteorology, hydrology, hydraulic engineering, and geography. Where sufficient records of streamflow are available, design floods are usually estimated by statistically analyzing past streamflow data. In regions without stream gauges or with insufficient streamflow data, design floods are usually estimated by either 1) interpolating data from regional streams, or 2) generating a design rainfall event, then using rainfall–runoff modeling to estimate water flow. The resulting estimate is incorporated into a hydraulic analysis to estimate the depth and extent of the resulting flood. This information can then be combined with topographic, infrastructure, population, and other geographic data to identify areas at risk.

drainage; and 7) changing risk due to societal factors, such as development in and near floodplains, land surface alteration, and the dynamic nature of social systems in general and societal vulnerability to flooding in particular.

Given the magnitude of flood-related damages and the uncertainty in the current estimates of flood risk, it appears that improving scientific information about flood risk could substantially benefit society. To explore this potential, a multidisciplinary group of researchers[1] initiated a pilot study of climate variability, scientific uncertainty, and hydrometeorological information for flood-risk decision making in the United States. As an initial focus, we selected the Front Range of Colorado's Rocky Mountains, a region where variable precipitation, steep terrain, and limited data make estimates of flood risk especially uncertain, and where a history of severe flash flooding and a growing population make managing flood risk especially important. The study's primary goal was to improve scientific information about the risk of extreme flooding for use in decision making. Because quantifying and communicating scientific uncertainty is currently being emphasized in various hydrometeorological fields (including weather, climate, hydrological, and climate change prediction), one of the initial ideas was to quantify variability and uncertainty in estimates of flood risk, then develop methods to effectively communicate that information to potential users.

In order to determine what types of new information might be most useful, the research team began by consulting with key actors in flood-risk estimation and management, including scientists, engineers, and planners. We conducted structured and semistructured interviews with employees of local, regional, state, and federal government agencies, and had informal discussions with agency employees, private sector consultants, and researchers at professional meetings and in other settings. The topics explored included lessons learned from recent floods, management efforts, and policy developments; roles of scientific and technical information (and uncertainty in that information) in flood-risk estimation and management; and interactions among different participants in flood-risk estimation and management. We also examined documents describing how information about flood risk is generated and used at the local, regional, state, and federal levels.

As the study progressed, the challenges involved in generating useful new scientific information about flood risk grew more salient. Practitioners in flood-risk estimation and management make decisions in complex settings characterized by significant change and uncertainty. They also operate under regulatory, institutional, political, resource, and other constraints that limit their capacity to use new scientific information. Coupled with the inherent uncertainty in the risk of extreme events, these factors led many of those with whom we spoke to prioritize other concerns over more sophisticated scientific information about flood risk, particularly when they could not readily see the feasibility or value of incorporating new or more detailed scientific information into their existing routines. Moreover, the practitioners perceived and responded to uncertainty sufficiently differently from researchers that the team began to question its initial conceptions and focus. Thus, a component of the study evolved into an examination of how scientific information and uncertainty interact with societal decision making, focusing on the case of flood-risk estimation and management,

[1] The core team, which included some of the authors of this essay, consisted of researchers trained in geography, climatology, meteorology, and statistics, with additional experience in other areas, such as the use of weather and climate information in decision making. Input from other experts was also incorporated into the study, as appropriate.

but also considering how the results might apply to management of other hydrometeorological hazards and long-term climate change.

SCIENTIFIC INFORMATION, UNCERTAINTY, AND DECISION MAKING: LESSONS LEARNED. This section reviews several lessons learned about the interaction among scientific information, uncertainty, and decision making, illustrated using flood-risk management examples from our study. Aspects of these lessons have been discussed by others conducting related research (e.g., Pulwarty and Redmond 1997; Moser 1998; Callahan et al. 1999; Sarewitz et al. 2000; Liverman and Merideth 2002; Pagano et al. 2002; Ray et al. 2003) and, more generally, in the science and technology studies literature (e.g., Funtowicz and Ravetz 1993; Jasanoff and Wynne 1998; Hunt and Shackley 1999). Nevertheless, our findings still run counter to traditional scientific wisdom on the connection between scientific research and decision making; thus, we present these findings here to synthesize this knowledge and share it with the atmospheric science community.

Decision makers: Diverse and intertwined. Scientists often conceive of producing information that is useful for "decision makers," without realizing that their conception of decision makers is an abstraction. Decision makers are not a coherent entity, but a collection of individuals, each of whom uses different information to address different goals in a unique context. In flood management, for example, decision makers range from local community floodplain managers to FEMA employees to private sector engineering consultants. Each of these categories also contains significant diversity. For example, local floodplain managers have a range of job responsibilities; have a variety of professional training and experience, goals, and personalities; and serve communities with different constituencies, cultures, histories, regulations, and levels of flood risk. Because decision makers are diverse, generating useable scientific information often requires working with specific decision makers to address their particular needs and context, rather than developing information for a generic decision maker.

Moreover, different decision makers interact. Floodplain management decisions are made within a complex web that includes local, regional, state, and federal government employees; elected officials; private consultants; professional associations; private businesspeople; and members of the public. Members of this web often find their decision-making opportunities constrained or opened up by others' actions. Because individuals have personal relationships within this web and move among roles, individuals' personalities and histories influence, and sometimes dominate, their interactions. Understanding who participates in decision making in a specific domain and how these participants interact can, therefore, be a key component of generating useable scientific information.

Given that the term "decision makers" represents a diverse group, hereafter when referring to those who make decisions as part of their professional responsibilities (the primary type of decision maker considered here), we use the term "practitioners."

Constraints: Practitioners' ability and motivation to use new methods and information. As noted above, practitioners' ability to use new methods and information is often constrained by others in their decision-making web. Local floodplain managers, for example, must act within federal, state, and local regulations and guidelines, and their capacity to incorporate new science and technology is limited by the technical ability of the private consultants who provide most of their flood-risk estimates. They must also balance the needs and desires of multiple constituencies, including local elected officials, private businesses, and the diverse populations at risk, and respond to these constituencies' decisions and demands.

In addition, practitioners are constrained by time, money, and other resources, particularly given their multiple responsibilities. They also use many types of information that evolve and thus compete with scientific information to be updated. Under such constraints, familiarity with existing processes often reduces practitioners' motivation to invest in learning to use new scientific methods and information. Given the resources already expended on existing processes and the costs of change, changes in science or technology—particularly incremental changes—are often insufficient to convince practitioners to alter how they make decisions. When they do seek scientific information, many of the practitioners with whom we spoke turned preferentially to specific, trusted experts with whom they had long-term relationships.

Under these circumstances, scientists who wish to aid decision making must generally not merely offer scientific knowledge, but rather develop information that clearly applies to practitioners' specific decision-making settings. Aiding decision making also often requires that scientists interact with practitioners over a period of time, to build trust and credibility.

Moreover, because practitioners' options are constrained by others in their decision web, scientists may have to help interested practitioners advocate for the ability to use new methods and information, by demonstrating that the science is authoritative and/or that using it has value.

Uncertainty: Scientists' and practitioners' different perspectives and responses. From a scientific perspective, uncertainty is something that can be conceptualized, estimated, and addressed. Thus, scientists often deal with uncertainty by attempting to reduce, quantify, analyze, and/or assess it. To do so, they generally seek to obtain additional data, perform more sophisticated analyses, or conduct additional research.

The practitioners we spoke with, on the other hand, view uncertainty as an unavoidable factor. Because all information about the future is uncertain, they must make decisions under uncertainty every day, in a complex, evolving social, institutional, and political environment. Given these conditions, and the limited information and time they have to address numerous demands, practitioners often deal with uncertainty by finding the best information they can quickly and easily obtain and interpret, making the decision required for the moment, and then moving on.

Although flood management practitioners might appreciate more certain hydrometeorological information, scientific uncertainty is often swamped by other factors, and thus is not a high priority. When describing the factors limiting their ability to make decisions that reduce flood risk, the floodplain managers we interviewed focused not on science or uncertainty, but on their communities' perceptions of flood risk, views of acceptable risk, and willingness to accept management responses. In other words, scientific uncertainty, and more generally, scientific information, is only one of many components of flood management decisions.

In theory, the practitioners with whom we spoke might also appreciate scientific information accompanied by a quantification or analysis of uncertainty. In practice, however, they must make discrete choices among alternatives, usually under a deadline. In floodplain management, for example, uncertainty about flood zone boundaries and flood levels must be translated into dichotomous decisions about where construction should be restricted or regulated and where it should not. Although techniques for formally incorporating probabilistic information into such decisions can be valuable in research settings, practitioners often lack the time and resources to perform such complex analyses. In such situations, sophisticated estimates of scientific uncertainty may only complicate practitioners' already difficult jobs, without benefiting the people they serve.

Scientists tend to view analysis or the reduction of uncertainty as a valuable end goal in itself and assume that the resulting information will be useful. Practitioners, on the other hand, evaluate information according to its effects on their decision process and outcome. Sometimes, additional analysis of scientific uncertainty will have little effect on decision making, either because major components of the scientific uncertainty are irreducible or intractable (e.g., due to complexity, stochasticity, or a fundamental lack of data or understanding), or because the effects of scientific uncertainty are negligible compared to other factors. For example, estimates of the risk of extreme flooding are inevitably uncertain, due to an evolving climate, changing land use and hydrology, and our limited experience. Moreover, the increasing flood-related damages in the United States are due as much (or more) to societal factors as to hydrometeorological factors (e.g., Pielke and Downton 2000; Burby 2001; Larson and Plascencia 2001). As a result, more knowledge does not necessarily reduce hazard losses (e.g., White et al. 2001), and physical science and engineering advancements can often only make a difference when societal factors, such as warning response and risk communication, are understood and addressed (e.g., Gruntfest and Handmer 2001). Consequently, even when additional scientific research could reduce or better characterize scientific uncertainty, other actions (such as addressing societal components of vulnerability; see, e.g., Sarewitz and Pielke 2000) may be more cost effective.

Practitioners also have methods of dealing with uncertainty in addition to seeking additional scientific information. In floodplain management, for example, scientific and other types of uncertainty are accounted for to some extent by adding a uniform (1 ft or greater) safety margin to freeboard requirements, effectively raising the level of protection. Such methods may be imprecise and even considered "unscientific" by some, but they are simple and often more cost effective than formal uncertainty analyses. More generally, in the presence of pervasive uncertainty about flood risk, communities have developed a variety of mechanisms to mitigate negative impacts of flooding, including floodplain regulation, flood control structures (e.g., dams and levees), warning systems, and insurance. These mechanisms rely on estimates of flood risk, yet by reducing negative impacts of flooding in general, they insulate people to some extent from uncertainty in scientific information (by hedging risk; see, e.g., Lempert and Schlesinger 2000).

The different perspective of practitioners regarding uncertainty does not necessarily mean that they do not appreciate the uncertainty in scientific information. Most of the practitioners we consulted understood that estimates of flood risk are, and will always be, uncertain; as one floodplain manager told us, "*All* the numbers are inaccurate." Rather, practitioners simply conceive of scientific uncertainty differently than scientists do, considering it in a very different context. As a result, the way scientists referred to and discussed uncertainty sometimes confused practitioners (e.g., inaccurate versus uncertain in the quote above). Thus, although uncertainty may seem to scientists like a basic, universal concept, the term and its interpretation can act as a linguistic barrier that limits transfer of knowledge between researchers and practitioners (e.g., Fothergill 2000).

Assumptions: Barriers to more useable scientific information. Because scientists and practitioners have different training, experience, responsibilities, and goals, the two groups tend to approach situations from a different perspective. Scientists generally frame issues using scientific knowledge and expertise, while practitioners frame issues based on societal goals and values (e.g., on their interpretation of their constituencies' greatest needs). Scientists also often have the luxury of making a complex issue more tractable by addressing a focused piece, for example, by studying floods using expertise in meteorology, climatology, or hydrology with little consideration of engineering or social science. Practitioners, on the other hand, work in the real world, where they cannot abstract one aspect of an issue from its context.

Scientists who are unaware of their different perspective often approach practitioners with assumptions that limit their potential to provide more useable scientific information. For example, when scientists frame an issue using scientific knowledge without considering its societal context, they often assume that scientific information "should" be used in decision making. Unfortunately, telling someone with a different perspective (and often limited capacity to change) that they "should" act differently does not necessarily convince them to do so; in fact, it can induce mental blocking. In making such assumptions, scientists limit their ability to answer questions that practitioners need answered, as well as questions based on scientific interest or capabilities. In doing so scientists lose a major opportunity to apply their knowledge for societal benefit.

Of course, practitioners approach scientists with assumptions of their own. Avoiding lost opportunities for useable science generally requires softening both groups' assumptions by developing interactive relationships based on mutual respect and willingness to learn from each others' form of knowledge (e.g., Hunt and Shackley 1999). By approaching practitioners with an open mind and an appreciation for practitioners' different perspectives and constraints, scientists can help both groups evolve their concept of useful information through mutual education.

Interactions between scientific information, uncertainty, and decision making: Two cases. Scientists also often assume that new scientific information will be incorporated into decisions in coherent, understandable ways. Most decision making, however, is complex, nonlinear, and involves many considerations in addition to science. When decisions also involve multiple actors and significant uncertainty, as is the case in flood management, information use can be diffuse, difficult to trace, and even counterintuitive. As discussed by Functowicz and Ravetz (1993), in situations characterized by high decision stakes and large uncertainties, the traditional domination of "hard (scientific) facts" over "soft values" can become inverted, leading to facts being interpreted in terms of values, or even to facts and values becoming so intertwined that they cannot be clearly separated. These complex interactions between scientific information, uncertainty, and flood-risk decision making are illustrated by two cases examined in our study [Both cases are discussed in further detail in Downton et al. (2005b, submitted to *Environ. Hazards*).]

In the first case, a controversy over modifying the Cherry Creek Dam near Denver, Colorado, the likelihood of a flood overtopping the dam is very small, but the potential consequences are very high due to the large population and property at risk. Scientific experts disagree about the risk of such an extreme event, state and federal government entities disagree about the level of acceptable risk, and some members of the public oppose construction to increase the level of protection. So far, this disagreement has spurred a decade of expensive studies and vehement debate over science and policy, but no agreement on an appropriate action. This illustrates how, even when scientific information is a key part of decision making, the interplay between significant scientific and societal uncertainty can lead to inaction, especially if no change means no short-term cost.

Another case we examined is Fort Collins' (Colorado) reevaluation of their design rainfall standard following a major flood in 1997. In Fort Collins, as in Cherry Creek, different hydrometeorological and statistical assumptions produced different estimates of the design rainfall, and scientific experts disagreed on the most appropriate value. Local stakeholders also disagreed on the acceptable level of risk, and their interpretation of acceptable risk was evolving rapidly, as memory of the recent flood began to fade. The panel of scientific experts presented four options to the Fort Collins City Council, which interpreted the scientific information largely in terms of its implications for the community's level of protection from flooding. The council then selected the new standard by vote. This illustrates how, when decisions must be made despite the lack of scientific consensus, the political process will take over. Scientific information may then only be useful to the extent that it informs (or supports different sides of) political and value debates.

In both of these cases, different scientific experts, using different methods and assumptions, produced very different estimates of the hydrometeorological risk of extreme flooding, providing participants in decision making with qualitative information about scientific uncertainty. The value of a more sophisticated analysis of scientific uncertainty in either of these cases is unclear; most likely, such an analysis would provide further motivation for inaction or for decision making based on values rather than science, sharpening, but not resolving, the political debate—at least in the short term. As we began to understand the complex spectrum of ways in which scientific information and uncertainty can interact with decision making, we realized the importance of taking a collaborative, integrated approach to developing new scientific information for flood-risk decision making.

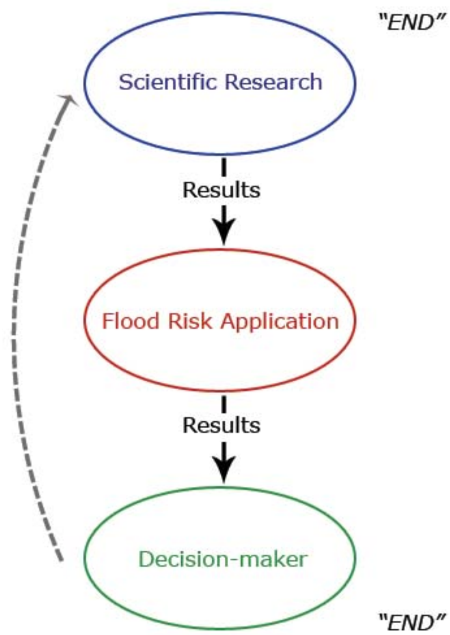


Fig. 1. Scientists' typical view of research and development to produce useful information for society: "end-to-end" research, illustrated for the case of flood-risk management. The connection from decision maker to research (represented by a dashed line) is mentioned in some implementations of end-to-end research, but in others is left implied or assumed.

RECOMMENDATIONS: END-TO-END-TO-END RESEARCH. Scientists often conceive of the interface between science and decision making as a linear process: basic research generates knowledge for applied research, whose results are then used to develop technological applications for society (e.g., Pielke 1997). In the classic form of this model, proposed by Vannevar Bush in the 1940s, scientific research provides a reservoir of knowledge for society to draw upon for developing applications (e.g., Byerly and Pielke 1995). More recently, this model has evolved into an emphasis on "end-to-end" research and system development. In meteorology and related fields, end-to-end generally refers to implementing all stages of the research and development process, from research (end 1) through to delivering an application to the end user (end 2), as depicted in Fig. 1 (see, e.g., Karl et al. 1993; NOAA 2003; May et al. 2004).

The end-to-end approach is valuable in that it emphasizes the importance of translating research into user applications. However, as many people involved in such work have noted, generating useable scientific knowledge or information often requires explicitly connecting the two "ends," in other words, incorporating decision-making needs into the research and development process. Doing so successfully requires long-term partnerships among scientists, product developers, and different groups of decision makers to mutually educate about opportunities and needs, develop trust, and build credibility (see, e.g., Meo et al. 2002; Overpeck et al. 2002a,b; NRC 2004). Such partnerships create an iterative, bidirectional process, from decision making to applications to research and back again, in which the participants collectively assess the fit between science and decision making and coproduce knowledge and tools (e.g., Hunt and Shackley 1999). Recalling that decision makers are a diverse, interconnected set of individuals, Fig. 2 presents a revised version of the end-to-end paradigm: integrated "end-to-end-to-end" (M. Glantz 2003, personal communication) or "iterative end to end" research and development for societal decision making.

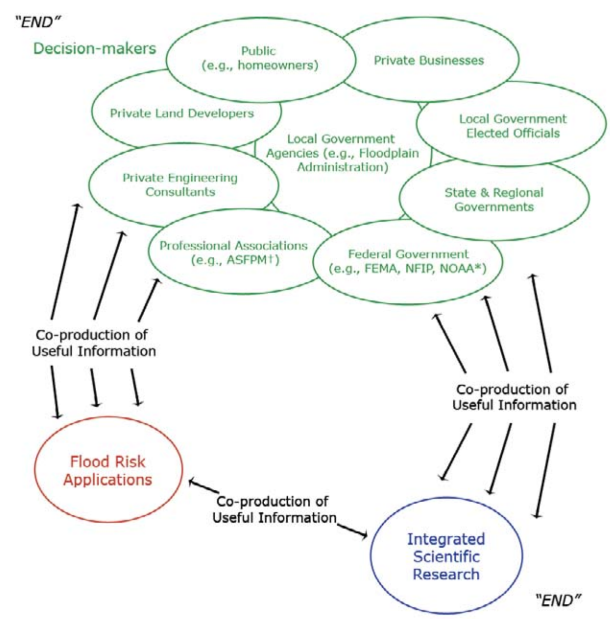
By promoting frequent feedback from and long-term partnerships with participants in decision making, the end-to-end-to-end approach can help scientists interested in aiding decision making surmount the challenges and barriers described earlier. The end-to-end-to-end approach also recognizes that one pass from end to end is generally insufficient, because practitioners' information use and needs tend to change as they interact with new information, and because successful examples help motivate people to adopt new methods and information. End-to-end-to-end research, therefore, involves multiple iterations to help information production and use adapt as science and society evolve. In situations with multiple interconnected decision makers, we learned to start by iterating from end to end with one (carefully selected) individual or group that is central to the decision, has flexibility to adopt new information, and/or is interested in becoming an early adopter of new technology. Building one successful partnership may then open up a range of additional opportunities.

Because natural and societal components of systems interact in complex ways, research that addresses only scientific aspects of a situation often fails to achieve the desired societal results. Thus, rather than taking the traditional approach of dividing work into disciplines or into basic and applied research, the end-to-end-to-end approach emphasizes integrated research. In flood estimation and management, this means considering climatology, meteorology, hydrology, statistics, engineering, geography, decision making, and the social and political system—not separately or sequentially—but together. As we explored the individual, interpersonal, and interinstitutional aspects of decision making that constrain flood estimation and management, the importance of interdisciplinary natural–social science research became evident.

Overall, the team learned that our initial conception of end-to-end multidisciplinary research, a conception common among researchers in the meteorological community, was insufficient; to make progress, we instead needed to pursue a more integrated, end-to-end-to-end approach. We also learned the importance of patience, and taking the time needed to build the relationships and understanding required to help science have a positive impact. Depending on the type of information and the decision context, the iterations from end to end may take days or months, or, in the case of a complex issue with entrenched policies and institutions (such as U.S. federal flood management policy), decades or longer.

IMPLICATIONS BEYOND FLOOD RISK.

While attempting to conduct end-to-end research to aid societal decision making, we elucidated a divide between how scientific researchers and practitioners perceive and deal with scientific information and uncertainty. This divide limits the ability of scientists to provide useable knowledge and information for decision making in arenas beyond flood risk. The lessons learned on bridging this divide can, therefore, contribute to other arenas where scientists



* FEMA = Federal Emergency Management Agency; NFIP = National Flood Insurance Program; NOAA = National Oceanic and Atmospheric Administration
† ASFPM = Association of State and Floodplain Managers

Fig. 2. Revised view of research to produce information that is useful in one or more specific societal applications: "end-to-end-to-end" research, illustrated for the case of flood-risk (specifically floodplain) management with diverse, interconnected decision makers. The end-to-end-to-end approach explicitly recognizes the importance of multidirectional communication; sustained interactions among researchers, application developers, and multiple decision makers; and multiple iterations around the loop to coproduce knowledge and tools. Integrated scientific research includes disciplinary and interdisciplinary work in statistics, climatology, meteorology, hydrology, engineering, geography, and the social sciences and humanities. The two ENDs in the figure represent the two ENDs in end-to-end research (Fig. 1); end-to-end-to-end research signifies iteration between these two ends.

seek to connect scientific research and information, particularly on scientific uncertainty, to societal decision making. One example currently of significant interest is global climate change, in which scientists often discuss reducing, quantifying, analyzing, and communicating scientific uncertainty to aid decision making (e.g., Allen et al. 2000; Schneider 2001; Dessai and Hulme 2003; Pielke and Sarewitz 2003; Webster et al. 2003). Communicating uncertainty is also of growing interest in weather and seasonal climate prediction.

More generally, the current scientific agenda calls for more research of the type performed in this study, including multi-/interdisciplinary research, societally relevant research, research incorporating stakeholders, and research to support decision making under uncertainty. Ongoing and new research of these types can also benefit from the lessons and observations presented here, along with those discussed in the related literature cited above.

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