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Making Science Useful to Decision Makers: Climate Forecasts, Water Management, and Knowledge Networks

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ABSTRACT

Moving from climate science to adaptive action is an immense challenge, especially in highly institutionalized sectors such as water resources. Knowledge networks are valuable strategies to put climate information to use. They overcome barriers to information adoption such as stovepipes, pipelines, and restricted decision space, and they can be responsive to issues of salience and the hurdles of reliability, credibility, and trust. Collaboration and adaptive management efforts among resource managers and forecast producers with differing missions show that mutual learning informed by climate information can occur among scientists of different disciplinary backgrounds and between scientists and water managers. The authors show how, through construction of knowledge networks and their institutionalization through boundary organizations focused on salient problems, climate information can positively affect water resources decision making.

1. Introduction

The impacts of global climate change and variability upon water resources are potentially profound. In the 1980s, climate scientists' models indicated that changes in patterns and amounts of precipitation would be an important consequence of climate change (Waggoner 1990). Water resources are already overstressed by growing demands even without the added burden of climate change. In the United States, these demands come from increasing population and expansion of human activity into semiarid regions such as the Southwest (Arizona, New Mexico, Southern California) and drought-prone regions such as the Southeast (e.g., states bounded by the Gulf of Mexico and their neighbors). Climate change is already affecting precipitation variability: floods that previously had a probability of 1 in 100 years may now be more frequent in some areas. Snowpack—the dominant source of freshwater for the western United States—is lower in volume and, on average, melts earlier in the spring. This affects and will continue to impact farmers (who must plan irrigation schedules accordingly) as well as water utility planners (who will have to anticipate potential decreases of supply in summer) (e.g., Smith and Reeves 1988; Attwood et al. 1988; Milly et al. 2005; Solomon et al. 2007).

One of the successes of earth systems science is significant improvement in the ability to predict many aspects of climate and hydrologic variability. Over two decades ago climate scientists began making remarkable advances in probabilistic forecasting of seasonal and interannual variation in climate conditions. Signals related to El Niño–Southern Oscillation (ENSO) enable predictions of precipitation, runoff, and streamflow from one season to one year in advance. Potentially, such information could be used to reduce vulnerability from flood, drought, and other climate variability events. Reducing vulnerability to changes and increased variability in climate depends upon our ability to bridge the gap between climate forecasting science and the implementation of policies responsive to such advanced warnings and opportunities.

Historically, the provision of climate and hydrologic forecast products has been a producer-driven rather than a user-driven process (Cash and Buizer 2005, p. 12). As a consequence, momentum in product development

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has been largely skill-based rather than a response to water manager demand. This article shows how progress has been made in increasing the utility of climate information for decision support in water resources management even when the skill levels of climate and hydrologic forecasts are not high. Collaboration and adaptive management efforts among resource managers and forecast producers show that mutual learning informed by climate information can occur among different disciplines and between scientists and managers. We focus on the role of *knowledge networks* as vehicles for bridging the gap between knowledge and action. These are composed of policy makers, scientists, government agencies, and nongovernmental organizations linked together in an effort to provide close, ongoing, and nearly continuous communication and information dissemination among multiple sectors of society involved in technological and policy innovations for managing climate impacts (Sarewitz and Pielke 2007; Jacobs et al. 2005). Unlike formal networks that connect monitoring or instrumentation systems or serve artificial intelligence functions,[1] knowledge networks connect people across disciplinary or occupational boundaries through various interactions. Knowledge networks, in turn, are related to—but distinct from—boundary organizations (see section 5). The latter play an intermediary role between different specializations and disciplines within a knowledge network by providing translation services between disciplines, mediating relations between information producers and users, and integrating user needs into producer activities. In the field of climate science and water, Regional Integrated Sciences and Assessments (RISAs) are examples of boundary organizations. They facilitate stronger knowledge networks among scientists, policy makers, and water resource managers in specific regions by encouraging targeted research to highly focused problems. Knowledge networks—together with their boundary organizations—are valuable ways to provide decision support and pursue strategies that can put climate knowledge to use in better managing water.

While the benefits of such linkages are great, so are the challenges. Networks require widespread, sustained, and persistent efforts through time. Moreover, collaborations across organizational, professional, disciplinary, and other boundaries must be accorded high priority. Incentives and reward structures, as well as leadership, are needed to encourage networking.

This article first considers why direct ''loading dock''–style delivery of climate information does not work. We turn then to a discussion of knowledge networks that are recursive, interactive, and end-to-end useful for scientists and on-the-ground decision makers. Boundary organizations and objects can be employed to institutionalize networks and embed collaborative practices. Last, we consider RISAs as reasonably successful applications of the knowledge network concept and evaluate their lessons.

2. Method

This study is based on an examination of a series of decision-support experiments and evaluations that used seasonal-to-interannual forecasts and observational data in policy making in cooperation with scholars from universities across the United States and with program managers from the National Oceanic and Atmospheric Administration (NOAA). This examination was sponsored and supported by the U.S. Climate Change Science Program and published in a NOAA report (Beller-Simms et al. 2008). The project began in 2006 when an interdisciplinary team of researchers, decision makers, and federal government employees with varied backgrounds in the social and physical sciences and law were identified based on a variety of considerations, including interests and involvements with decision-support experiments and their knowledge of the field as demonstrated by practice and/or involvement in research and/or publications in refereed journals.

A public meeting, convened by NOAA, was held in January 2007 in which key stakeholders were invited to discuss their decision-support experiments with the team: many of these participants were also participants in knowledge networks. The climate change science report published by NOAA (available online at http://www.climatescience.gov/Library/sap/sap5-3/final-report/default.htm) synthesized and distilled lessons for the water resources management sector from efforts to apply decision-support experiments and evaluations using seasonal-to-interannual (SI) forecasts and observational climate data. It entailed examining barriers from case studies on the application of SI forecast information and efforts to span organizational boundaries dividing scientists and users. As lead authors of the report, we draw heavily on its content and findings. In the case of our discussion of RISAs, we further draw upon self-analyses by RISAs as well as external assessments and evaluations.

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[1] Formal networks, by contrast, can be various forms of ''artificial neural networks'' (e.g., Trimble et. al. 1997) that provide an information processing paradigm that functions like a brain in processing information. These networks are composed of a large number of interconnected processing elements (neurons) that work together to solve specific problems and, like the brain, the entire network learns by example. Another type of formal network familiar to climate scientists is Snowpack Telemetry (SNOTEL), a weather-related automated or telemetered monitoring system of weather stations that serves as a snowfall depth monitoring network (established by the U.S. Geological Survey).

3. Climate forecasts and decision support

The idea of decision support has been evolving from the provision of products to support for practices (Ingram and Stern 2007). Until recently, the loading-dock model of decision support has been regular practice among climate scientists. This model predicates that scientists prepare models, products, forecasts, or other information for general use without consulting with, or understanding the needs of, the anticipated user—but with the expectation that users will find the information useful (Cash et al. 2006). Simply put, the evidence shows that it does not work (Cash et al. 2006). Merely putting out prepackaged information to be used by whoever needs it is misguided. The loading-dock notion is accompanied by several other mistaken ideas that govern the relationship between science and decision makers.

a. Stovepipes

Within and among climate science organizations information tends to flow in narrow, restricted channels. Communication usually takes place among specialists who use their own jargon and are reluctant to share information with nonspecialists. In the academic community and within agencies, knowledge involved in production of climate forecast information is often produced in ‘‘stovepipes’’ isolated from neighboring disciplines or applications (NRC 1999, p. 278). In short, there is a lack of adequate cross-disciplinary interaction among science, engineering, public policy making, and other knowledge and expertise sectors, as well as across agencies, academic institutions, and private sector organizations. This makes it difficult for decision-support information providers to communicate with one another (Ingram and Bradley 2006). As a result, climate and water scientists feel more comfortable talking to people who share their interests and skills. Although climate scientists already began communicating to hydrologic forecasters some years ago, climate and water forecasters have not included another set of specialists: social scientists. The latter know much about changing organizational behavior and broadening communication. However, they are also partial to talking among themselves.

b. Pipelines

A common misconception about the use of scientific information in decision making is that it flows from the ‘‘well head’’ (i.e., scientists) directly toward the ‘‘storage tanks’’ (the brains of those who need it). Such a pipeline notion is a leading contributor to the existing problem of data overload in which intended science recipients are overwhelmed with information they do not know how to use (e.g., Stokes 1997). When forecasts are actually used, it is in a nonlinear fashion that engages decision makers at all levels in designing and adding to forecasts through reciprocal relationships (Letson et al. 2001; Podestá et al. 2002; Patt et al. 2005). When transmission lines are actually working, they resemble loops and zigzags, not pipelines.

c. Decision space

Some people occupy roles that permit them to look at the big picture while others must restrict themselves to detailed knowledge of what is in front of them. Climate scientists’ room to investigate problems is often bounded by disciplines and the professional norms and expectations of the academic organizations in which they are housed. These include tenure, retention and promotion, and the fact that universities’ reward systems rarely recognize interdisciplinary work, outreach efforts, use-inspired research, and publications outside of academic journals (Jacobs 2003). By contrast, water managers are confined to their own agencies’ missions and are constrained by available resources and the need to serve designated constituencies.

Whereas scientists’ worldviews are strongly influenced by the boundaries of their own research and disciplines, decision makers’ worldviews are conditioned by ‘‘decision space’’ (Jacobs et al. 2005; Johnston et al. 2007; Patt and Gwata 2002; Orlove and Tosteson 1999)—the range of realistic options available to them to resolve particular problems. New, scientifically derived tools or sources of information may have obvious applications when viewed from a theoretical perspective. However, a decision maker may be constrained from using a tool or information by at least three factors. These range from, first, the nature of policy ‘‘attentiveness’’ in administrative organizations (in which awareness of alternatives is often driven by elected officials’ demands instead of new information) (Kingdon 1995) to, second, organizational goals and objectives that restrict information flow and feedback. A third reason revolves around the nature of indirect commands within organizations that evolve through trial and error. Over time, these commands take the form of rules and protocols that guide and prescribe appropriate and inappropriate ways of using information in bureaucracies (Stone 1997; Torgerson 2005).

In water resources, many actors make climate-sensitive decisions, each with their own distinct and often narrow decision space. Water serves a number of functions, including agriculture, ecosystems, municipal water supply, coastal zones, hydropower production, and floods. Consequently, the category ‘‘water manager’’ covers a wide variety of actors, each with specific problems, including municipal water officials, who need to impose watering restrictions; federal agency managers, who need to make decisions regarding how to operate a storage facility; members of Congress, who must make choices regarding funding for recovery efforts for an endangered species; and state government water department employees, who have to make water purchases necessary to ensure compliance with negotiated interstate compacts. These and other water managers operate in a context that further constrains their decision space through too little time, too few staff resources, and pressures from political, legal, and institutional forces.

Water managers need information when they need it, or it does not do them much good. Farmers have a decision calendar and must decide at a certain time how many acres to plant. Reservoir operators have a certain schedule for deciding how much water to release from dams (Ray et al. 2007). Unless forecasting information meshes with such calendars, its usefulness is limited. Forecasts must be relevant and customized to particular needs and situations.

d. Salience, reliability, and trust

Crisis has a way of riveting attention and making water issues salient. Water managers who are most likely to use weather and climate information are those who are likely to have experienced weather and climate problems in the recent past—their heightened feelings of vulnerability are the result of negative experiences with weather or climate. The implication here is that simply delivering weather and climate information to users may be insufficient to hasten its use unless the decision maker perceives climate to be a salient hazard. Some vulnerabilities are simply more important than others when it comes to water. Managers often perceive greater financial and other difficulties to arise from coping with flood or drought than from their ability to find water and supply it to customers. Therefore, climate scientists have an uphill climb to convince many policy makers of the threat to public and other forms of supply from climate variability (Cash et al. 2003).

Managers' perceptions about climate information usefulness vary with exposure to adverse events and their financial, regulatory, and institutional settings. If a water manager is put into a position with few resources to fortify a region against flooding or drought, or where there are no regulatory or institutional incentives to do so, then these threats will be a lower priority than more routine management tasks (O'Connor et al. 2005). Achieving a better understanding of these contexts and of the informational needs of resource managers requires working directly with them. Scientists have different notions about the reliability of information from water managers—they are used to dealing with probabilities and are comfortable with the idea that some uncertainty is inherent.

Water managers are also bound by their own set of institutional constraints, although these differ from those of academics. For example, they are confined to specific agencies that predispose them to following established decision "heuristics" when faced with incomplete or uncertain risk information (Tversky and Kahneman 1974; Kahneman et al. 1982; Payne et al. 1993). They often interpret uncertainty as unreliability—one symptom of their reliance upon heuristics. Also, water managers are used to dealing with water variability without climate forecasts; they have their own routines and are much more likely to trust information with which they are familiar (Knopman 2006; Vandersypen et al. 2007). Experience with climate forecasts is recent and therefore less trusted. Organizations are biased toward information that comes from the inside rather than from the outside since the former is more likely to be compatible with the organization's mission and orientation. Through networks established among scientists and decision makers, forecast knowledge becomes an inside product.

e. Decision support as network building

A primary objective of decision support is to foster transformative information exchange that will appropriately modify the kind of information that is produced and the way it is used (NRC 1989; Stern and Fineberg 1996; Stern and Easterling 1999; Brewer and Stern 2005; NRC 2006; Ingram and Stern 2007). Effective decision support involves engaging effective two-way communication between the producers and users of climate information (Jacobs et al. 2005; Lemos and Morehouse 2005; Stern and Easterling 1999; NRC 2006) rather than just developing tools and products that may appear useful but are not really functional. This conception of decision support brings into focus human relationships and networks in information use. The test of transformed information is that it is trusted and considered reliable and fostered by familiarity and repeated interaction between information collaborators and the working and reworking of relationships. A knowledge network is built through such interactions across organizational boundaries, creating and conveying information useful for all participants from scientists to decision makers.

Knowledge networks combine the talents of policy makers, scientists, government agencies, and nongovernmental organizations to provide close, ongoing, and continuous communication—as well as the spreading of information—among those who develop climate forecasts and those who use them, including water resource managers. Knowledge networks connect people across disciplinary or occupational boundaries, often through reliance upon boundary organizations. The latter (see section 5) are special entities, agencies, or stakeholder groups who help connect science and policy-making activities around specific problems and usually in a specific geographic place (e.g., a cooperative extension service office in a specific region or a watershed council in a particular river basin). Successful application of climate information to water resource problems—those, in other words, that overcome the stovepiping problem and avoid the loading-dock myth—tend to occur when people are poised to take advantage of unexpected opportunities to collaborate, a task of networks.

In water policy, knowledge networks help to ensure that scientific information gets used by tying together information with the needs of the user community. In the United States, one of the oldest knowledge networks for water is the long-standing relationship among public-supported land grant colleges, local irrigation district managers, and county extension agents who, among other things, transform highly technical knowledge about, say, drought, other weather conditions, and the needs of crops and livestock into information useful to farmers, ranchers, local governments, and homemakers (Cash 2001). Using this example as an archetype, effective knowledge networks facilitate good communication between those who generate climate information and those, like water managers or members of the public, who need this information to manage drought, alleviate flood damage, water their crops, and even manage fire hazard risks.

Networks perform this function by permitting person-to-person sharing of information and allowing water and other resource managers to share what they know about local conditions with what scientists know about, say, climate conditions generally. We call this blended knowledge (Skogstad and Shaver 2005, 8–9). An example in the climate science community is the effort by some forecast centers to base operational predictions on a combination of expert judgment subjectively applied to statistically based prediction models. NOAA's Climate Prediction Center and International Research Institute for Climate and Society construct their monthly and seasonal outlook reports by including subjective weighting of guidance provided by different forecast tools. This weighting is often highly sensitive to the recent evolution and current state of the tropical ENSO. However, decadal trends in precipitation and surface temperature may also influence the final official climate forecasts (Sarewitz and Pielke 2007).

Finally, networks permit coproduction of knowledge—generating new technologies through collaboration of scientists and engineers on the one hand and nonscientists on the other, thereby incorporating values and criteria from both communities (Lemos and Morehouse 2005; Wynne 1996).[2] Coproduction leads to new models, maps, and other forecast products that can help manage real-world problems (e.g., not just knowing ''what is the maximum probable flood stage of a river during large rain events?'' but ''how many homes and businesses will be threatened if a river crests at a certain level?'')[3] Such dialogue allows users to independently verify the usefulness of climate forecast information and to share what they know with scientists so their knowledge can feedback into the process of generating new models. Conventional organizations that generate climate and water knowledge are not always equipped to provide this kind of information. Universities do not often reward scholarship across different disciplines (e.g., political science, meteorology), and they are not particularly good at ensuring practical application of knowledge. Students are trained to get a degree and take up a career; they cannot serve as permanent staff to engage in networking activities.

4. Developing knowledge networks

Efforts to identify factors that improve the usability of SI climate information have found that effective knowledge networks focus on promoting broad, user-driven management objectives (Cash and Buizer 2005). These objectives, in turn, are shaped by the decision context, which usually contains multiple stresses and management goals (Western Water Policy Review Advisory Commission 1998). Research on water resource decision making suggests that goals are defined very differently by agencies or organizations dedicated to managing single issue problems in particular sectors (e.g., irrigation, public supply) when compared with decision makers working in political jurisdictions or watershed-based entities designed to comprehensively manage and coordinate several management objectives simultaneously (e.g., flood control and irrigation, power

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[2] This conception of coproduction should not be confused with that of S. Jasanoff, a science and technology studies scholar who uses the term to denote the way scientific knowledge is socially constructed by the complex interaction/participation in the enterprise of science by special interests, funders, corporations, government agencies, and markets as well as by the relationship among culture, power, and learning capacity (Jasanoff 2004).

[3] A good example of a tool, developed through boundary-spanning efforts by climate and hydrological scientists on the one hand and water managers and other decision makers on the other, is the Advanced Hydrologic Prediction Service, which was developed by NOAA and whose purpose is to provide floodplain managers and local governments with answers to precisely these types of questions (see Beller-Simms et al. 2008, section 3.3.1.2).

generation, and in-stream flow). The latter face the unusual challenge of trying to harmonize competing objectives, are accountable to numerous users, and require ''regionally and locally tailored solutions'' to problems (Western Water Policy Review Advisory Commission 1998; Kenney and Lord 1994).

Effective knowledge networks should be designed for learning rather than knowing; the difference being that the former emphasizes the process of exchange between decision makers and scientists, constantly evolving in an iterative fashion rather than aiming for a one-time-only completed product and structural permanence. Learning requires that knowledge–action systems have sufficient flexibility of processes and institutions to effectively produce and apply climate information, encourage diffusion of boundary-spanning innovation, be self-innovative and responsive, and develop ''operating criteria that measure responsiveness to changing conditions and external advisory processes'' (Cash and Buizer 2005). Often, nontraditional institutions that operate outside ''normal'' channels, such as nongovernmental organizations or regional coordinating entities, are less constrained by tradition or legal mandate and thus more able to innovate. Examples include the Arizona Water Institute, formed as a consortium of Arizona's three major public universities as a means of fostering innovation in the water sector among universities, public agencies, local communities, tribes, and the private sector. The institute seeks to build capacity through improving access to hydrologic data for decision making, assists in visualizing decision impacts, and provides workshops, training, and employment pathways.

For climate forecast and information producers and end users to better communicate with one another, they must be engaged in long-term dialogue about each others' needs and capabilities. To achieve this, knowledge producers must be committed to establishing opportunities for joint learning. When such communication systems have been established, the result has been the gaining of user knowledge (Ingram and Stern 2007; Cash et al. 2003). The discovery that climate information must be part of a larger suite of decision-relevant information can help producers understand the decision context and better appreciate that users manage a broad array of risks. Lead innovators within the user community can lay groundwork for broader participation of other users and connections between producers and users (Cash and Buizer 2005).

Such tailoring or conversion of information requires organizational settings that foster communication and exchange of ideas between users and scientists. For example, a particular user might require a specific type of precipitation forecast or even a different type of hydrologic model to generate a credible forecast of water supply volume. This producer–user dialogue must be long term, must allow users to independently verify the utility of forecast information, and must provide opportunities for verification results to ''feed back'' into new product development (Cash and Buizer 2005; Jacobs et al. 2005).

Studies of this connection refer to it as an ''end to end'' system to suggest that knowledge networks must engage a range of participants including those who generate scientific tools and data, those who translate them into predictions for use by decision makers, and the decision makers themselves (Agrawala et al. 2001). End-to-end useful also implies a broad fabric of utility created by multiple entities that adopt forecasts for their own reasons and adapt them to their own purposes by blending forecast knowledge with know-how, practices, and other sources of information more familiar to them—such as local knowledge (see section 5b).

A forecast innovation might combine climate factor observations, analyses of climate dynamics, and SI forecasts. In turn, users might be concerned with varying problems and issues such as planting times, in-streamflows to support endangered species, and reservoir operations. As Cash and Buizer note, ''Often entire systems have failed because of a missing link between the climate forecast and these ultimate user actions.'' Avoiding the missing link problem varies according to the particular needs of specific users (Cash and Buizer 2005).

Users want useable information as well as answers—an understanding of things that will help them explain, for example, the role of climate in determining underlying variation in the resources they manage. In effect, the two are complementary. Knowledge networks must provide more than simply decision support conventionally defined. They must provide a broad range of information for risk management, and not just forecasts of particular threats. Measures to hasten, encourage, and sustain these knowledge–action systems must include practices that empower people to use information through providing adequate training and outreach and sufficient professional reward and development opportunities. Three organizational measures are essential: 1) incentives to produce boundary objects, such as decisions or products that reflect the input of different perspectives; 2) involvement of participation from actors across boundaries; 3) clear lines of accountability to the organizations spanned (Guston 2001).

5. Boundary organizations, objects, and networks

A variety of institutional mechanisms and tools can be employed to foster the creation of knowledge networks and the coproduction of knowledge that transcends what is already available. Among these are boundary organizations that play an intermediary role between different organizations, specializations, disciplines, practices, and functions, including science and policy (Cash 2001; Cash et al. 2002; Guston 2001; Gieryn 1999; Ziervogel and Downing 2004). Important is that such boundary-spanning efforts have been observed in developing regions—including sub-Saharan Africa and Latin America—as well as in developed countries (Lemos and Morehouse 2005; Ziervogel and Downing 2004; Patt et al. 2007). A boundary object is a prototype, model, or other artifact through which collaboration occurs across different kinds of boundaries. It need not be a formal organization but may simply be a one-time forum or other opportunity where people representing different disciplines may come together to learn from one another. In many forms of scientific endeavor, collaborators may come to appreciate the contribution of other kinds of knowledge, perspectives, expertise or practices and how they may augment or modify their own knowledge through engagement (Star and Griesemer 1989).

Boundary organizations, for their part, link different social and organizational worlds to foster innovation, provide two-way communication among multiple sectors, and integrate production of science with user needs. Whereas knowledge networks are the entire array of collaborations among disciplines and between users and producers of information, boundary organizations perform translation and mediation functions between producers of information and their users (Guston 2001; Jacobs et al. 2005).

''Translation'' is an aid to network communication that boundary organizations perform by taking the technical, difficult-to-understand jargon of scientific forecasting and turning it into useful information for water managers and the lay public (see Cash et al. 2006; Ingram and Stern 2007). For example, scientists often talk about the probability of floods, the likely severity of drought, and the risk of wildfires. An organization such as a regional agricultural extension service office can help to translate this complex information into a form that is useful to the types of decisions policy makers have to deal with in a certain region by taking information that is shrouded in varying degrees of certainty and providing decision makers with various ''if–then'' scenarios, simulations, and hypothetical problems such as how precise must climate information be for long-term planning; or, how effectively can various demand-side management strategies mitigate the effects of reduced water availability?

''Mediation'' refers to activities such as convening forums that provide common vehicles for conversations and training and for tailoring information to specific applications. This is important because boundary organizations span not only disciplines but different conceptual and organizational divides (e.g., science and policy), organizational missions and philosophies, levels of governance, and gaps between experiential and professional ways of knowing—and, as shall be seen, they are often region specific. In effect, if a knowledge network is thought of as a knowledge transfer system, then boundary organizations—when performing such functions as translation and mediation—may be thought of as intermediaries between nodes in the system, most notably between scientists and decision makers.

Boundary organizations are important to decisions in three ways. First, they serve as communication brokers between supply and demand functions for particular areas of societal concern. In the United States, for example, local irrigation district managers and county extension agents often serve this role in mediating between scientists (hydrological modelers) and farmers (Cash 2001). Second, they enhance communication among stakeholders. Effective tool development requires that affected stakeholders be included in dialogue, and that data from local resource managers (blended knowledge) are used to ensure credible communication. Successful innovation is characterized by two-way knowledge (Sarewitz and Pielke 2007; Guston 2001).

Third, boundary organizations overcome the aforementioned problems with the loading-dock model of climate product development by serving the function of translation: converting technical, scientific, and technological jargon into a form useable by a range of decision makers. Under the conventional loading-dock model of climate product development, translation is not considered necessary because information as generated by scientists and model builders is assumed to be automatically useful and useable. In fact, however, in relations between experts and decision makers, understanding is often hindered by jargon, language, experiences, and presumptions; for example, decision makers often want probabilistic information and are more likely to trust and use it—but meteorologists and other scientists often assume they want deterministic answers (Patt 2001, 2006). Ironically, however, decision makers often mistake probabilistic uncertainty as a kind of failure in the utility and scientific merit of forecasts, even though uncertainty is a characteristic of science (Brown 1997). With respect to translation, boundary spanning can be important in providing greater understanding of uncertainty and its source. This includes better information exchange between scientists and decision makers on, for example, the decisional relevance of different aspects of

TABLE 1. Boundary organizations for decision-support tool development (from Beller-Simms et al. 2008).

Cooperative extension services: Housed in land grant universities in the United States, they provide large networks of people who interact with local stakeholders and decision makers within certain sectors (not limited to agriculture) on a regular basis. In other countries, this agricultural extension work is often done with great effectiveness by local government (e.g., Department of Primary Industries, Queensland, Australia).

Watershed councils: In some U.S. states, watershed councils and other local planning groups have developed, and many are focused on resolving environmental conflicts and improved land and water management (particularly successful in Oregon, e.g.).

Natural Resource Conservation Districts: Within the U.S. Department of Agriculture, these districts are highly networked within agriculture, land management, and rural communities.

Non-governmental organizations (NGOs) and public interest groups: Focus on information dissemination and environmental management issues within particular communities. They are good contacts for identifying potential stakeholders and may be in a position to collaborate on particular projects. Internationally, a number of NGOs have stepped forward and are actively engaged in working with stakeholders to advance use of climate information in decision making (e.g., Asian Disaster Preparedness Center in Bangkok, Thailand).

National agency and university research activities: Expanding the types of research conducted within management institutions and local and state governments is an option to be considered—the stakeholders can then have greater influence on ensuring that the research is relevant to their particular concerns. RISAs are an example.

uncertainties and methods of combining probabilistic estimates of events through simulations to reduce decision maker distrust, misinterpretation of forecasts, and mistaken interpretation of models (Brewer and Stern 2005).

Not every intellectual enterprise makes a good boundary organization. Jacobs (2003) suggests that universities can be good locations for the development of new ideas and applications but may not be ideal for sustained stakeholder interactions and services, in part because of funding issues and because training cycles for graduate students, who are key resources at universities, do not always allow a long-term commitment of staff. Many user groups and stakeholders either have no contact with universities or may not encourage researchers to participate in or observe decision-making processes. University reward systems rarely recognize interdisciplinary work, outreach efforts, and publications outside of academic journals, limiting incentives for academics to participate in real-world problem solving and collaborative efforts. Table 1 depicts a number of effective boundary organization examples for climate change decision support.

a. *Application to climate forecasting and water resources—RISAs*

One example of boundary organizations that use boundary objects as a focus of collaboration and create knowledge networks is the RISAs established by NOAA. The nine RISA teams, located within universities and often involving partnerships with NOAA laboratories throughout the United States, are focused on stakeholder-driven research agendas and long-term relationships between scientists and decision makers in specific regions. Each RISA builds a regional-scale picture of the interaction between climate change and the local environment from the ground up. By funding research on climate and environmental science focused on a particular region, the RISA program currently supports interdisciplinary research on climate-sensitive issues. In some cases, information specialists act like agricultural extension services in responding to user needs. Table 2 depicts current RISAs.

Each region cited in Table 2 has its own distinct set of vulnerabilities to seasonal climate variations, including water supply, fisheries, agriculture, wildfires, spread of pests and diseases, and so on, and RISAs' research are focused on questions specific to each region. Among the various practices that have made RISAs effective are the ones described in the next three sections (McNie et al. 2007).

b. *RISAs and user-driven research*

Some RISAs rely on an approach that uses a combination of formal mechanisms such as surveys and personal interviews with likely users. For instance, the Southeast Climate Consortium RISA (SECC), composed of researchers at universities in Alabama, Georgia, and Florida, employs a top-down approach to developing stakeholder capacity to use climate information in the Southeast's $33 billion agricultural sector (Jagtap et al. 2002). Early on, SECC researchers recognized the potential to use knowledge of the impact of ENSO on local climate to advise farmers, ranchers, and forestry sector stakeholders on yields and changes to risk (e.g., frost occurrence). Through a series of need

TABLE 2. RISAs.

ACCAP	Alaska Center for Climate Assessment and Policy (AK)
CAP	California Applications Program (CA, NV)
CISA	Carolinas Integrated Sciences and Assessments (NC, SC)
CIG	Climate Impacts Group (Pacific Northwest: WA, OR, ID)
CLIMAS	Climate Assessment for the Southwest (AZ, NM)
NEISA	New England Integrated Sciences and Assessments (formerly funded: ME, NH, VT, MA, CT, RI)
Pacific RISA	Hawaiian and U.S.-affiliated islands (HI, Marshall Islands, Guam, American Samoa, Palau, Micronesia, Northern Marianas)
SCIPP	Southern Climate Impacts Planning Program (TX, OK, AR, LA, MS, TN)
SECC	Southeast Climate Consortium (AL, FL, GA)
WWA	Western Water Assessment (CO, UT, WY)

and vulnerability assessments (Hildebrand et al. 1999; Jagtap et al. 2002), SECC researchers determined that potential for producers to benefit from seasonal forecasts depends on the flexibility and willingness to adapt farming operations to forecasts and the effectiveness of the communication process—not merely documenting the effects of climate variability and providing better forecasts (Jones et al. 2000).

SECC's success in integrating new information is founded on sustained interaction with agricultural producers and extension agents. The former are members of the SECC research team while the latter are engaged through planned outreach, including monthly video conferences, one-on-one meetings, training workshops to gain confidence in climate decision tool use and to identify opportunities for their application, and traditional extension activities (e.g., commodity meetings, field days) (Fraisse et al. 2005). SECC leverages the trust engendered by Cooperative Extension's long service to the agricultural community and its access to local knowledge and experience to build support for its AgClimate online decision-support tool (available online at http://www.agclimate.org; see Fraisse et al. 2006). Direct engagement with stakeholders provides feedback to improve the design of the tool and to enhance climate forecast communication (Breuer et al. 2007).

c. *RISAs as ''information brokers'' and participant advocates*

Another RISA role is focusing on packaging and communicating information in a usable form. A good example of this is the Climate Assessment for the Southwest (CLIMAS) RISA. CLIMAS shows how cultural sensitivity is often required to link information with minorities such as Native Americans and Latinos living in rural areas. Team-oriented networking strategies are used. Underlying the broker role is the need to build trust both among team members and with the users. An iterative approach of constantly returning to the users and reformulating the problem continuously is employed. The Colorado River basin drought that began with the onset of a La Niña episode in 1998 and alerted regional water resources managers to the need to incorporate climate variability and change into their plans and reservoir forecast models exemplifies this ''broker'' role. Paleohydrologic estimates of streamflow document extended periods of low flow and demonstrate greater streamflow variability than the information found in the gauge record. As such, they can be persuasive examples of the nonstationary behavior of the hydroclimate system (Woodhouse et al. 2006; Meko et al. 2007).

Following a 2005 scientist–stakeholder workshop on the use of paleohydrologic data in water resource management (http://www.climas.arizona.edu/conferences/CRBpaleo) NOAA RISA and California Department of Water Resources (CDWR) scientists developed strong relationships to improve the usefulness and usability of science in water management. CDWR, whose mission includes preparing for potential impacts of climate change on California's water resources, led western states' efforts to partner with climate scientists to coproduce hydroclimatic science to inform decision making. CDWR led the charge to clarify scientific understanding of Colorado River basin climatology and hydrology, past variations, future projections, and impacts on water resources, by calling upon the National Academy of Sciences to study these issues (NRC 2007). In 2007, CDWR developed a memorandum of agreement with NOAA to better facilitate cooperation with scientists in NOAA's RISA program and research laboratories (CDWR 2007)—an enduring ''broker'' role.

CLIMAS also demonstrates a participant-advocacy approach in this knowledge-broker role inasmuch as researchers join with forecast users in supporting additional resources that are directed toward specific problems such as drought response, wildfire prevention, and pest control. Also, many RISAs embrace the notion of using information to transform the system. This role puts the most strain on traditional academic behavior. An example of this participant-advocacy approach is also afforded by CLIMAS, a RISA project that draws upon the resources of staff at The University of Arizona and provides insights into ways in which coproduction of science and policy can be achieved in a structured research setting (Lemos and Morehouse 2005). In this project, RISA staff work with The University of Arizona's Cooperative Extension to produce a newsletter containing official and nonofficial forecasts and other information useful to many decision makers in the area, particularly farmers (see http://www.climas.arizona.edu/forecasts/swoutlook.html).

d. RISAs and basic research

This approach tends to be adopted in situations in which experts are unable to deliver needed information because of gaps in basic knowledge. For instance, the California Applications Program RISA has identified gaps in modeling as an inhibitor of prediction and forecasting. To produce context-sensitive and policy-relevant information to fill these gaps, CAP views interaction with decision makers as a means to learn more about how certain resources, for example, forests, estuaries, and fisheries, actually adapt to changes in precipitation or streamflow. The collaborative effort that followed the 2005 scientist–stakeholder workshop on use of paleohydrologic data in water resource management, discussed above in the ''information broker'' discussion, also illustrates this basic research role (see McNie et al. 2007).

RISAs have been proposed to fulfill part of the research function that a National Climate Service (NCS) might require, should it become established. The NCS would engage in observations, modeling, and research nested in global, national, and regional scales with a user-centric orientation (Miles et al. 2006). The potential for further development of the RISAs and other boundary-spanning organizations that facilitate knowledge-to-action networks deserves study. While small in size, these programs are very successful long-term efforts by the national government to integrate climate science in sectors and regions across the United States [see P. W. Mote's testimony to the House Subcommittee on Energy and Environment (available online at http://democrats.science.house.gov/Media/file/Commdocs/hearings/2009/Energy/5may/Mote_Testimony.pdf) and to the Committee on Science and Technology (available online at http://science.house.gov/publications/hearings_markups_details.aspx?NewsID=2449)].

6. Evaluating RISA and boundary organization success

Collaboration between producers and users of climate information in a water management context must be grounded in an appreciation for the perspectives of those who work in water management, including their decision context and multiple stresses. Collaboration in effective systems—what we have termed knowledge–action systems—does not permit a particular tool or technology (e.g., ENSO forecasting) to drive the dialogue between scientists and decision makers. Instead, communication among experts, policymakers, and lay audiences is guided by the ultimate outcomes all protagonists agree must be advanced: the reduction of risk from climate variability (Cash and Buizer 2005; Sarewitz and Pielke 2007). This brief examination, based in part on RISA self-assessments, suggests that three factors discussed below are essential to collaboration: leadership, resources, and integration skills.

a. Leadership

Effective knowledge networks are led by inclusive leaders who incorporate the knowledge, skills, resources, and perspectives of their organizations and the groups and other entities they serve. Often these leaders are ''change agents'' who have a guiding vision that sustains them through difficult times, a passion for their work and an inherent belief in its importance, and a basic integrity toward the way in which they interact with people and approach their jobs. They lead by deliberation and transparency; people feel empowered to use information when serving under such leaders, and the leaders themselves provide adequate training and outreach opportunities as well as sufficient professional reward and development opportunities for their own staff. For example, a clear consensus emerged from a National Science Foundation (NSF)-sponsored workshop to research the RISAs held at the East–West Center in Honolulu in 2005 that subgroup leaders responsible for research and integrated assessment are key to achieving balance between research on new subjects and assessment/compilation of existing knowledge as well as establishing overall research priorities (McNie et al. 2007).

b. Funding and other resources

Stable funding promotes long-term stability and trust by allowing researchers to focus on user needs over long periods of time and allowing decision makers to develop confidence that researchers will be around awhile to work with them. Reports from several RISAs consistently indicate the importance of selecting projects that are supportable within the scope of what can be funded within a single budget cycle—especially in a climate of diminishing resources (e.g., the Pacific RISA reported that it focuses mostly on assessment of shared learning and joint problem solving with users because of funding limitations [for a review of all these self-assessments, see McNie et al. (2007)]. This balance also was chosen because it was identified through dialogue with users as a high-priority project for its initial Pacific Islands climate assessment (McNie et al. 2007). Likewise, the Western Water Assessment (WWA) and California Applications

Program (CAP) RISAs report that they have adopted a similar philosophy of only taking on tasks supportable within a single fiscal year, in part because funding delays make longer-term planning difficult and because it is important to demonstrate short-term success to bolster continue stakeholder interest in RISA activities and credibility (McNie et al. 2007).

c. *Integration skills*

Well-functioning RISA-based knowledge networks emphasize the development of ''integration skills''—they cultivate people who can bridge different ways of knowing about issues. Such integrators are often self-selected managers and decision makers with particular aptitude or training in science, or they can be scientists who are particularly good at communication and practical applications (Jacobs 2003). Training may entail curriculum development, career and training development for users as well as science integrators, and continued midcareer in-stream retraining and reeducation. Many current integrators have evolved as a result of doing interdisciplinary and applied research in collaborative projects, and some have been encouraged by funding provided by NOAA's Climate Programs Office (formerly Office of Global Programs) (Jacobs et al. 2005).

While RISA programs seem to have been successful, there is little indication that the RISA model is being replicated elsewhere on different climate variation problems such as urban areas that are located in coastal areas and flood plains susceptible to climate variability crises. RISAs continue to struggle for funding while RISA-generated lessons are widely acclaimed (McNie et al. 2007; McNie 2007). To a large extent, they have not influenced the federal climate science policy community outside of the RISAs themselves, though progress has been made in recent years. Further, the funding of RISAs has come at the expense of other social science research in NOAA. In 2002, the House Science Committee held hearings to explore the connections of climate science and the needs of decision makers. Guided by the question, Are climate research efforts focused on the right questions? the Committee found that the RISA program is a promising means to connect decision-making needs with the research prioritization process, because ''[it] attempts to build a regional-scale picture of the interaction between climate change and the local environment from the ground up. By funding research on climate and environmental science focused on a particular region, [the RISA] program currently supports interdisciplinary research on climate-sensitive issues in five selected regions around the country. Each region has its own distinct set of vulnerabilities to climate change, e.g., water supply, fisheries, agriculture, etc., and RISA's research is focused on questions specific to each region.''

Self-evaluations have been conducted by several RISAs [summarized in McNie et al. (2007) on the following pages: CAP, 24–32; CISA, 33–35; NEISA, 36–40; Pacific RISA, 41–53; CIG, 54–60; SECC, 61–62; CLIMAS, 63–75; and WWA, 76–81; acronyms are found in Table 2]. CLIMAS has undertaken self-assessment to ''prioritize research initiatives, assess success in knowledge transfer and exchange, and assess the utility, usability, and timeliness, of specific products or suites of products,'' while WWA has tried to measure ''sustained interaction'' with stakeholders. All RISAs have sought ''immediate and informal feedback at meetings or workshops'' to gauge the usefulness of their products (McNie et al. 2007).

7. Conclusions

Better integration of climate forecasting science into water resources and other sectors will likely save and improve lives, reduce damages from weather extremes, and lower economic cost related to adapting to continued climate variability. Skill is a necessary ingredient in perceived forecast value, yet more forecast skill by itself does not imply more forecast value. Forecasts must flow through knowledge networks and across disciplinary and occupational boundaries. Thus, forecasts need to be useful and relevant in the full range from observations to applications—this is what makes them ''end-to-end useful'' (see section 4). By the end of the process of transfer, translation, and transformation of information, forecast information may look very different from what scientists initially envisioned.

We conclude by noting that, in light of our findings, the ramifications of social science research funding should be more carefully considered. In 2003, a review panel recommended that NOAA should readjust its research priorities by additional investment in a wide variety of use-inspired social science projects (Anderson et al. 2003), including support for building additional RISA-type networks (i.e., the Sectoral Applications Research Program) (see, e.g., NOAA Budget for Fiscal Year 2008, available online at http://www.corporateservices.noaa.gov/nbo/08bluebook_highlights.html). In reinforcement of this, we would add that more use-inspired social science research is of inestimable value. This is especially true in light of the fact, seen in this article, that the relatively modest funding thus far expended on social science–related research has yielded considerable benefit in regard to understanding the barriers and opportunities for knowledge network germination and the role of boundary organizations in hastening communication and collaboration between science producers and users.

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