Making short-term climate forecasts useful: Linking science and action

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This paper discusses the evolution of scientific and social understanding that has led to the development of knowledge systems supporting the application of El Niño-Southern Oscillation (ENSO) forecasts, including the development of successful efforts to connect climate predictions with sectoral applications and actions "on the ground". The evolution of "boundary-spanning" activities to connect science and decisionmaking is then discussed, setting the stage for a report of outcomes from an international workshop comprised of producers, translators, and users of climate predictions. The workshop, which focused on identifying critical boundary-spanning features of successful boundary organizations, included participants from Australia, Hawaii, and the Pacific Islands, the US Pacific Northwest, and the state of Ceará in northwestern Brazil. Workshop participants agreed that boundary organizations have multiple roles including those of information broker, convenor of forums for engagement, translator of scientific information, arbiter of access to knowledge, and exemplar of adaptive behavior. Through these roles, boundary organizations will ensure the stability of the knowledge system in a changing political, economic, and climatic context. The international examples reviewed in this workshop demonstrated an interesting case of convergent evolution, where organizations that were very different in origin evolved toward similar structures and individuals engaged in them had similar experiences to share. These examples provide evidence that boundary organizations and boundary-spanners fill some social/institutional roles that are independent of culture.

boundary organization | decision support | El Niño-Southern Oscillation | knowledge

> "Effective knowledge systems require face-to-face engagement at the scale of the decision..."

Climate variability poses challenges for decisionmaking for sustainability, introducing significant uncertainty in management of resources and support of human populations. Important advances have been made in the past two decades in understanding climate drivers, the most effective modes of communicating climate science, and specific applications of climate information within sectors. Institutional approaches have forged and supported linkages between various types of knowledge, the actors who produce them, and those who use them. However, the impacts of climate variability are specific to geographic regional and local scales, and the establishment of knowledge systems for decision support is inconsistent and poorly funded. The ability to translate successes in the use of climate forecasts broadly is limited, resulting in environmental, economic, and social consequences that may have been avoidable. This paper examines the components of climate-based knowledge systems and linkages between them, with particular focus on the boundary organizations that bridge between actors and their knowledge sources in the water/climate arena.

The specific international case studies examined are from Ceará, Brazil; Hawaii and the Pacific Islands; the US Pacific Northwest; and Australia. These cases were selected because they have highly evolved climate knowledge systems that include boundary organizations. The specifics of these cases were explored in a participatory workshop in May 2004 sponsored by the National Research Council. This international workshop involved producers of climate science, science integrators, program managers, and users of decision support systems in a wide range of sectors, including agriculture, health, energy, environment, and manufacturing in an effort to understand links between research and decisionmaking. The National Research Council published the workshop summary, Knowledge-Action Systems for Seasonal to Interannual Climate Forecasting: Summary of a Workshop, in 2005 (1).

Boundary institutions link the producers of knowledge with decisionmakers and generally facilitate flows of information in both directions. They were described initially by using Guston's definition that successful boundary organizations (*i*) exist between the worlds of politics and science, but have accountability to each; involve actors from both sides of the boundary; and provide opportunities for the creation of "boundary objects," which can include models, forecasts or assessment reports and (*ii*) facilitate both collaborative and independent activities (2). This paper addresses questions such as, How have such institutions evolved to bring into alignment the demand for, and supply of, knowledge to support action? To what degree has their design been purposeful, as opposed to reactionary to specific conditions?

Although the investigation of the potential for prediction was initially science inquiry-driven, since 1990, attention has shifted to identifying the impacts that can be attributed to El Niño-Southern Oscillation (ENSO), and then to assessing the social and economic context of impacts through programs including Knowledge Systems for Sustainable Development, International Human Dimensions Program on Global Environmental Change, and the National Oceanographic and Atmospheric Administration (NOAA) Climate Program Office [formerly the Office of Global Programs (OGP)], Human Dimensions Program. Through these interdisciplinary social and physical science programs, a deeper look at integrated human-natural system has evolved. This new focus includes evaluating science and decisionmaking linkages and the components of successful boundary organizations.

The ENSO

For at least a century, fishermen off the coasts of Ecuador and Peru have known about the "El Niño" phenomenon. They observed that every few years, "warm" surface ocean water would appear around Christmas time, altering the abundance of local fish stocks. They termed this current "Corriente del Niño,"

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or "El Niño Current," referring to the Christ child (3). Through the work of Jacob Bjerknes in the late 1960s, we now know that this oceanographic phenomenon is physically linked to a related atmospheric event referred to as the "Southern Oscillation." The Southern Oscillation is, as described by Trenberth "a see-saw in atmospheric mass involving exchanges of air between eastern and western hemispheres in tropical and subtropical latitudes with centers of action located over Indonesia and the tropical South Pacific Ocean." Climate scientists commonly use the term ENSO* when referring to this interplay between the tropical Pacific Ocean and the atmosphere (4).

Research dedicated to ENSO prediction began in earnest in 1985 with the initiation of the 10-year international Tropical Ocean and Global Atmosphere (TOGA) program established under the auspices of the World Meteorological Organization (WMO) and the Intergovernmental Oceanographic Commission (IOC) of the United Nations.

Within a year, Mark Cane and Steve Zebiak, two climate modelers at the Lamont-Doherty Earth Institute of Columbia University, produced the first successful ENSO forecast (5). This scientific breakthrough was complemented with others such as the deployment of TOGA's Thermal Array for the Oceans, or TOGA-TAO, a system of moored buoys spread across the tropical Pacific Ocean (6).

By 1987, officials at the NOAA Office of Global Programs (OGP) had garnered sufficient optimism to consider organizing scientists and governments around the world to create a system for the regular production, distribution, and application of seasonal climate forecasts. It was imagined that, in the previous example, if drought could be predicted several months in advance and coupled with response options effectively communicated to local farmers and politicians, employment and food supply could be maintained, allowing the government to save scarce financial resources and the people to avoid unnecessary suffering.

Without losing sight of the need for continued physical climate system research critical to the production of more effective forecasts, NOAA officials began conceptualizing what was to become the International Research Institute for Climate and Society (IRI). The IRI is a research and applications center that focuses attention on the use of ENSO timescale climate forecast information for sectors significantly affected by climate variability (7). Through dedicated projects and governmental research organizations, forecast products are tailored to specific regions and research needs. Work originally focused on countries that had a strong ENSO signal and impacts from climate variability, specifically Brazil, southeast Asia, and Africa. At the center of IRI's vision is the role of information users in defining the products of the IRI.† Designed as a boundary organization, the IRI organizes its science around articulated needs. It is housed at the Lamont-Doherty Laboratory of Columbia University's Earth Institute.

Simultaneously, OGP initiated a Climate and Societal Interactions (CSI) program focused on the interface between scientific information and environmental and societal decisionmaking, particularly with relation to climate. Programs conducted by CSI promoted the study and use of new information and tools to enable society to prepare for changing environmental conditions and coping with multiple stresses. CSI also enhanced research efforts to advance understanding of socio-economic vulnerabilities to impacts of climate variability. CSI also qualified as a "boundary organization" under the definition used above. Its goals were to:

- Identify, explore, and communicate the information needs of a diverse suite of decisionmakers to foster a solution-oriented focus in NOAA research and services;
- Identify, understand, and assess the sensitivity and adaptability of managed systems to climate;
- Explore the uses and identify the limits of evolving knowledge in managing risks and opportunities related to climate variability and change; and
- Catalyze and accelerate the development, prototyping, and evaluation of tools and methods to connect science to decisionmaking needs and structures productively.

Recognizing that the connections between climate science and societal use of this information were critical to reducing vulnerability on a global scale, and that there was little documentation of what had been learned in climate applications projects, NOAA funded the Knowledge Systems for Sustainable Development (KSSD) project. This project represents a dedicated, scholarly approach to evaluating knowledge production and use systems in the climate/human space. The KSSD Project seeks to understand and promote the design of effective systems to harness research-based knowledge for sustainability. The KSSD Project team views "knowledge systems" as consisting of networks of linked actors, organizations, and objects that perform a number of knowledge-related functions (including research, innovation, development, demonstration, deployment, and adoption) involved in linking knowledge and know-how with action. In particular, KSSD's research asks, What are the characteristics of effective knowledge systems? How does the effectiveness of such systems depend on social and environmental contexts? How can knowledge systems be made more effective in specific circumstances.‡

The Evolution of Boundary Organizations

Boundary organizations often arise out of the desire to regularize activities within the boundary space. Institutions generally do not invest in boundary functions (e.g., workshops, forums, and reports) that are not core to their mission; governments or private funders may not want to invest in the creation of freestanding boundary organizations. In these instances, boundary organizations serve a highly desirable function—to institutionalize these activities within an organization or to create an independent organization that specifically serves this function. A critical challenge for these organizations is to serve in this capacity while maintaining the flexibility to adjust to and organize around the constantly changing needs for specific information products (8).

Challenges also exist in the need to create careers in the boundary space and provide incentives and rewards to individuals working in these areas. It is also important to recognize that in many knowledge-to-action systems, there are informal communities of actors who play no explicit role in the system itself. However, these individuals often create connections between explicit actors who otherwise might not meet and relationships that otherwise might not exist. These actors may be difficult to identify, yet they are sometimes crucial to the success of the system—especially along and between boundary spaces.

The Programmatic Underpinnings. The initial boundary-spanning activity was to build the ENSO physical science knowledge system, first integrating oceanography and meteorology then the biological and social sciences. Once it became apparent that ENSO events could be forecasted, CSI made a concerted effort to build a research and applications program that bridged the

*ENSO refers to an entire suite of processes, including El Niño (the warm phase) and the opposite La Niña (the cold phase). The latter generally results in an opposite climate.

†(International Research Institute for Climate Prediction: http://iri.columbia.edu/).

‡(Knowledge Systems for Sustainable Development: www.hks.harvard.edu/kssd/).

gaps between the disciplines. The IRI improved on this program, adding components to address issues raised in the social and economic sciences as well as in the resource management realm. The CSI and IRI efforts helped define the science needed to improve forecasting. It soon became apparent that the process of integrating disciplinary work to form a truly interdisciplinary and scientifically defensible approach required a continuous effort. Not only in garnering trust and mutual respect between practitioners of the various scientific disciplines, but also in understanding the methods and challenges of each and in defining a common vocabulary.

The Production of Forecasts. The second phase of boundary-spanning efforts focused on production of global climate forecast products and regional/national-scale forecasts. Generally, researchers working at the global climate scale do not work at the smaller, regional scale and the statistical methods used to achieve higher-resolution regional forecast products are often different from the dynamic methods used by global modelers. Furthermore, datasets necessary for regional forecasts are owned and often controlled by the National Meteorological Services (NMS) within countries. These NMSs must therefore play a critical role in the regional forecasts, not only to provide the data but also to build confidence in the quality of the products, and thereby gain "ownership" of them. Climate Outlook Forums (COFs), a regularized convening of global and regional modelers and meteorological service scientists, exemplify boundary-spanning activities that bring these stakeholders together. The process by which they arrive at a consensus forecast is a typical boundary-spanning function.

The concept of Regional COFs emerged out of a Workshop on Reducing Climate-related Vulnerability in Southern Africa, sponsored by the IRI, NOAA/OGP/CSI and the US Agency for International Development (USAID) October 1996 in Victoria Falls, Zimbabwe (9). Participants at the Victoria Falls workshop proposed that producers of forecasts from modeling centers around the world meet periodically with representatives of NMSs in the region and potential users of the information to produce "consensus" climate forecasts. These meetings would be convened in regions heavily dependent on rainfall for agriculture, where that rainfall is highly variable from year-to-year, where ENSO forecasts had the potential to be useful, and where the national capacity to forecast is limited. Regions included southern Africa and northeastern South America, among others. It was recommended that these meetings be timed to coincide with critical decision periods for the planting of crops, such as just before the agricultural "rainy season."

The 1997/98 ENSO forecast provided the impetus to begin the COFs, and the first was convened September 1997 in Kadoma, Zimbabwe, for the southern African region. Three South American COFs quickly followed. With each COF, the process was further refined and improved. However, the primary objectives remained the same:

i. Develop and communicate a consensus seasonal climate "outlook."
ii. Facilitate research cooperation and data exchange within and between regions.
iii. Improve coordination within the climate forecasting community.
iv. Create and enhance a regular dialogue between producers and users of the climate information.

The IRI and NOAA, with financial assistance from USAID, together with regional partners, conducted 36 regional COFs around the world between 1997 and 2001. For many parts of the world, in the absence of a more permanent institutional structure for the production and distribution of regional climate forecasts, the COF became the de facto climate service. At these meetings, IRI experts provided their technical expertise, latest forecasts, and interpretations, combining them with those of other international experts as well as with knowledge from local meteorologists, farmers, and public health and other officials in the region. Local hosts were critically important to the success of the COF. Their unique knowledge of the region was essential for climate forecasts to be created and used on a regular basis in the regions (10).

Building the Delivery Systems. Next, steps were undertaken to bridge the gaps between regional climate-forecast producers and information users such as agriculture, water and resource managers, disaster preparedness officials, and others responsible for resources or services impacted by climate. The many differences between these communities, including major challenges—i.e., language, methods, motivation, timeframes of operation, scale, etc.—led to the need for an intensive boundary-spanning effort. This effort was aimed at reducing the impediments to the two-way transfer of knowledge—the technical knowledge of the producers and the practical, contextualized knowledge of the users in specific sectors. These efforts were less centrally controlled and, in some cases, developed relatively spontaneously in response to the exposure of decisionmakers to climate products produced for other sectors and regions.

The KSSD team concluded that it was time to compare the "lessons learned" in successful boundary organizations to enhance development and use of these lessons. The following is a discussion of boundary organizations, their characteristics, and organizations' use of boundary-spanning activities.

Comparative Study of Boundary Organizations

> "Probability is a good thing, part knowledge, part ignorance. Seasonal forecasts are about which way to lean, not jump. . ."

The following summaries, from the international KSSD workshop held in Irvine, CA, on May 6–8, 2004, provide perspective on the boundary organizations evaluated within this study and identify key findings from the conversations. The case studies included participants from four sites in Australia, the state of Washington, the Pacific Islands, and Brazil. For each case, representatives included information producers, information users, and representatives of boundary organizations. The conversations were facilitated and recorded by the conference organizers.

Queensland, Australia.[§] Workshop participants included a primary producer from Dalby in southeast Queensland; a program leader and principal scientist from the Queensland Department of Primary Industries and Fisheries; the coordinator of the Climate Variability Program, a research and development corporation; and a specialist in climate applications then working for the New South Wales Department of Primary Industries.

In Queensland, a large proportion of the agricultural community has access to climate forecasts, particularly in the dominant cropping and grazing industries. At least 40% of this community uses climate forecasts for decisionmaking. Intermediaries have played a significant role in facilitating the use of this information. In the 1990s, a network of dedicated agricultural climate extension officers was established under the Queensland Centre for Climate Applications (QCCA) after prolonged drought from 1991 to 1994. This resulted in a partnership between climate researchers, farmers, and agricultural industry groups—an example of effective collaboration between private and public sector interests. This collaboration has enabled farmers to link climate forecasts with crop models and modify management decisions in a timely manner.

[§]Meinke H, Stone RC (2005) Seasonal and interannual climate forecasting: the new tool for increasing preparedness to climate variability and change in agricultural planning and operations. *Clim Change* 70:221–253.

One successful boundary organization identified in this context is the Agency for Food and Fiber Sciences of the Department of Primary Industries and Fisheries. Individuals in the organization work with farmers, first understanding their management challenges, then providing tailored climate information as input for the farmers' decision process. The Agricultural Production Systems Research Unit (APSRU) is a second effective boundary organization. It is a joint venture of the Queensland State Government, Commonwealth Scientific and Industrial Research Organization, and University of Queensland. APSRU focuses on the need to manage risks by integrating climate information into a diverse set of risk management tools in ways that help farmers make decisions about cropping patterns, stocking rates, and irrigation scheduling. Funding for APSRU comes from levies on production, thus ensuring user-driven problem definition and ownership by the user community. The Queensland case is the only case we examined where the private sector is a major source of funding for the knowledge system.

This case study also illustrated the most sophisticated and robust climate information system of those we evaluated, in large part because climate information is now formally included in economic decisionmaking in the agricultural sector. Participants noted that the futures market is a good integrator of the uncertainty.

Key findings included that focusing research investment within regions and sectors supports user-driven rather than centrally framed (and less use-oriented) research. In addition, access to climate data can be a contentious issue. Given the government's interest from a policy perspective and the private sector's interest from an economic perspective, which often do not align, the need to provide equitable access to information and be an impartial broker of climate data were emphasized.

Hawaii and Central Pacific Islands. Workshop participants included the chief of the Division of Utilities, Palau; the director of the Social Science Research Institute, University of Hawaii—representing the Pacific Basin Development Council; and the Climate Projects Coordinator for the East-West Center in Hawaii.[¶]

The Pacific ENSO Applications Center (PEAC) was established in 1994 as a joint venture of the universities of Guam and Hawaii, the Pacific Basin Development Council, and the US National Weather Service. PEAC serves the American-affiliated Pacific Islands by interpreting regional ENSO forecasts; providing rainfall, drought, and tropical cyclone forecasts through its *Pacific ENSO Update* newsletter; and briefing government officials, focusing on emergency managers, water managers, and health officials. OGP funded the establishment of this boundary organization, which was developed by representatives from climate research, social science research, and potential users of climate forecasts.

From the beginning, the intent was to establish a mechanism to produce and disseminate useful climate forecasts for end users. PEAC had to create the middle of the "end-to-end" system by working with people on the islands to determine how the local climate worked, then develop models for local-level rainfall forecasts. Users needed to learn how to identify climate impacts and provide guidance to the forecasters as well as use the climate information. The newsletter was developed as the primary outlet for forecasts and staying in touch with information users.

Capacity building at PEAC has been focused on the science of local climate modeling and education on how to use the resulting information. In addition, they are building a cadre of weather service people on the islands to sustain the system, and they are combining science with indigenous knowledge. For example, PEAC worked to convert information into local languages for different islands/user groups. Oral traditions were found to be an important source of climate information depending on the culture. Local participants could describe climate patterns from traditional cultural history. As a result, the need for adaptation to cultural norms of communication was noted as key to success. Coproduction of climate history was found to be a useful approach because it gave climate scientists perspective on how their information would be used.

PEAC has also been working to ensure the stability of the knowledge system in a changing political, economic, and climatic context by modeling adaptive behavior, focusing on their translator role, and building legitimacy and user ownership. They noted the importance of scientists knowing the people who were providing forecast data as well as understanding how the annual climate cycle works. An important part of the organization's success has been recognizing the limits of what they can do well and how it pertains to knowledge users. For example, a fundamental shift in the level of engagement was noted when researchers stopped talking about forecasts and started talking about regional resource problems and how climate affected the things that local people cared about. Previously climate services had started with forecasts instead of with an understanding of climate impacts and user needs.

US Pacific Northwest.[‖] Workshop participants included the director of the Climate Impacts Group (CIG), a water resources engineer from Seattle Public Utilities, a research scientist from CIG, and a National Weather Service hydrologist from the Northwest River Forecast Center.

CIG was established at the University of Washington in the Pacific Northwest in 1995 as the first of the Regional Integrated Science Assessments (RISA) programs of NOAA's OGP. It serves as a facilitator between climate information producers and natural resource managers, particularly those associated with fisheries, energy production, and water management in the Columbia River Basin. CIG was deliberately designed to provide seasonal to interannual climate information to regional stakeholders as well as to maintain an outreach program focusing on the needs of managers in water resources, forest ecosystems, aquatic ecosystems, and the coastal zone, private sector energy interests, the fisheries sector, community organizations, and educational institutions.

Working in partnership with this wide range of stakeholders, CIG produces decision support tools, convenes forums for resource managers, and helps translate and integrate scientific knowledge and user expectations into language that can be understood. CIG staff also work in tandem with end users to jointly identify information needs and develop products. Politics enters into the process at times because although all of the users' needs are legitimate, they often conflict. For example, Seattle sells the water in its reservoir system. If there is a probability of high temperatures and low rainfall, Seattle makes money. This situation can lead to conflicts between the need for revenue versus conservation, which is often bound by social and biological constraints. Furthermore, Indian tribes who have traditional and cultural uses of water often prefer certain stream flows or water uses that may be in direct conflict with other stakeholders.

Key findings include the need for an "honest broker" of climate information. The need to communicate with operations-level decisionmakers rather than top-level players also was noted, as was

¶Anderson C, Shea E, Weyman J, Colasacco N, Jones S (2007) Evolution of a Climate Risk Management Process in the Pacific: PEAC to PaCIS. Conference Volume, IPCC WG1 Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA), An Expert Meeting on Regional Impacts, Adaptation, Vulnerability, and Mitigation, June 20–22, 2007, Nadi, Fiji.

‖Pacific Regional Integrated Science and Assessment (Pacific RISA). Available at http://www.pacificrisa.org/cms/.

the need for improved forecast skill. Managers do not respond well to "mistakes" in forecasts because they are naturally risk averse and prefer deterministic rather than probabilistic forecasts.

Because of CIG's efforts, there is now greater awareness among the region's natural resource managers about the natural climate variations that affect regional resources and how this knowledge can be used to improve management. Changes in management approaches have developed relative to water resources, forest fire, salmonids, and coastal emergency preparedness in response to CIG's climate information services.

Northeast Brazil—State of Ceará.** Workshop participants from Ceará included a member of the Lower Jaguaribe River Watershed Committee, the president of the Cearense Foundation of Meteorology and Hydrology (Fundação Cearense De Meteorologia E Recursos Hídricos or FUNCEME), the superintendent of the Brazilian National Water Agency, and a U.S. professor who has performed extensive research in seasonal climate forecasting and policymaking in Ceará for 10 years (15).

In the early 1990s, the Ceará area was identified as having high vulnerability and high predictive capacity. The interior of the state, or the sertão, normally gets ≈600 mm of rain during the February to May "rainy season," but periodically faces droughts that are often associated with ENSO. Citizens who live off low-scale, rain-fed agriculture and cattle ranching face hunger, unemployment, and dislocation every time there is a water shortage.

The IRI has been working with state agencies and local institutions such as FUNCEME and the Water Resource Management Company (Companhia de Gestão dos Recursos Hídricos or COGERH) to develop a decision-support system for drought mitigation for nearly a decade. The program has three primary thrusts: (*i*) seasonal-to-interannual water forecasting and management, (*ii*) drought mitigation and relief, and (*iii*) long-term water management and infrastructure development. The IRI, itself a boundary organization, interfaces with a number of other boundary organizations and citizens to develop improved capabilities and integrate them into a useful framework. For example, FUNCEME oversees forecasting and management of meteorological and hydrological data, COGERH is responsible for reservoir simulations and analysis, and the Secretariat of Planning and Development (SEPLAN) oversees analyses of water and drought management options. Local watershed groups also participate in decisionmaking, so there is a complex fabric of players to be coordinated.

In the past, FUNCEME's focus has been on how improvements in the forecasts (based on El Niño conditions) improve the quality and timeliness of decisions; however, there is growing recognition of the need to understand social factors as well. FUNCEME and COGERH now use climate information primarily as background information for defining the amount of water in reservoirs that will be provided to users in the subsequent year, usually assuming zero rainfall to limit risk forecast scenarios (11).

Equity issues are a major consideration because water allocation is so critical to the livelihoods of citizens who live in poverty in Ceará (12). As one participant noted, "strong technocratic insulation is predicated on the 'knowledge equals power' theory." Users decide on the allocation of water within watersheds, but is that really democracy? Who is representing future generations or sustainability? How much is stacked on the side of the users at the expense of the rest of society? Much has been learned about the role of information in advantaging some at the expense of others and about the need for boundary organizations to maintain their roles as "honest brokers." From a program management side, this case was rich in examples of applications and social perspectives. NOAA-OGP has focused more on social science in its climate services because of their engagement in Ceará.

Lessons from the Boundary Organizations: Closing Gaps Between Users and Producers of Climate Information

> "There is a tension between not letting what we don't know confound what we do know."

The Queensland Department of Primary Industries and Fisheries, the NOAA-funded activities at CIG and PEAC, and the IRI are all institutions with authority to build end-to-end knowledge systems. All were deliberately created to disseminate climate information. Although all of these organizations have shortcomings, particularly in that they continue to be too centralized and underfunded, all have been successful as boundary organizations.

These organizations initially resulted from opportunistic niche filling or link-making by external actors lacking system-wide authority. In many ways, NOAA's CSI-sponsored activities and the IRI were a response to a combination of climate vulnerability in key parts of the world with an evolving understanding of climate prediction tools. It was recognized early in the ENSO program that because droughts, floods, and cyclones are so economically devastating to key sectors, there is much to be gained from early predictive capacity. The initial agenda was largely determined by the strength of teleconnection (predictability) and the mission of funding sources.

This initial, opportunistic approach was effective in that it placed resources quickly in areas that appeared would likely benefit from early investments in climate predictions. However, it was recognized over time that a more organized, long-term investment in integration with existing organizations and decision structures is required for long-term sustainability of knowledge systems. A more deliberate approach to establishing boundary organizations in the last decade has resulted in substantial improvement in program effectiveness. Because the U.S. group has been highly integrated through the efforts of CSI, the lessons learned in international activities at IRI and CSI and domestic activities, primarily through the RISA program, have been integrated and well disseminated to the affected boundary organizations.

Boundary organizations have played a critical role in bridging several gaps in the knowledge system, including gaps between scientific disciplines; between global forecast products and regional/national products; and between regional forecasts and specific sectoral applications such as water management, agriculture, fisheries, and forestry.

Design Principles: Lessons from the Case Studies

Standard knowledge-production institutions tend to produce information that is useful only within specific disciplines, whereas decisionmaking and management activities must integrate various types of information in a complex environment comprised of political, economic, and social factors. Many of the observations from the workshop focused on the issue of how to acknowledge and integrate social, political, and economic context into knowledge systems.

Boundary organizations seem to evolve naturally in cases where there is both a push (from the knowledge producer) and a pull (from the consumer) for information. In other words, the desired outcome is a set of solution options that are informed by research-based knowledge framed within the decision context. Although this comparative analysis focused primarily on the boundary between knowledge producers and consumers of knowledge, it is evident that boundary spanning between and

**Lemos MC, Finan T, Fox R, Nelson D, Tucker J (2002) The use of seasonal climate forecasting in policymaking: lessons from Northeast Brazil. *Clim Change* 55:479–507.

within organizations is critical to effectiveness. Internal boundaries that may need to be bridged occur in both horizontal (laterally within the organization) and vertical (up the decision chain) dimensions. Many of the gaps discussed come from organizational culture as indicated above or form between communities of actors. For example, different motivations lead to different incentive structures in academia, agencies, and communities. Some gaps in knowledge systems appear to be deliberately created by organizations to establish value for their information assets (because the information generates income). The desire to preserve a particular power structure can also result in deliberately constructed boundaries.

A characteristic of effective boundary organizations is engaging individuals in boundary-spanning activities at appropriate scales and levels within agencies and institutions. Often political imperatives and broad policy perspectives at higher levels of an organization replace the appetite for technical information, thereby devaluing technical knowledge. Determining the proper entry points for engagement is critical and boundary-spanning activities need to occur within organizations to ensure that decisionmakers have access to information that may be critical to outcomes.

The examples reviewed in this workshop shared several critical features. In all cases, they were led by innovators and fostered individuals who were capable of translating scientific results for practical use while also framing research questions from the perspective of the information user. Successful techniques for translational science and facilitation often included convening of user-producer forums, training exercises, and data access systems. Sources of funding for building the information system in all cases influenced the construction of the climate services provided. Further, based on the case studies, the participants agreed that key roles for effective boundary organizations include serving as: (*i*) broker, connecting information needs with sources of information. This role requires quite literally speaking the language of both scientists and users as well as serving as an efficient and timely hub of information; (*ii*) convener of dialogue, establishing a forum for individuals who otherwise would not have occasion to work together and facilitating solution-based conversations; (*iii*) translator and integrator, combining scientific knowledge and user expectations into language that can be understood as tractable research questions while simultaneously arriving at the types of integrated decision support products that are required by users; (*iv*) facilitator and participant in the coproduction of knowledge, ensuring that the perspectives of the producers and the users of information are equally valued and respected, (*v*) arbiter of equity, providing access to economically valuable information; and (*vi*) exemplar of adaptive management behavior, ensuring the stability of the knowledge system in a changing political, economic and climatic context.

The lessons derived from examples around the world can help inform the discussions currently being undertaken within the US federal agency and scientific communities about the design and formation of a "national climate service." Although a number of options have been put forth, the suggestions advanced by Miles et al. (13) underscore the critical role that boundary-spanning organizations play in a comprehensive knowledge-to-action system aimed at serving the public with usable climate forecast products.

Conclusions

There is a natural tendency to fill knowledge gaps in a system that is not functioning optimally—the organizations and individuals that fill these gaps may or may not do so purposefully in the initial stages. The cases reviewed here originated from a clear need to improve adaptive capacity, coinciding with an understanding that climate science had progressed to a point where useful probabilistic predictions could be made at the seasonal to annual time scale. The international examples reviewed in this workshop demonstrated an interesting case of convergent evolution, where organizations that were very different in origin evolved toward similar structures and individuals engaged in them had similar experiences to share. These examples provide evidence that boundary organizations and boundary-spanners fill some social/institutional roles that are independent of culture.

Certain features are critical to the success of boundary-spanning activities, whether the boundary organization evolved organically or was systematically designed. Final observations include the following: (*i*) Boundary spanners tend to be inherently risk takers and have well-considered thresholds for credibility of information and trust in information sources; (*ii*) successful boundary organizations depend on a foundation of credible scientific knowledge as well as the capacity to usefully engage in social and economic systems within a local context; (*iii*) bringing information to scale and using the right tools to convey information appear to result in a more effective knowledge system; (*iv*) successful boundary organizations are entrepreneurial, solution-focused, and integrative, in addition to being accountable to both sides of the science-action boundary; (*v*) boundary organizations fill gaps of different dimensions, so they are necessarily different in form—but mutual understanding of a shared goal is a required element for success; (*vi*) technical information placed in the context of management experience leads to more robust knowledge and contextual applicability in the knowledge system. The two forms of knowledge together produce more salient information for decisionmaking, and when properly integrated form a knowledge-to-action system that is more effective; and, (*vii*) when the actors in the system trust each other and the outcome of the communications lead to credible knowledge products, there is a significant increase in effectiveness of the knowledge system.

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