Knowledge-Action Systems for Seasonal to Interannual Climate Forecasting: Summary of a Workshop

Roundtable on Science and Technology for Sustainability, National Research Council

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Knowledge-Action Systems for Seasonal to Interannual Climate Forecasting

Summary of a Workshop

Report to the Roundtable on Science and Technology for Sustainability

DAVID W. CASH AND JAMES BUIZER

Roundtable on Science and Technology for Sustainability
Policy and Global Affairs

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We wish to express our sincere thanks to the many individuals who played significant roles in planning the Workshop on Decision Support Systems for Seasonal to Interannual Climate Forecasting. Steering committee member William Clark (Harvard University) chaired the workshop and ensured that the workshop was well integrated into activities of the Task Force on Linking Knowledge to Action for Sustainable Development. The three additional steering committee members, who devoted a considerable amount of time to designing and planning the workshop, include Nicolas Graham (Scripps Institution of Oceanography), Kathy Jacobs (University of Arizona), and Ed Miles (University of Washington).

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this report: Daniel Basketfield, Seattle Public Utilities; Gregg Garfin, University of Arizona; Michael Glantz, National Center for Atmospheric Research; Maria Carmen Lemos, University of Michigan; and Holger Meinke, Agency for Food and Fibre Sciences.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the content of the report, nor did they see the final draft before its release. The review of this report was overseen by Thomas Dietz, Michigan State University, who was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authors and the institution.

Finally, we would like to recognize the contributions of the following National Research Council staff: Gregory Symmes, Director of the Roundtable on Science and Technology for Sustainability, who provided oversight for task force activities; Laura Holliday, Senior Program Associate for the Science and Technology for Sustainability Program, who coordinated the project; Tabitha Benney, who developed the project Web site; and Stacey Speer, who organized the logistical arrangements.

David W. Cash James Buizer

PREFACE

The National Academies' Roundtable on Science and Technology for Sustainability provides a forum for sharing views, information, and analyses related to harnessing science and technology for sustainability. Members of the roundtable are drawn from senior decision makers from the U.S. government, industry, academia, and nonprofit organizations who must grapple with the issues of sustainable development and who are in a position to propose and mobilize new strategies for sustainability. Through its deliberations, the roundtable identifies new ways in which individuals and institutions can more effectively link science and technology (S&T) to the needs of decision makers in both the public and the private sectors. Each year, the roundtable seeks to make significant headway on two or more important issues that have been identified by the roundtable members. The roundtable selects issues that are of central importance to advancing a sustainability transition and that could benefit substantially from roundtable involvement.

During the roundtable's 2003 annual meeting, roundtable members emphasized science and technology's centrality to sustainable development. Members noted, however, that much of the science and technology generated by existing R&D systems is not efficiently used. To address this challenge, the roundtable established a task force charged with exploring mechanisms for effectively connecting research with the needs of policy makers and practitioners and reporting back to the roundtable with suggestions for activities that might be pursued by the roundtable, its members, or members' institutions, to better link knowledge to action in support of sustainable development. The task force, which includes roundtable members and invited outside experts, was also instructed to collaborate with and build on other ongoing initiatives related to the subject, both within and outside the National Academies. The roundtable named the following individuals to its Task Force on Linking Knowledge to Action for Sustainable Development: William Clark (Harvard University, co-chair), James Mahoney (National Oceanic and Atmospheric Administration, co-chair), Robert Frosch [Harvard University (retired)], Gerald Keusch (Boston University), Pamela Matson (Stanford University), James McGroddy [IBM (retired)], Vernon Ruttan (University of Minnesota), and Emmy Simmons (U.S. Agency for International Development).

In conducting their work, the task force members organized, participated in, or drew from a series of workshops designed to document and evaluate experiences around the world in harnessing S&T to the service of societal goals. These workshops include:

1. *International perspectives on the state of the art:* In this workshop, carried out with task force member participation under auspices of the International Council for Science, Third World Academy of Sciences, and the Initiative on Science and Technology for Sustainability, participants discussed findings of a series of regional dialogues between scientists and decision makers that were conducted in preparation for the World Summit on Sustainable Development.

2. *International research systems:* In this workshop, hosted by Harvard University, an international group of scholars, including task force members, compared studies of the effectiveness of efforts to link knowledge to action in a wide range of sectors, including agriculture, health, energy, environment, and manufacturing.

3. *The case of climate forecasts: Decision Support Systems for Seasonal to Interannual Climate Forecasts:* This workshop, summarized in this report, was hosted by the National Academies and explored in detail the institutional and process linkages of decision support systems for seasonal to interannual climate forecasts. The workshop brought together producers, managers, and users of decision support systems from Brazil, Australia, Hawai'i and the Pacific Islands, Colombia, and the Pacific Northwest.

4. *Managing the linkage:* This workshop, hosted by the National Academies, brought together a group of program managers who were identified as having been exceptionally innovative or

successful in linking knowledge to action. The program managers had experiences in very different fields, such as technology, health, the environment, and engineering. Participants gave presentations on lessons they have learned and discussed commonalities in their experiences.

5. *The role of universities:* This workshop brought together an international group of leaders who are restructuring university-based programs to better harness science and technology for sustainability. Participants identified what works, common challenges, and needs.

These workshops used a variety of approaches, ranging from in-depth analyses of case studies to broad, cross-sectoral comparisons, and sought diverse perspectives from several sectors in order to identify broadly applicable commonalities in linking knowledge to action and to determine in which instances generalizations are not appropriate. Observations from these activities were reported to and discussed by the full roundtable at its annual meeting.

The workshop featured in this report, Decision Support Systems for Seasonal to Interannual Climate Forecasting, was held May 6-8, 2004. It served to provide an examination of lessons learned about the design of effective systems for linking knowledge to action based on experience from the specific case of decision support systems for seasonal to interannual climate forecasting. The area of seasonal to interannual climate forecasting was chosen because: (1) climate variability has significant impact on decision making for sustainability; (2) there have been important advances in the science of climate forecasting in the last two decades; and (3) there is active experimentation underway in that area, involving various institutional approaches to producing and using climate forecasts. Lessons for institutional design may also be easier to draw in the area of seasonal to interannual climate forecasting compared to others because it is a relatively new field—young enough to include some systems that were designed “from scratch” as knowledge-action systems—but still includes the more typical incremental systems. In addition, the nature of seasonal to interannual climate forecasting, which involves complex, rapidly changing, interdisciplinary science at scales ranging from local, to regional, national, and supranational, makes it particularly relevant to other areas of sustainability science, which often involve similar complexities.

The workshop was designed and planned by a steering committee consisting of six members, including David W. Cash (Harvard University, co-convener), James L. Buizer (Arizona State University, co-convener), Nicolas Graham (Scripps Institution of Oceanography), Kathy Jacobs (University of Arizona), Ed Miles (University of Washington), and Bill Clark (Harvard University).

The steering committee identified a set of rich cases representing a wide range of approaches and experiences to learn from at the workshop. The cases represented at the workshop were from: Colombia; Ceará, Brazil; Hawai’i and the Pacific Islands; Queensland, Australia; and the Pacific Northwest, United States (see Section III). For each of these cases, the steering committee identified as invitees to the workshop a small group of experienced individuals drawn from three communities: *users* of seasonal/interannual climate forecasts, including managers, policy makers, and planners; *producers* of such forecasts, including researchers, modelers, applications specialists, etc.; *program managers* who have been involved in the funding and support of decision support efforts. (See Appendix C for a list of participants.) These participants included key scientists and decision makers with expertise and extensive experience in producing and using climate forecasts and designing information and decision support systems.

Additional information about the Roundtable on Science and Technology for Sustainability; the activities of the Task Force on Linking Knowledge to Action for Sustainable Development; and specifics of the Workshop on Decision Support Systems for Seasonal to Interannual Climate Forecasting can be found at <http://www.nationalacademies.org/sustainabilityroundtable/>. Full text of this report is available online at <http://www.nap.edu>.

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I

INTRODUCTION

The last 20 years have seen dramatic progress in scientific efforts to understand seasonal to interannual climate dynamics, characterize social and environmental impacts, and predict El Niño/Southern Oscillation (ENSO) events months in advance (National Research Council, 1999; Glantz, 2003). As forecasting ability has improved, concerted efforts to apply this growing knowledge to decision making have been made by international organizations, national agencies, regional and local governments, and research institutions. Climate application efforts have been targeted at such areas as emergency preparedness, agriculture, food security, tourism, public health, and fisheries, with the goal of bringing a suite of benefits to society including decreases in mortality and morbidity, increased economic profit, improvements of agricultural harvests, more efficient operations of reservoirs, and better planning for natural hazards. There is wide variance in the structure and function of these applications efforts, and wide variance in their success.

While there is a growing literature and accumulating practical experience on what contributes to successful applications efforts, there has been little synthesis in the field and few efforts to extract common, overarching, complementary or collective lessons learned from these multiple academic and practical efforts in different regions (Glantz, 1992; National Research Council, 1999; Broad, 2000; Buizer et al., 2000; Glantz, 2000; International Research Institute for Climate Prediction, 2000; O'Brien et al., 2000; Patt, 2000; Broad et al., 2002; Lemos et al., 2002; Glantz, 2003; Jacobs, 2003; Cash et al., in review).

This workshop was an attempt to provide a forum where various perspectives could be brought together to explore the institutional challenges, opportunities, and strategies for connecting climate research and decision making in order to discover and distill general lessons about the design of effective systems for linking knowledge to action. Taking advantage of the last decade's experience with the production and application of seasonal to interannual climate forecasts, participants examined a range of case studies of efforts to link research with decision making in the climate arena, attempting to glean a composite picture of what works, how, and under what conditions.

The cases featured at the workshop represent a wide range of approaches and experiences. They were from Colombia; Ceará, Brazil; Hawai'i and the Pacific Islands; Queensland, Australia; and the Pacific Northwest, United States (see Section III). For each of these cases, invitees included a small group of experienced individuals drawn from three communities: *users* of seasonal/interannual climate forecasts, including managers, policy makers, and planners; *producers* of such forecasts, including researchers, modelers, applications specialists, etc.; *program managers* who have been involved in the funding and support of decision support efforts (see Appendix C for a list of participants). These participants included some key scientists with expertise and extensive experience in producing climate forecasts and decision makers who routinely use the information and who have been involved with the development and design of decision support systems. The workshop organizers attempted to strike a balance between having all potential perspectives represented and a small enough group to facilitate in-depth discussion. In attempting to strike this balance, some expertise and points of view that would have added considerably to the discourse were not included. For example, agricultural extension, which has a long history in the United States of acting as an intermediary between science and practice was not fully represented (Cash, 2001). This is, in part, because the agricultural extension system has not played an active role in the seasonal climate forecasting process.

Because this report is a workshop summary, its contents are limited in scope to the discussions that took place during the workshop. In the interest of promoting candid discussions, the workshop was held with the understanding that comments would not receive individual attribution in the report. As a record of those discussions, the report includes opinions from individuals and groups who attended the workshop. However, the opinions expressed in this report do not necessarily reflect the views of all workshop participants, their affiliated organizations, or the National Academies. The report does not contain consensus findings or recommendations from the workshop participants as a whole.

Chapter II includes a brief overview of each case that was presented and discussed at the workshop. Chapter III includes a framework in the form of a workshop "theme paper" that was offered by the workshop co-conveners as background reading that could serve as an analytical tool for understanding the challenges of connecting research to action.[1] Chapter IV provides summary descriptions of the components of effective knowledge-action systems. These descriptions are organized into a series of "lessons learned" that were identified by various workshop participants. Each lesson learned is followed by a box that includes one or more "cases" provided by participants including examples of how they apply the principles in the lesson within their organizations or communities—practiced examples.

[1] The discussion paper is available on the workshop Web site <http://www7.nationalacademies.org/sustainabilityroundtable/Decision_Support_Rountable_Main.html> and is an unpublished document that was provided to participants as a possible framework for discussions.

II

CASE MATERIAL[2]

The following cases were selected for discussion at the workshop with a view toward capturing the range of experiences alluded to in the introduction:

1. Queensland Australia

The system of climate research, forecasting, and applications is well developed and highly institutionalized in Australia, especially compared to many other climate forecasting systems throughout the world. This has been achieved through the use of existing institutions such as the national Commonwealth Scientific and Industrial Research Organisation, the Bureau of Meteorology, the state-level Queensland Department of Primary Industries and Fisheries, and the Queensland Department of Natural Resources and Mines. Gaps in institutional capacity have been met by the formation of new collaborative institutions such as the National Climate Center within the Bureau of Meteorology, designed to disseminate forecasts, and formal joint ventures—such as (1) the Agricultural Production Systems Research Unit, which is a joint venture of the Commonwealth Scientific and Industrial Research Organization (federal), the Department of Primary Industries and Fisheries (state), the Department of Natural Resources, Mines, and Energy (state), and the University of Queensland; and (2) the Queensland Center for Climate Applications, a joint venture of the Queensland Department of Primary Industries and Fisheries and the Queensland Department of Natural Resources and Mines. Despite some early difficulties to overcome, such as an initially somewhat hesitant relationship among the partners, the collaboration has managed over time to relatively effectively link science and decision making. This collaboration has resulted in an allocation of responsibilities that cuts across scales, from large-scale climate modeling through local-scale decision-making tools that incorporate climate as one factor in management or decision scenarios. The organizations' "end-to-end" system employs iterated multidirectional communication among the Bureau of Meteorology, the Queensland Department of Primary Industries and Fisheries, the Queensland Department of Natural Resources and Mines state agencies other institutional partners and collaborators, and decision makers such as the farm sector, rural industries, government policy makers and regulators in the Queensland Environmental Protection Agency, the National Agriculture and Fisheries Department, the National Australian Greenhouse Office, and others. Joint ventures like the Agricultural Production Systems Research Unit and emerging partnerships with private sector institutions or businesses (e.g., private consultants, private agricultural extension services) serve critical intermediary functions. The outputs of these collaborative activities span a range of products, services and outcomes including, flexible, user-friendly risk management models, forecasts, individual consultations, formal written reports and assessments.

2. Pacific ENSO Applications Center (PEAC)

In the early 1990s, the Office of Global Programs (OGP) at the U.S. National Oceanic and Atmospheric Administration (NOAA) began to explore the utility of new forecasts for resource managers on Hawai'i and the U.S. Affiliated Pacific Islands.[3] With OGP funding, a partnership between OGP, the Social Science Research Institute at the University of Hawai'i, and the Pacific Basin Development Council

[2] This section is drawn from the background material for the workshop, including materials supplied by the participants.
[3] American Samoa, Guam, the Commonwealth of the Northern Mariana Islands, The Federated States of Micronesia, the Marshall Islands, and Palau.

(a regional association of the U.S. Affiliated Pacific Islands governments), held a scoping meeting in early 1992. Organized and driven by actors representing the continuum from climate research, social science research, and potential users of climate forecasts, the meeting brought together a range of perspectives to describe the current state of the science, but more importantly, to ask the question: How could forecasts be produced so that they might be useful to managers in the region? This scoping work led to the birth, in 1994, of the Pacific ENSO Applications Center (PEAC).[4] In addition to the original partners, PEAC included the participation of the NOAA National Weather Service/Pacific Region, the University of Hawai'i/School of Ocean and Earth Science and Technology, and the University of Guam/Water and Energy Research Institute. PEAC's mission is to conduct research and provide seasonal to interannual climate forecasts and climate information products for the benefit of the U.S. Affiliated Pacific Islands and the islands' various emergency management economic, environmental, and human services sectors.

3. The U.S. Pacific Northwest

In the Pacific Northwest, the system of weather research, forecasting, and applications is strong, whereas the system for climate is at a much earlier level of development. In the early to mid-1990s, prior to the establishment of the Climate Impacts Group at the University of Washington, the region's climate forecast system was relatively decentralized. The National Weather Service's River Forecast Center issued water supply volume forecasts for several points in the Columbia and Snake River basins. These forecasts were coordinated with the Natural Resources Conservation Service, the U.S. Army Corps of Engineers, and the Bureau of Reclamation. These forecasts were then and still are the most commonly used in the Columbia River Basin management system, and the River Forecast Center remains the dominant forecast provider. However, these forecasts are primarily resource forecasts. Whereas the forecast providers do use the forecasts issued by NOAA's Climate Prediction Center/National Center for Environmental Prediction, most stakeholders who could benefit from these climate forecasts are still not using them in 2004, even though their awareness of these forecasts is now much greater. Barriers to forecast use include perceptions of low forecast ability, a predilection for deterministic rather than probabilistic forecasts, and a wide variety of institutional hurdles.

In July 1995, OGP established a pilot program at the University of Washington—the Climate Impacts Group—which became the precursor of what is now known as the Regional Integrated Sciences and Assessment (RISA) program. The role of the Climate Impacts Group was to conduct research on the impacts of climate variability and the projected impacts of climate change on the Pacific Northwest across four sectors: hydrology/water resources, forest ecosystems, aquatic ecosystems, and coastal zones; to disseminate the results of this research widely; to work in partnership with a wide range of stakeholders; and particularly to focus on the applications of seasonal to interannual climate forecasts. It was also expected that, over time, the Climate Impact Group would produce a steady stream of decision support tools for stakeholders. As a result of the Climate Impact Group's efforts, there is now greater awareness among natural resource managers in the region about the natural climate variations that underlie variations in regional resources and how this knowledge can be used to improve management. Subtle changes in management approaches are now beginning to surface relative to water resources, forest fire, salmonids, and coastal emergency preparedness.

4. Integrated Climate Prediction in Northeast Brazil

Ceará is an economically stressed, semiarid state on the northeastern coast of Brazil. According to the 2000 census, about 49 percent of its 7.42 million inhabitants live in extreme poverty, making less than US$30 per month per capita. This includes 76 percent of rural inhabitants and 58 percent of urban inhabitants. The interior of the state, or the *sertão,* normally gets approximately 600 millimeters of rain

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[4] See < http://lumahai.soest.hawaii.edu/Enso/> for more information.

during the February to May "rainy season," but it periodically faces droughts, often associated with ENSO. Citizens who live off of low-scale, rain-fed agriculture and cattle ranching face hunger, unemployment, and dislocation during drought episodes.

The program to develop a decision support system for drought mitigation builds on nearly a decade of collaboration. It has three primary thrusts: (1) Seasonal to interannual water forecasting and management, (2) drought mitigation and relief, and (3) long-term water management and infrastructure development. The International Research Institute for Climate Prediction (IRI), based in Columbia University in the United States, collaborates with state agencies and local institutions to develop improved capabilities and integrate them into a framework for use by government and stakeholders. For example, the State Foundation for Meteorology and Hydrology [Fundação Cearense de Meteorologia e Recursos Hídricos (FUNCEME)] oversees forecasting and management of meteorological and hydrological data, the Water Resource Management Company (Companhia de Gestão dos Recursos Hídricos) is responsible for reservoir simulations and analysis, and a commission involving many state-level departments oversees analyses of water and drought management options. Besides the IRI, other research collaborators in the program include the University of Illinois; the Federal University of Ceará and its Center for the Improvement of Northeastern Economics (Centro de Aperfeiçoamento de Economistas do Nordeste); and the University of Arizona to provide analyses of its system and components. The Ceará state government, through its secretariats of agriculture, rural development, and water resources, has key management roles within its respective mandates.

5. Climate Forecasting and Malaria in Colombia

More than 5 million people in Colombia live in endemic malaria regions. The geographical distribution of malaria in Colombia is associated with prevalent climatic conditions. Mean annual temperature and precipitation are related to diverse factors such as elevation over the Andes, the distance to the Caribbean Sea and the Pacific Ocean, and the influence of the circulation, vegetation, and land-surface feedbacks of the Amazon basin and the tropical Andes, which vary at annual and interannual timescales. Since the 1990s, public health officials in the Colombian Ministry of Health (through the National Public Health Surveillance System), and research scientists associated with Colombian universities (e.g., Universidad Nacional de Colombia), the Inter-American Institute for Global Change Research, the IRI and the Climate and Health Information Exchange have attempted to make seasonal and interannual climate forecasting useful in predicting and addressing malaria outbreaks.

III

USEFUL FRAMEWORK FOR UNDERSTANDING FORECASTING EFFORTS

As input to the meeting, the workshop organizers drafted a background paper for discussion purposes that identified several themes that were thought to be constructive in thinking about the challenges of connecting research about climate to action.[5] The concepts were discussed by participants and the two items described below distill what about the themes resonated most with participants' experience. They are presented as a scaffolding of ideas, or way of thinking about the challenges that confront scientists, decision makers, and program managers in producing and using climate forecasting information.

1. Systems for Linking Knowledge to Action

As an analytical tool, it can be useful to think about linking research and decision making from a systems perspective. One term that many participants found useful in describing the assemblage of institutions and activities that produce and utilize climate information is *knowledge-action system*.[6] These systems are generally viewed as organized efforts to harness science and technology in support of social goals. Such systems have been developed at the national and international levels for social goals ranging from food production and health to manufacturing competitiveness, and defense. In general, they encompass the set of relationships, actors, institutions, and organizations that set priorities, mobilize funds, do the R&D, review publications/promotions, facilitate practical application and reinvention, and provide evaluative feedback on performance. Such systems are not generally designed from scratch, but rather evolve through time as a result of multiple and only partially integrated interventions. This is seen, for example, in the evolving role of FUNCEME in Brazil, from primarily a meteorology agency to one that integrates climate and weather information with hydrology, soil sciences, other natural resource sciences, and social responses. It does so with broadening relationships with international, national, state, and local partners. While far from complete, the efforts in Colombia to link climate forecasting to public health efforts demonstrate the emergence of a knowledge-action system and the mobilization of both existing and new resources to solve a variety of social health challenges.

2. The Challenge of Producing Information That Is Salient, Credible, and Legitimate

Workshop participants used a pragmatic working definition of what constituted an *effective* system for linking knowledge to action: Such systems may be considered more "effective" to the extent that a greater proportion of the potentially relevant knowledge that science has to offer is actually taken into account by users when making their decisions about which actions to take.

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[5] The discussion paper is available on the workshop Web site <http://www7.nationalacademies.org/sustainabilityroundtable/Decision_Support_Rountable_Main.html> and is an unpublished document that was provided to participants as a possible framework for discussions.

[6] The formal title of the Workshop referred to "Decision Support Systems," reflecting current usage in the United States (e.g., in the core documents of the Climate Change Science Plan). Participants pointed out that this term has a substantial and not particularly distinguished history of use in which it implies a rather narrow and technocratic approach to computer-assisted decision making. (See, e.g., the special issue of *Agricultural Systems* Vol. 74(1), Oct 2002, on "Probing the enigma of the decision support system for farmers: Learning from experience and theory." See also "A brief history of decision support systems" by DJ Power, Editor, DSS Resources.com <http://www.dssresources.com/history/dsshistory.html>. Participants preferred to use the full phrase "systems for linking knowledge to action" or, for short, "knowledge-action systems." This phrase is not without its own problems, but it is adopted here as preferable to "decision support systems" for use, at least in international contexts.

What are the general attributes of such relatively effective systems? Workshop participants discussed a hypothesis based on earlier work that systems for linking knowledge to action are more likely to be effective to the extent that they produce information that is perceived by users to be simultaneously *salient*, *credible,* and *legitimate* (Cash et al., 2003; Clark et al., in review). These three terms are not precisely defined but have been differentiated as follows:

- *Salience* relates to the perceived relevance of information: Does the system provide information that decision makers think they need, in a form and at a time that they can use it? For example, farmers in some areas need to know something about the timing of first rains, as opposed to average expected precipitation over a season; or emergency preparedness managers need to have forecasts early enough to start preparations for potential natural hazards.
- *Credibility* addresses the perceived technical quality of information. Does the system provide information that is perceived to be valid, accurate, tested, or, more generally, at least as likely as alternative views to be "true"? For example, do other scientists agree with underlying assumptions of a model? Or does ground-truthing of general research reveal that the general findings hold in a specific place?
- *Legitimacy* concerns the perception that the system has the interests of the user in mind or, at a minimum, is not simply a vehicle for pushing the agendas and interests of other actors. The term *fairness* has been used to characterize *legitimacy,* but was felt by some workshop participants to convey an overly negative or suspicious view of the system. Questions about legitimacy often take the form of concerns about process or the peer group that the forecaster belongs to. For example: Who is involved in producing the knowledge? How were those involved selected? When and how are stakeholders engaged? How are R&D agendas set?

As described in the paper, the challenge of designing effective systems for linking knowledge and action—systems that produce information that is perceived to be salient, credible, and legitimate—is complicated by two aspects of the linkages among these criteria (or dimensions). First, it appears that if a system is perceived to be seriously lacking on any one of these dimensions, its likelihood of producing influential information falls significantly. (In other words, no amount of investment in, say, credibility, will make up for a serious shortfall in salience.) Second, it appears that the attributes of salience, credibility, and legitimacy are tightly linked: efforts to enhance one may either enhance or degrade another, depending on the circumstances and the strategies used. For example, greater involvement of stakeholders may increase salience (the right questions are asked) and legitimacy (a more transparent process ensues), but credibility might decrease (the science may appear to be politicized).

The art of designing effective systems for linking knowledge to action thus can usefully be viewed as the art of designing institutions (processes, organizations, norms) that balance such tradeoffs in ways that produce information perceived by users to meet simultaneously at least minimum standards of saliency, credibility, and legitimacy. *How* this has been done in efforts to bring knowledge about climate and its variability to bear on practical problems around the world was the focus of most of the comparative analysis conducted at the Workshop. Lessons learned emerging from those comparisons are summarized in the following chapter "Components of Effective Systems."

IV

COMPONENTS OF EFFECTIVE SYSTEMS

Within the preceding framework, the co-conveners identified six recurring themes from the participants' discussions about what contributed to effective systems. These lessons included: collaborative, user-driven, problem definition; the continuum of decision maker to knowledge producer; boundary organizations; learning orientation; funding; and investments in capacity. These lessons were discussed in plenary and commented upon by the individual case teams. Participants from the various cases identified specific examples of how they apply the principles in the lesson within their organizations or communities—practiced examples. Each lesson learned is described below and is followed by one or more practiced example, as submitted by several participants.[7]

1. Problem Definition That Is Collaborative but User-Driven

Effective knowledge-action systems support processes for the production of useful knowledge through collaboration between knowledge users and knowledge producers. Knowledge "users," in this context, may include decision makers such as farmers, water managers, governments, etc. Knowledge "producers" may include not only scientists and engineers, but also individuals with relevant expertise derived from practice. Such individuals often include knowledge "users," who, in turn, become "producers" as they translate, repackage, or further analyze information they have received for the use of still others in the system. This reflects the tangled backward and forward linkages in the creation and use of knowledge.[8]

Many workshop participants emphasized that crucial to the success of such systems is that they incorporate user-driven definition and framing of the problem to be addressed. "User-driven" is used here to mean that the agendas of analysts, forecasters, scientists, and other researchers are at least to some degree set by the potential users of forecasts.[9] The process of collaborative problem definition would be user driven, but reflect input from the scientific (producer) community on what is feasible. Many workshop participants suggested that effective knowledge-action systems avoid the common pitfall of allowing particular research or technology capabilities (e.g., ENSO forecasting) to drive the dialogue, but recognized that learning about such capabilities could expose some users to the potential utility of such information for their decision needs. Rather, effective systems ground the collaborative process of problem definition in user perspectives regarding the decision context, the multiple stresses bearing on user decisions, and ultimate goals that the knowledge-action system seeks to advance. Some of those participants explained that, in the particular case of knowledge-action systems that address climate change and variability, this generally means shifting the focus toward the promotion of broad, user-driven risk-management objectives, rather than advancing the uptake of particular forecasting technologies. To ensure that the objectives are more user driven, a knowledge-action system would need to be evaluated relative to the achievement of decision makers' ultimate goals (e.g., more effective risk management), rather than the goals of the S&T community (e.g., more or better understanding and use of climate forecasts). Clearly, such evaluation needs to involve users in central roles (see below under "learning orientation"). One

[7] As is mentioned above, the "practiced examples" were submitted by participants. A few that illustrated the lesson were selected, but their inclusion does not imply that other cases do not also offer examples of the highlighted themes.
[8] In reality, as knowledge is co-produced or co-learned, the distinction between knowledge user and producer blurs or even vanishes. It is however, helpful to identify users and producers are traditionally categorized in an effort to analytically explore how and under what circumstances their roles blend.
[9] User driven might best be understood in contrast to the commonly used term "curiosity-driven" in reference to the conduct of research.

researcher suggested that the enhanced legitimacy of a more collaborative, but user-driven system might even enable such a system to better withstand a “failed” forecast.

In addition, given the multiple dimensions of risk management efforts, climate information is usefully seen as one part of a stream of information about many topics that decision makers must evaluate. A workshop participant explained that users need to integrate climate knowledge into their risk management framework in a continuous fashion, just like all the other pieces of knowledge that are taken into account in decision making. It is important for users to recognize the relative contribution of climate knowledge versus all the other pieces of knowledge for particular decisions. For some decisions (e.g., where climate extremes pose serious risks to health, safety, or economic well-being), climate information will be a major factor, whereas for other decisions, climate information may be one of many factors taken into consideration by the user.

Box 1 - User-Driven Problem Definition

Case: Ceará, Brazil

In the early 1990s, the Ceará government designed a new set of institutional arrangements that aimed at both democratizing and improving water management in the state. The new water law replaced a system that was mostly centralized, fragmented, and dominated by “technical solutions” with one based on integrated, decentralized, participatory, and environmentally sustainable water management. The new law also defined the river basin as the territorial unit for planning and decision making and created a series of decision-making bodies—river basin committees and water users commissions—whose mandate included decisions regarding water use and distribution, reservoir management, and construction of infra-structure. That recent innovation in governance in Ceará has facilitated the process of problem definition and risk management and has become a model in Brazil. The recently created Hydrographic Basin Committees include an assembly of decision makers that have been given authority by the state to manage water resources in the hydrographic region. The committees are composed of water users (30 percent of the members), civil society (30 percent), public municipal power (20 percent), and public state and federal powers (20 percent).

The formation and operation of the Hydrographic Basin Committees are coordinated by the State Secretariat of Water Resources (managing agency of water resources of the State of Ceará). A significant advance in the participatory management of water resources in the Lower Jaguaribe River of Ceará is the determination in advance of the amount of water that users are allowed to access from the reservoirs and the negotiation of how that water is allocated. The definition of this allocable volume requires forecasts of supply goal for the next season or year. To predict the available supply for the next season or year, the Users Commission, which mirrors in composition the Hydrographic Basin Committees in that the state, users, and organized civil society are represented, uses forecasting products from FUNCEME that are developed in collaboration with the Companhia de Gestão dos Recursos Hídricos (COGERH). Based on the needs that the Users Commission has communicated, FUNCEME supplies climatic information and forecasts for precipitation and outflows, as well as basic studies in the area of water and environmental resources. The Users Commission in turn use these forecasts as one of several key factors for determining how much water the users should be allowed to withdraw for the upcoming season.

Case: Australia

Through multiple institutional structures, the knowledge-action system in Queensland, Australia, ensures that knowledge production is strongly influenced by the needs of end-users. The basic operating principle of client engagement—from problem definition, to determination of R&D focus, to identification of future research priorities—is a central focus of the works of the various agencies engaged in climate-related research, development, and engineering in the region. Farmers have identified their central need as information that will help them manage a variety of interacting risks, from climate variability, to soil stress, to market volatility. Via its engagement of clients, the Agricultural Production Systems Research Unit (APSRU) determined that the need to manage multiple risks had to be at the core of its approach and products. APSRU has integrated climate information into a diverse set of risk management tools and packaged the tools in ways (through models, for example) that help farmers make decisions about tactical and strategic management decisions (e.g., cropping patterns, input levels, stocking rates, irrigation scheduling.) To ensure user-defined problem definition, legislation in the Primary Industries and Energy Research Development Act of 1989 established sector-specific R&D programs and prescribed an innovative R&D funding mechanism that is based upon levies on production. This system of funding originating from the users of information, and multiple-stakeholder input into determination of R&D expenditures, helps ensure that problems are ultimately defined by those who will use the R&D output. (See Box 5 for more details.)

2. Complete Inclusion on the Continuum of Decision Maker to Knowledge Producer

Many participants noted that effective knowledge-action systems generally are end-to-end systems linking user needs to basic scientific findings and observations. In the cases discussed at the workshop, this means connecting a primary scientific innovation combining observations, climate dynamics, and seasonal/interannual forecasts to ultimate decisions about planting times, reservoir charges and discharges, and disease surveillance targeting. Often entire systems have failed because of a missing link between the climate forecast and these ultimate user actions. How to avoid the missing link problem varies according to the particular needs of specific users. Some general guidelines were discussed by workshop participants:

- Designing fully end-to-end systems means that knowledge producers begin by going into the field and listening to users, learning their perspectives, their problems, and their needs. In some places where these conversations have been user focused, it has been discovered that users need climate information as one type in a suite of information that can help them manage a broad array of risks.
- Users generally want understanding they can use themselves more than they want particular answers that they do not understand. For example, users of climate information want to know what the role of climate is in explaining the underlying variation in the resources they manage and utilize. In this connection, effective knowledge-action systems will focus on providing the broad range of information needed for risk management rather than focusing exclusively on forecasting particular threats. Shifting the emphasis to risk management will require partnerships to be established with users.
- Initiating conversations with lead innovators within the user communities appears to be a key factor to success. Such leaders can lay the groundwork for broader participation of other users and a greater connection between producers and the user community.
- Climate forecasts often require some form of tailoring or conversion before they can be applied by the users. For example, more specific precipitation forecasts might be needed or an additional model, such as a hydrologic model to create credible forecasts of water supply volume. Depending on which type of conversion is needed, the missing link might be provided by the climate forecasters themselves

(more specific precipitation information) or by a different organization with relevant capacity (the application of a regionally or locally tailored hydrologic model). The organizations providing such conversions will vary depending on the context, but the conversions are a critical link.

- Maintaining the dialogues over the long term is important to successfully linking knowledge to action. A time-tested relationship between users and producers that is based on mutual understanding, respect, and trust is necessary for climate information to be considered by users as they manage their affairs. Such iterated dialogue increases the probability that all three attributes described in Section 3—salience, credibility, and legitimacy—will be met.
- Ongoing efforts at verification of the climate forecasts can be crucial. Over time, the climate forecast needs to be perceived as credible. To do this, a proven track record needs to be established. If the climate forecast is not perceived as credible, if the system cannot point to some type of evidence of success, there will be no compelling reason to change.
- Effective systems are generally designed so that forecasts and other scientific information can be linked straight through to decision needs at the times when the required information is needed. This will often require the communication of more than static forecasts, instead recognizing trends and antecedent conditions and providing regular updates on a schedule that meets user needs. Put more bluntly, the forecast is not the end point. Understanding how climate variability links to important impacts and non-climate-related issues is the key to effective utilization of the information provided.
- Beyond partnerships with users, knowledge producers who are successful in linking knowledge to action tend to maintain a larger outreach effort aimed at the wider community through programs designed for the media, schools, universities, community organizations, and the private sector.

Box 2 - Complete Inclusion on the Continuum of End-User to Knowledge Producer

Case: Australia

As noted in **Box 1**, the knowledge-action system in Queensland is deliberately designed to effectively link the decision maker with the most proximal information producer. Its system has institutionalized communication among relevant groups and includes co-production of information - the act of producing information or technology through the collaboration of scientists/engineers and nonscientists who incorporate values and criteria from both communities. Decision makers are encouraged to actively influence the direction and conduct of the R&D process and form an integral part of the R&D team, with an emphasis on co-learning and a genuine desire to understand each other's businesses and cultures. In this context, cross-organizational arrangements such as APSRU provide technology and communication platforms that connect state and national climate R&D centers, such as the Queensland Department of Primary Industries and Fisheries, the Bureau of Meteorology, the Commonwealth Scientific and Industrial Research Organization, and other relevant state agencies with their constituencies. In fact, APSRU is a joint venture of the Queensland State Government, the Commonwealth Scientific and Industrial Research Organization, and the University of Queensland. The formation of APSRU brought together systems analytical expertise; i.e., the ability to simulate and quantify the behavior of farming systems in response to management intervention against the background of a highly variable climate. In collaboration with other agencies throughout Australia, the group's "linking" role was fundamental in getting computer-based discussion support tools accepted by their rural partners. This local success has led to formal collaboration between the Queensland government and international climate research bodies, including the World Meteorological Organization (WMO), the U.S. National Oceanic and Atmospheric Administration's Office of Global Programs (NOAA/OGP), and the International Research Institute for Climate Prediction (IRI).

Case: PEAC

Unlike many of the other knowledge-action systems represented at the workshop, the system in Hawai'i and the Pacific Islands was consciously designed and planned in the mid-1990s. Its goal was to link users throughout the region (e.g., water managers, emergency management officials, utilities, etc.) to the emerging forecasting efforts at the University of Guam, the University of Hawai'i, and NOAA's Climate Prediction Center. NOAA/OGP played a critical role in providing funds and program management to initiate the venture. The challenge was to create the middle of the system (the people and institutions that would link the user and producer parts of the continuum) by working with the people in the islands to figure out how the climate worked locally and then develop the models for the local-level rainfall forecasts. With expertise at the University of Guam and University of Hawai'i, where local-scale models were built, and the Climate Prediction Center, where larger-scale models were developed, PEAC acted as the broker, the link in the chain, to bring these two bodies of expertise together. In addition, they facilitated the communication between Climate Prediction Center's modelers and the managers on the islands. Forecasters at the University of Guam had to learn how to do the locally relevant climate forecasts. Users had to learn how to use the information and provide guidance to the forecaster. Users had to learn how their climate worked and identify climate impacts. PEAC played the role of helping both arenas learn the necessary skills to integrate their knowledge.

3. Boundary Organizations

Workshop participants discussed the idea that given the importance of spanning end-to-end in a knowledge-action system, effective systems cultivate individuals or institutions that act as intermediaries between nodes in the system—most notably between scientists and decision makers. Several participants from the academic community pointed out that knowledge—including that involved in the production of climate forecast information—often is produced in "stove-pipes" isolated from neighboring disciplines or agencies. In contrast, based on users' descriptions of their decision-making processes, it appears that action for the management of resources is more integrative. Effective knowledge-action systems therefore generally anchor themselves in "boundary organizations" dedicated to bridging both the barriers that separate disciplines and those that separate knowledge production and application. These organizations are solution focused and integrative in nature. They also often need to perform translational and mediation functions, including convening user-producer forums, conversations, and training exercises, among others. Where effective, boundary organizations are the sites of co-production of knowledge—the act of producing information or technology through the collaboration of scientists/engineers and nonscientists who incorporate values and criteria from both communities. This is seen, for example, in the collaboration of scientists and users in producing models, maps, forecast products, etc. Some participants observed that boundary organizations seem to work best when accountable to the individuals or interests on both sides of the boundary they bridge, in order to avoid capture by either side and to align incentives such that interests of actors on both sides of the boundary are met.

In short, boundary organizations serve to make information from science useful and to keep information flowing (in both directions) between producers and users of the information. They serve to foster mutual respect and trust between users and producers. Several workshop participants suggested that the critical role of bridging organizations within knowledge-action systems be recognized, encouraged, and supported.

A few participants emphasized that the boundary organizations that seem to be such essential components of successful knowledge-action systems tend to require particularly effective leadership. Within such organizations there is a need for individuals simultaneously capable of translating scientific results for practical use and framing the research questions from the perspective of the user of the information. These key intermediaries in boundary organizations need to be capable of integrating between disciplines and defining the research question beyond that which focuses on the disciplines.

Box 3 - Boundary Organizations

Case: Pacific Northwest

The Climate Impacts Group at the University of Washington, created with funding from NOAA/OGP, was designed as a bridging institution during its pilot phase. Its mission was to serve as an intermediary between federal climate science (NOAA/CPC) and stakeholders in the Pacific Northwest. Situated in a university setting (i.e., not a government agency and not a sectoral stakeholder group), the Climate Impacts Group plays the role of broker, connecting the agendas and information needs of stakeholders with the forecasting capacity of government science agencies. It is a place (both physically and institutionally) where policy makers, researchers, and forecasters can be convened to discuss research agendas, the constraints and needs of decision makers, and the forecast products that will be the most useful to decision makers. The institution that facilitates the integration of climate information into the broad sweep of other impacts that concern water managers, hydroelectric producers, and fish managers. The center develops new, custom-tailored climate forecast products for specific stakeholders as well as providing feedback to federal forecast providers on the design and production of climate forecast products. Acting as a stable boundary organization within an ever-changing political context, the Climate Impacts Group provides the links necessary to maintain contact and connections with multiple political organizations, agencies, and actors at multiple levels. One significant characteristic of the institutional structure of the Climate Impacts Group is that the institution and the actors in it have dual accountability. The federal government (NOAA/OGP) periodically reviews the effectiveness of the organization and has the power to withdraw funding or not renew funding. Stakeholders that the Climate Impacts Group has a mission to serve can walk away from the table or reduce communication and collaboration with the organization. This dual accountability helps ensure that Climate Impacts Group's interests are aligned with those of the two arenas that it is supposed to bridge.

Case: PEAC

A different model of boundary organizations is seen in the Pacific case. Here, a wholly new "organization" or network and virtual organization were started as a deliberate collaboration among researchers at universities in the region, at NOAA, and representatives of the governments in Hawai'i and the American flag islands. The early scoping of the PEAC idea is representative of the style of boundary crossing that has been the hallmark of PEAC. Both scientists and representatives of government agencies met to identify whether climate forecasts would be useful and, if so, how to proceed. The result was the creation of an organization with full buy-in from multiple parties that would evolve into a facilitator, translator, and mediator among researchers at international, national, and island-level scales and among researchers, forecasters, and managers in a wide variety of sectors. PEAC's organizers deliberately strive to create information that is not only credible but is tailored to the needs of islanders (salient) and is produced in such a way that both managers and researchers have ownership of the process (legitimacy). They communicate regularly through meetings, workshops, and electronic means with the above-mentioned communities in order to serve this bridging role.

4. Learning Orientation

Many participants characterized effective knowledge-action systems as systems designed for learning rather than knowing. They identified flexibility of processes and institutions as a hallmark of systems that have been successful over the long term in producing and applying climate information. Organizations that are intended to encourage diffusion of innovation need to be innovative and responsive themselves. Because institutions tend to become more rigid and unresponsive over time, it is critical that bridging or boundary organizations (see lesson 3) be solution-focused and introspective to avoid the tendency to force approaches that are inappropriate to the circumstances. Mechanisms to ensure adaptive management of the organization itself would include establishing operating criteria that measure responsiveness to changing conditions and external advisory processes. Often, nontraditional institutions that operate outside of "normal" channels, such as nongovernmental organizations (NGOs) or regional coordinating entities are less constrained by tradition or legal mandate and thus more able to innovate.

Several workshop participants noted that effective knowledge-action systems tend to build long-term relationships and invest in understanding the context in which they are operating. This requires careful observation of changing conditions; identification of social, political, and economic trends; and other context-related aspects of decision making. It also requires learning from past mistakes, appropriate responses to ensure effectiveness, and understanding potential alternative future conditions. Many participants suggested that introspective evaluations of the organization's ability to learn and adapt to the institutional and knowledge-based changes around them should be combined with mechanisms for feedback and advice from clients, users, and community leaders. However, it is important that these review processes not become an end in themselves or be so burdensome as to affect the ability of the organization to function efficiently.

Many workshop participants indicated that balancing flexibility and stability is a key concern in knowledge-action systems. For example, as is explained in lesson 5, it is important that there be long-term funding and an expectation that services will be provided over the long term, so that users will invest in relationships with producers and momentum can build over time. At the same time, stability is a critical characteristic of a system in which the private sector is willing to invest and take risks. Participants discussed the complex and challenging task of finding the right balance between stability and innovation. Some suggested that critical parts of the knowledge-action system, such as boundary organizations, need to establish evaluation criteria and a rigorous user-inclusive review process to avoid excessive bureaucratic rigidity. They would also need to reassure participants that there is a long-term commitment to investing in high-performing participants and building expertise in addressing the key regional issues. This is particularly critical when partnering with firms in the private sector.

Box 4 - Learning Orientation

Case: FUNCEME, Brazil

In order to adapt to national and state political changes and rapid changes in scientific understanding, FUNCEME has both changed its internal mission and task and has partnered with outside organizations. FUNCEME initially focused on the physical aspects of the water deficit problem, but adapted to focus on climate modification, then on meteorology, and finally on the broader suite of interacting issues including climate, water, soils, and environmental issues. This constantly evolving focus included a major effort to provide the state with essential knowledge and participate in the effort to reform Ceará 's outdated drought response system and adopt a new approach couched in state-of-the-art technology. Hence, FUNCEME became an important player in this new system focused on supporting drought response planning efforts by creating an integrated structure for drought relief in the mid-1980s. By the early 1990s as climate forecasting skills improved, the reform effort envisioned the possible addition of climate forecasts as a useful tool to incorporate in the integrated drought-planning approach.

During this process, FUNCEME identified the need to build its own internal technical capacity, both through tapping into Brazilian expertise and through building partnerships with international organizations like the World Bank, the Inter-American Institute for Global Change Research, Scripps, European research institutes, and NOAA. During this period, FUNCEME experienced a period of critical learning and capacity building through the hiring of personnel, training, and acquisition of equipment.

Although early forecasting successes during the 1991-1992 ENSO event improved credibility and support, failure to predict the rains of 1993 led to a sharp decrease in credibility and resulted in an internal evaluation that questioned the overly technocratic model that FUNCEME was using. This introspective evaluation resulted in the exploration of how to better communicate risk with different stakeholders and users. FUNCEME has initiated a period of more intense involvement with stakeholders both within the state and outside, including carrying out workshops with users and extension agents in rural areas, more effort to improve communication with the media, and increased integration of the agency's products, particularly climate knowledge, into policies being implemented in the state.

Case: PEAC

As noted in **Box 3,** the organizers of PEAC and the funding organization (NOAA) entered the process relatively openly and flexibly, attuned to the needs of the potential users of forecasts. In this spirit of reflectivity, PEAC has used a variety of mechanisms for self-monitoring the system: (1) periodic, and now regularly scheduled, discussions among the PEAC team members and other partner institutions; (2) input from the local weather service offices who often play important roles as local information brokers for PEAC forecasts; (3) periodic discussions with representatives of key user communities in the context of other Pacific Island climate-related programs and activities (e.g., Pacific assessment and assessment follow-on outreach meetings/workshops and the Pacific RISA program); (4) research projects such as climate and health projects in the Pacific that involve discussions with potential user communities; (5) consultations with regional organizations representing Pacific Island interests (e.g., SPREP) and with other institutions in the region engaged in similar forecasting and applications work (i.e., professional colleagues); (6) monitoring government reports, media and press articles, and public speeches describing how PEAC forecasts were used in government, business, or community decision making during a given ENSO event (e.g., the 1997-1998 El Niño); and (7) undertaking a formal review/evaluation of the first decade of performance of PEAC.

Using these means of evaluation, PEAC has developed and packaged forecasts, arrived at ways of productively addressing uncertainties, and structured their monthly newsletter so that both take advantage of their own and partners' expertise—all in a way that meets users' needs.

Case: Colombia

Note: Given that climate forecasting has only recently been developed in Colombia, it does not yet offer its own lessons as the other cases from the workshop do. Instead, the actors within Colombia see the institutions and activities as evolving rapidly and see learning happening on many levels, including through their participation in this workshop. Below is a description from one of the Colombian participants on the practical utility of the lessons learned from this workshop:

The case of Colombia on the linkages between climate variability and human health illustrates the possibilities, challenges, and limitations of implementing knowledge-action systems in the third world. This specific case of malaria and ENSO in Colombia is similar to many public health problems, with malaria being a multifactorial disease, involving multiple stressors and confounders besides climate and weather patterns. Long-term climate change and the environmental social and economic impacts can threaten the stability and solvency of existing systems and create new gaps. El Niño causes droughts in Colombia that lead to electricity curtailments and malaria outbreaks, which can enhance or trigger social disruption.

There is the need to understand the precise role of each of those confounders to adequately set up knowledge-action systems based upon climate and weather forecasts at the local (municipality) level. More than climate forecasts, there is the need to understand how climate conditions affect malaria transmission indices, taking into account the dynamics of transmission, including mosquito ecology, parasite life cycle, human hosts, environmental and climate conditions, availability of breeding sites, human migratory patterns, programs of public health intervention, etc. Mobilization of resources and establishment of control and mitigation programs for malaria need to take into account climate forecasts that are translated into possible malaria outcomes at the very local level.

During the last decade, the Graduate Programme in Water Resources, Universidad Nacional de Colombia at Medellin, in cooperation with PECET (Universidad de Antioquia) and Corporacion para Investigaciones Biologicas (an NGO research agency) has created a transdisciplinary research team including hydrologists, climatologists, entomologists, epidemiologists, and public health experts to develop scientific research toward understanding the exact linkages between malaria outbreaks in Colombia associated with El Niño events, using diagnostics of historical events, laboratory experiments, field work, and mathematical explanatory modeling. Several research papers have been published.

Currently, the system is reaching the Colombian Ministry of Social Protection (formerly the Ministry of Health) motivating linking the results of the research team into a knowledge system for malaria and dengue, at national, regional, and local levels.

We aim to establish a proper and effective collaboration to (i) understand the climate-malaria linkages, (ii) be able to develop explanatory models at the local level, and (iii) see the failure of "predictive models" of malaria due to the establishment and implementation of proper and timely interventions and resource mobilization of public health programs; in particular, during El Niño events. The success of such a chain of events would guarantee a successful end-to-end system. All of these goals are related to the issues of salience, credibility, and legitimacy at several levels, ranging from the scientific research team, to the Ministry of Social Protection, and through mayors who make decisions on the local level. One of the enormous barriers to building a system is that the political process in third world countries is quite fragile. Distrust of local scientists, institutional and language barriers, lack of funding for scientific research, lack of adequate scientific information, and corruption impose heavy constraints on the production of information that is effective, salient, credible, and legitimate.

In our case, the problem is user driven within the framework of the multiple stressors and multiple confounders of malaria in the tropical Americas. But the "providers" must collaborate in such a way that legitimacy is reached. An important lesson from the workshop relates to the importance of boundary organizations in guaranteeing that the information production process be salient, credible, and legitimate. In this regard, the participants from Colombia identified the creation of a boundary organization formed by the universities and research centers, the Ministry of Social Protection, and IDEAM (Meteorological Service) to discuss and plan the pathway toward establishing a knowledge-action system addressing the links between climate and malaria. This organization will continue to deepen ongoing collaboration with the Inter-American Institute for Global Change Research (IAI), Scripps, NOAA, CIRES (University of Colorado), and CHIEX.

Funding is a critical issue for the success of these efforts, for basic research, and for implementation of plans and programs at national, regional, and local levels. There is a huge deficit of funding for scientific research in Colombia (see Poveda, Leaders need to realize that science can offer a route out of poverty, Nature, Vol. 409, 8 February 2001, p. 662), that hampers all these efforts.

The development of human capacity and curricula reforms toward more transdisciplinary graduate and undergraduate programs is required to tackle this problem more efficiently and holistically.

5. Funding

Effective knowledge-action systems can produce both public and private goods. For example, the Queensland system for incorporating climate information in the management of farming risks that was discussed at the workshop has a strong private-good component—individual farmers who use the system effectively capture individual benefits of more profitable production. In contrast, the malaria management system being designed in Colombia is almost entirely a public good provider. Several workshop participants explained that sustainable funding strategies for knowledge-action systems need to recognize their dual public/private character, and balance sources of support accordingly. In addition, as climate knowledge extends into previously untouched areas, the public/private good mix may change.

A central challenge for the design of effective knowledge-action systems is thus determining which aspects of the system should be provided as a general public good, which as intermediate public/private, and which should be understood to be the responsibility of the user. The selection of design and appropriate funding systems for this range of goods would vary depending on user communities' needs and capacities to self-tailor knowledge-action systems. Some participants commented that public funding would be appropriate for the creation of more generic systems that could afterwards be tailored to users' needs. Co-funding with users is appropriate, and possibly necessary, for the development of a collaborative system design that more effectively meets users' needs. Many participants observed that systems that have explored and developed a plan to continue to strive to understand users' needs and capabilities in order to tailor the nature and long-term funding strategies of the knowledge-action systems accordingly tend to be more successful than those that do not. Several workshop participants stressed that adequate funding of the "middle" of the chain is especially important because this is the point at which system integration and learning often take place, typically within the context of the boundary organizations discussed earlier, and there are often inadequate resources.

Another important funding challenge described by some workshop participants is ensuring enough continuity in funding to foster long-term relationship building between users and producers. Several cases discussed during the workshop suggest that an effective strategy to encourage innovation is to require programs to recompete after an appropriate time period. In some cases, it may be appropriate over the longer term to encourage transition to partially or entirely user-funded systems. This, however, can be challenging with myriad risks including loss of continuity or mission capture.

Box 5 - Funding

Case: Australia

Climate applications R&D in Australia includes a national collaborative program, "Managing Climate Variability" that targets improved climate risk management through the use of seasonal climate forecasts in farm and natural resource management decisions.

The Managing Climate Variability program is a small but unique part of the Australian system for rural industry R&D. The system has evolved to provide a range of partnership arrangements between the Australian government, industry, and research providers. Thirteen mainly commodity-based R&D corporations fund strategic and applied research and technology-development activities. Funds are derived from industry levies on production, e.g., a tax of 1 percent on a farmer's value of production from a wheat crop that goes into the Grains R&D Corporation funding pool. The pool includes further matching contributions up to defined limits from the Australian government. The R&D corporations operate under Australian government legislation requiring R&D on production, environment, and capacity-building issues. Importantly, the R&D agendas are set by both government and industry representatives. The resulting projects are funded with research providers such as APSRU, or a university, a state department of agriculture, or of national resources. The agencies contribute matching resources in what are effectively project-level partnerships. The Managing Climate Variability Program has funded a number of projects undertaken by APSRU. One example is the scaling up of promising climate-risk-management science from a regional to a national level.

Climate applications R&D is a relatively recent focus for research. Although there has been a long tradition of curiosity-driven climate science as a core research function of national agencies, this has not been closely linked to applications in agriculture. More recently, climate change has become a major competitor for resources, although there can be significant synergies. Within agriculture, the current institutional arrangements can potentially fund climate applications research if advocates ensure the priority is recognized by the relevant industry. But climate research typically has major spin-off benefit for other industries. Free-riding is inevitable. Priorities such as improved seasonal forecasts are often generic, with widespread community benefits. These characteristics contribute to market failure and underinvestment by society. The initial catalyst for the current national applications program came from Australian government funding as part of a new drought policy. More recently, some industries are beginning to take greater responsibility, consistent with a government policy of increased self-reliance in relation to drought risk management. But funding under this model is likely to be inadequate and episodic because of the nature of droughts. The impacts of droughts in some industries have even been a factor limiting availability of industry funding for the Managing Climate Variability program.

The Managing Climate Variability program <www.managingclimate.gov.au> is now a mix of Australian government funding and funding from a wide range of industries. The unique aspect of the program is that it is an outstanding example of commodity-based R&D corporations developing effective collaborative arrangements to advance a user perspective in climate applications research.

The Managing Climate Variability program is administered by Land & Water Australia, an R&D corporation with a broader charter than industry-based corporations, but without a tax base. The program has developed a simple formula: half of the total funding is allocated to their partner's generic issues and half to their specific industry issues. This is an effective solution to the market failure and spillover issues. The formula can ensure partner equity. The limitations, such as the portfolio marketing and transaction costs, good startup funds followed by lack of institutionalizing projects, and the potential loss of identity and accountability for the funders are recognized and can be managed. The approach has been effective in strengthening collaboration between the wide range of disciplines and agencies involved, and in investing in R&D in a way that makes it more accountable to science and society. The current challenge is to expand areas of collaboration to respond to the increased demand in a variety of sectors for climate risk management as driven by climate change.

6. Long-Term Investments in Capacity

In their discussions, participants emphasized that effective knowledge-action systems require people who can work across disciplines, issue areas, and the knowledge–action interface. Currently, a critical problem is that people with training and experience to promote such bridging are scarce. Building capacity in this area is essential, especially for the long-term existence of knowledge-action systems. The following three areas of capacity building were discussed during the workshop:

- Building curriculum, providing research funding, and providing application placements (undergraduate, graduate, and postgraduate) for:
  - Interdisciplinary, user-driven science education: for existing applied sciences such as engineering this would require changing curriculum, etc. to train students in understanding user perspectives, encouraging user-definition of problems, and collaborating on setting research agendas. More fundamental changes would be required for disciplines that have historically not been as applied.
  - Intermediaries: focusing on bridging science and decision making and building skills of mediation.
- Providing career and professional incentives that reward interdisciplinary user-driven science and intermediary activities. For example, tenured faculty positions for interdisciplinary science with appropriate incentive structures and evaluation processes that value user-driven science.
- Creating innovative and flexible education programs that focus on training of practitioners in the kinds of forecasting and probability analysis that can improve already existing risk management efforts.

Box 6 - Long-Term Investments in Capacity

While none of the cases provided exemplary systemic investments and commitments to building long-term capacity, several of the cases included examples of parts of what a systematic effort might look like:

PEAC:

PEAC made long-term investment in capacity building among both information users and PEAC information providers. They learned together how the climate system worked locally and what climate information could be produced and proved useful. At a higher level of technical capacity building, fellowships for new local weather service employees in the Freely Associated States and increases in National Weather Service staff in the territories have also contributed. Graduate assistantships at the University of Hawai'i also provided knowledge and experience with climate forecasting for the University of Hawai'i Meteorology Department graduate students, but much of that knowledge and experience will likely be lost to other regions of the world because of the limited number of positions in the field. In addition, many staff members at University of Hawai'i are trained as science translators and problem solvers.

Pacific Northwest:

The Climate Impacts Group at the University of Washington has begun a systematic process of education to train students to undertake an interdisciplinary course of study. Interdisciplinary problems will be the focus of dissertations and other projects with the idea that the students will eventually move into agencies at every level (municipal, state, and federal). Students can get recognition/awards for the interdisciplinary work, and innovative coursework has been developed and implemented. In 2001, the Climate Impacts Group introduced a course that has since been taught every year and is cross-listed with several units. The purpose is to teach students how to do integrated assessment using the Pacific Northwest as a case study (Climate Impacts on the Pacific Northwest). In spring 2003, three more courses were introduced, two in the Evans School of Public Affairs (The Role of Science in Environmental Decisions; and Decision Making in the Face of Uncertainty: Practitioner Views on Environmental Resource Challenges) and one in the School of Marine Affairs (Integrated Assessment Applied to Marine Policy Problems). The School of Marine Affairs course is now integrated into the curriculum Marine Affairs Practice.

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Appendixes

APPENDIX A

ACRONYMS

APSRU	Agricultural Production Systems Research Unit (Australia)
BOR	Bureau of Reclamation (U.S.)
CAEN	Centro de Aperfeiçoamento de Economistas do Nordeste/Center for the Improvement of Northeastern Economics (Brazil)
CHIEX	Climate and Health Information Exchange
CIG	Climate Impacts Group (U.S.)
COGERH	Companhia de Gestão dos Recursos Hídricos/Water Resource Management Company (Brazil)
CPC	Climate Prediction Center (U.S.)
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
DNR&M	Queensland Department of Natural Resources and Mines (Australia)
DPI&F	Department of Primary Industries and Fisheries (Queensland, Australia)
ENSO	El Niño/Southern Oscillation
FUNCEME	Fundação Cearense de Meteorologia e Recursos Hídricos/State Foundation for Meteorology and Hydrology (Brazil)
IAI	Inter-American Institute for Global Change Research
IRI	International Research Institute for Climate Prediction
KAS	knowledge-action system
MCV	Managing Climate Variability
NCEP	National Center for Environmental Prediction (U.S.)
NGOs	nongovernmental organizations
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NOAA/OGP	National Oceanic and Atmospheric Administration's Office of Global Programs
NRCS	Natural Resources Conservation Service
NWS/PR	National Weather Service/Pacific Region (U.S.)
OGP	Office of Global Programs (U.S., within NOAA)
PBDC	Pacific Basin Development Council
PEAC	Pacific ENSO Applications Center (U.S., U.S.-API)
PNW	Pacific Northwest (U.S.)
QCCA	Queensland Center for Climate Applications (Australia)
RISA	Regional Integrated Sciences and Assessment program (U.S.)
S&T	science and technology
SEPLAN	Secretaria do Planejamento e Coordenação/State Planning Secretariat (Brazil)
UFC	Federal University of Ceará (Brazil)
UH/SOEST	University of Hawai'i/School of Ocean and Earth Science and Technology (U.S.)
UOG/WERI	University of Guam/Water and Energy Research Institute (U.S.)
USAPI	U.S. Affiliated Pacific Islands (U.S.)
WMO	World Meteorological Organization

APPENDIX B

WORKSHOP AGENDA

Decision Support Systems for Seasonal to Interannual Climate Forecasting Workshop
Hosted by the
U.S. National Academy of Sciences
Arnold and Mabel Beckman Center
Irvine, California, USA
May 6-8, 2004

Agenda

Summary of workshop activities:

On **Day 1** (Thursday) we will spend most of our time discussing each of the cases. We will start each discussion with a focus on the needs of the users of forecasts and try to get beginning answers to questions such as (1) What "success" of the forecasting system means. (2) Where is the system close to and far from success? (3) What have been the greatest barriers or challenges? (4) How have those been successfully addressed? **WHILE WE WOULD LIKE YOU TO ARRIVE AT THE WORKSHOP HAVING THOUGHT ABOUT YOUR CASE AND EXPERIENCE IN LIGHT OF THE THEME PAPER WE WILL SEND, WE DO NOT WANT YOU TO HAVE A PREPARED POWERPOINT SLIDE SHOW. WE SEE THIS MORE AS A GIVE-AND-TAKE DISCUSSION.**

On **Day 2** (Friday), we will take a cross-cut look at the different cases, focusing on our three themes: (1) What makes forecasts **salient, credible, and legitimate?** (2) How do systems deal with **cross-scale interactions** (e.g., international to local)? and (3) What kinds of **institutional and organizational structures** contribute to success? On the evening of Day 2, participants will begin identifying lessons learned.

On **Day 3** (Saturday), we will have an in-depth discussion of the lessons participants identify - discussing parallels across cases and interactions across themes. The activities of this day are critical in synthesizing the work of the prior two days.

AGENDA:

Wednesday May 5

~6:30pm	Dinner - Workshop Goals, Introductions

Thursday May 6

8:00-8:30	Breakfast at Beckman Center
8:30-8:45	Plenary - Outline of workshop, plan of work
8:45-9:30	Plenary - Central themes/questions on which we'll focus
	Salience, credibility, and legitimacy
	Scale
	Institutions

9:30-10:45	Plenary - Case: U.S. Pacific Northwest Each Case discussion will start with a focus on the users, and probe questions about (1) What does "success" mean? (2) Where is the system close to and far from success? (3) What have been the greatest barriers or challenges? (4) How have those been successfully addressed?
10:45-11:00	Break
11:00-12:15	Plenary - Case: Brazil
12:15-1:15	Lunch
1:15-2:30	Plenary - Case: Pacific ENSO Applications Center
2:30-2:45	Break
2:45-4:00	Plenary - Case: Colombia
4:00-5:15	Plenary - Case: Queensland, Australia
5:15-5:30	Plenary - Wrap-up
5:30	Adjourn
6:00	Dinner

Friday May 7

8:00	Breakfast at Beckman Center
8:30	Plenary - Charge for the day
8:30-10:00	Parallel break-out groups - Theme 1: Salience, credibility, and legitimacy.
10:00-10:15	Break
10:15-11:00	Plenary - Discussion of Theme 1 Report out by three rapporteurs
11:00-12:30	Parallel break-out groups - Theme 2: Linking global to local, cross-scale interactions.
12:30-1:30	Lunch
1:30-2:15	Plenary - Discussion of Theme 2 Report out by three rapporteurs
2:15-2:30	Break
2:30-4:00	Parallel break-out groups - Theme 3: Institutions for linking forecasts to decision making
4:00-4:45	Plenary - Discussion of Theme 3 Report out by three rapporteurs
4:45-5:00	Break
5:00-5:45	Plenary - Discussion of connection between themes, missing issues Charge for the report writers
5:45	Adjourn

Saturday May 8

9:00-10:00	Plenary - Report on lessons learned
10:00-12:00	Break-out groups by case: Discussion of case-specific examples of lessons learned
12:00-1:00	Plenary - Next steps; Closing remarks/discussion
1:00	Adjourn

APPENDIX C

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