
Paper:
Kirchhoff, CJ, Lemos, MC and Dessai, S (2013) *Actionable knowledge for environmental decision making: Broadening the usability of climate science.* Annual Review of Environment and Resources, 38. 393 - 414. ISSN 1543-5938

http://dx.doi.org/10.1146/annurev-environ-022112-112828

Actionable Knowledge for Environmental Decision Making: Broadening the Usability of Climate Science

Christine J. Kirchhoff,[1] Maria Carmen Lemos,[2] and Suraje Dessai[3]
[1]University of Michigan, School of Natural Resources and Environment, Ann Arbor, Michigan 48109-1041, USA; e-mail: orange@umich.edu
[2]University of Michigan, School of Natural Resources and Environment, Ann Arbor, Michigan 48109-1041, USA; e-mail: lemos@umich.edu
[3]Sustainability Research Institute and ESRC Centre for Climate Change Economics and Policy, University of Leeds, School of Earth and Environment, Leeds, LS2 9JT, UK; e-mail: S.Dessai@leeds.ac.uk

Please Note: This article has been accepted for publication by Annual Review of Environment and Resources *in a revised form. http://www.annualreviews.org/doi/full/10.1146/annurev-environ-022112-112828*

Running Title: Broadening Usable Climate Science

Keywords

Science-policy model; producer-user interaction; user typology; information usability; climate information use

Abstract

Consistently scholars have sought to characterize society's relationship to science, especially to understand how it shapes the way science is produced and used in decision making. These efforts spurred a rapid evolution in models of science-society interaction with growing levels of complexity both in terms of interdisciplinarity and involvement of stakeholders. Despite these efforts, the rate of use of science in decision-making remains below expectations. This suggests a persistent gap between production and use which, to date, efforts to re-think and restructure science production have not been able to surmount. We review the different models of science-society interaction and the emergence of new approaches to knowledge creation to understand how they have influenced the organization of knowledge production and application. We then examine

what influences use of scientific information in environmental decisions, especially those related to climate variability and change. Finally, we propose a model to explain and broaden use focusing on a typology of users and illustrate its application for up-scaling climate information provisioning.

Table of Contents

1. INTRODUCTION

What is society’s relationship to science and how does this relationship shape the science that is produced? How does science move from production to use in decision making? These are among the questions scholars have increasingly sought to explore for both normative and practical reasons. For the past fifty years there has been a rapid evolution of science-society interaction thinking, ranging from the 1940’s linear model—characterized by a strong disciplinary-based, basic research focus, to more complex models of science production that embrace interdisciplinary approaches and involve users to help solve societal problems. One outcome of this effort is the emergence of a robust empirical literature focusing on exploring different ways of producing/delivering scientific information that can more effectively support decision making. These include institutionalizing more participatory approaches through boundary organizations, knowledge systems, and scientific assessments.

While these new models and structures for knowledge production have increased information use in environmental decision making in general, for climate information in particular, the pace of use has not been commensurate with expected need. This suggests a persistent gap between production and use that, to date, efforts to re-think and restructure science production have not been able to surmount. That is not to say that no progress has been made. In climate-related decision making in particular, empirical evidence suggests that scientific information uptake can be improved for specific decision makers in specific contexts. But the urgency and widespread reach of projected climate change impacts demands more than incremental improvement. Moreover, as the problem becomes more salient for decision makers across the world (with more intense storms, rising seas, etc.), the demand for usable climate information may quickly outstrip our ability to produce it using the approaches we currently employ. Hence, there is an urgent need to re-consider how we approach the challenge of creating usable climate information from what has been predominately a focus on individual users or small groups of users to approaches that meet the needs of a broader diversity of decision makers.

This review aims to contribute to this practical and scholarly discussion by surveying the rapid evolution of the field and highlighting the practical lessons that can both support the creation of new science/policy interfaces and inform the institutionalization of successful models. Throughout the review, we strive to identify where the intellectual community in this area has made strides and where it still needs to narrow knowledge gaps. In addition, we aim to provide a roadmap for those interested in participatory forms of knowledge production as both participants (that is, as producers and users of science) and as objects of study.

Drawing on our review and synthesis of a wide range of research on science-policy models and empirical research on factors, processes and structures that influence science usability, we propose that to move beyond the current paradigm requires better understanding users not just at the individual but at the aggregate level as well to explore the opportunities and challenges of scaling information production while maintaining and/or increasing usability.

We start this review by examining different models of science-policy interface and how they have influenced the organization of knowledge production and application. We then explore how these models have been challenged both from academia and society and how new approaches to the creation of knowledge have emerged including those that involve potential users in the process and that involve different levels of interaction between producers and users. This includes institutions and organizations designed to broker information from science to decision-making as well as different approaches to organize the communication and interaction between scientists and decision-makers. In the third part of this review, we examine what influences use of scientific information focusing predominantly on the uptake of climate information. We begin by exploring how perceptions, attitudes and beliefs of the social actors involved in the process of science production and use shape potential users' willingness to uptake scientific information. Then, we explore how different institutions, organizational cultures and frames shape the ability of users to uptake scientific information. Here, we specifically examine how different decision-environments and goals affect the use of scientific information. Finally, we propose a conceptual framework—a typology of users at the aggregate level—that we use to explore the opportunities and challenges of scaling information production while maintaining and/or increasing usability. We then focus on climate information production and use for adaptation, as an illustration of the different challenges and opportunities to narrow the usability gap.

2. SCIENCE-POLICY MODELS

2.1. Science the Endless Frontier and the Frontiers of Science Production and Use

In *Science the Endless Frontier,* Vanevar Bush argued that science benefits for societal progress ensue innately from the unencumbered linear flow of information from both basic (research that contributes to general knowledge and understanding of nature and its laws) and applied (research undertaken for some identified individual, group, or societal need) research to decision-making (1, 2). The report also advocated for the separation of science from society to maintain objectivity and credibility and to ensure that science is not tainted by values and politics. This highly influential report not only provided the basis for the reorganization of the scientific enterprise in the United States in the mid-20th century but also established many of the tenets for science production still in existence today (3). One of these tenets, that is, that societal benefits accrue precisely because of the separation of science from society, has been increasingly under fire for the past thirty years.

Part of the reason for challenging this model—hereto forth referred to as Mode 1—is that despite the steady and continuous progress in the production of science, there is a widespread concern that not enough of the public decisions that should benefit from the science produced actually do (4, 5). Specifically regarding climate science, while trying to explain why that is, a number of researchers have speculated about a ‘‘disconnect’’ between the science produced ostensibly to inform decision making and actual policy processes (5-10). More generally, one explanation is that Mode-1 science makes ‘‘a number of unsubstantiated assumptions about the resources, capabilities and motivations of research users’’ (11:p 12) including that the science produced is expected and presumed to be useful to solve problems (6). For example, empirical research has shown that a whole range of contextual and intrinsic factors affect the use of information in decision making, including informal and formal institutional barriers, what the decision and policy goals are, the information’s spatial and time scale resolution, the level of skill required to utilize the information, and the level of trust between information producers and users, among others (8-16). A second explanation for this disconnect is that Mode 1 science is overly focused on disciplinary knowledge originating from university settings ignoring both other sources of knowledge and other disciplinary perspectives (17).

Another challenge to the Mode 1 construct is that there is no such thing as science produced separately from society. Influential scholars such as Bruno Latour and Sheila Jasanoff have convincingly argued, and empirically shown, that the separation between science, policy and society is artificial (18, 19); in reality, knowledge is neither unfettered nor neutral and science and policy are co-produced in the day to day interaction between scientists and their social environment (17, 20). Rather than objective and value free, knowledge influences and is influenced by social practices, identities, discourses and institutions (21). Taken together, scholars in this tradition argue that the interface between science and society is a hybrid, mutually constructed arena in which social relations between producers and users of science shape facts about the natural world being studied (18, 22-24). More recently, the idea of co-produced science and decision-making has become associated with the purposeful creation of institutions and organizations (e.g., boundary organizations) that facilitate the interaction between science producers and users (8, 25).

2.2. Mode 2, Postnormal, and Hybrid Science-Policy Models

As a response to the argued failure of Mode 1 science to fulfill its social contract, new models have emerged that better characterize the evolving relationship between science, scientists, the public, and policy. Proponents of these new models argue for two major changes in the way science for societal benefit is produced. First, the complexity of contemporary problems requires more than one disciplinary view to solve them.

Moreover, science should go beyond providing neutral, credible and legitimate support for decision-making to incorporate other kinds of knowledge and different ways of "knowing" (26, 27). Second, science produced for the solution of problems needs to be more flexible and the process of production needs to be more iterative and interactive. Together, these changes help ensure that the science produced this way is more likely to help solve pressing problems and meet its public value functions (i.e., knowledge for its own sake, economic value, information useful for decision-makers, participation in agenda-setting by stakeholders, and communication of findings to the public) (5, 28).

Hence, new models of science production for societal benefit have become more complex both in terms of how scientific information is organized and co-produced and in terms of how it is communicated, disseminated and used (or not). In the production function, this complexification has increasingly challenged not only the motivation of scientists (e.g. basic vs. applied science) but also the ways they interact with the potential users of the knowledge they create and with society in general (e.g. 'normal' vs postnormal science) (23, 28-30). It has also put growing pressure on the scientific enterprise to produce 'usable' science, or that which decision-makers perceive as fitting their needs and decision environments seamlessly (7, 8, 31, 32).

Gibbons and his colleagues proposed a new model, which they call Mode 2, in which science production is organized at increasing levels of interaction and integration across disciplines (from multidisciplinary to transdisciplinary) and across the science-society divide. In contrast to Mode 1, this new approach produces science that is heterogeneous, reflexive, and more socially accountable (17, 33). In this model, multidisciplinarity refers to understanding a problem from the viewpoint of different disciplines while interdisciplinarity combines perspectives, methods, and ideas to foster innovation in ideas, solutions and decision tools. Transdisciplinarity, in turn, goes beyond the mere bringing together of teams of specialists from different disciplines to guiding scientific inquiry by specifiable consensus with regards to appropriate cognitive and social practices (17). Whereas interdisciplinarity has been widely supported by the scientific community as an ideal and as a practice (34-36), transdisciplinarity is more contested, both in terms of institutional resources as well as regarding the role of scientists themselves in working beyond the science boundary (36). In addition, integrating across organizations can be more challenging than across disciplines despite overall scholarly and practical benefits of integrative science (27).

Beyond Mode 2, postnormal science is both a framework (30) and a practical approach (37) for problem situations in which stakes are high and science uncertain. In this case, scientific knowledge alone is not enough to solve societal problems and constituents need their own forms of knowing to better evaluate their risk situation (30). For both Mode 2 and postnormal science, interaction between producers and users of science across the science-society interface means the specific involvement of stakeholders. Here, stakeholder interaction involves more than simple communication *from* science *to* society. It entails substantive multidirectional interactions and involvement of constituents in the research process that can go as far as to include problem definition and formulation of research questions, data collection, selecting methods and conducting actual research, analyzing findings, and developing usable information (8, 33, 38). Figure 1 illustrates the evolution in the complexity in both knowledge production on the one hand (from Mode 1 through postnormal science) and user participation on the other.

Insert Figure 1 about here

Arguments for participatory modes of knowledge production and use range from issues of democratization, citizenship, civics and accountability to calls for a new way of producing science that meets the need of decision-makers seeking to solve ever increasingly complex environmental problems. In this new mode of knowledge production, society speaks back to science, affecting the "scientific activities both in its forms of organization, division of labour and day-to-day practices, and deep down in its epistemological core" (33, page 161). Different forms of participatory science production include boundary organizations and science shops, participatory technology assessment, citizen science, knowledge networks, integrated assessments, public ecology and science-policy dialogues (25, 26, 39-49).

At its most participatory, science at the interface is carried out in non-hierarchical, heterogeneously organized forms, involving close interactions with many actors throughout the process of knowledge creation. Knowledge produced in this way is expected to be more relevant and usable for solving problems and supporting management (e.g. improving the fit between what users want and what science can offer); more likely to be 'bought in' by stakeholders and be more legitimate in their eyes; and more likely to build trust and improve communication (26, 39-41, 47, 50-53). In addition to producing more usable information, participatory processes also amplify the role of science in society (the scienticization of decision-making) and the role of society in science (the politicization of science) (54, 55).

As information moves across disciplines and between producers and stakeholders in highly iterative modes of knowledge creation and use, the process of interaction itself reshapes the perceptions, behaviors, and agendas of the participants (8, 14, 31, 56). Indeed, science and its application give rise to a new politics of expertise in which scientists rather than ‘speaking truth to power ‘become part of a much broader, messier social experiment (18-20, 38). On the one hand, the creation of participatory knowledge production and governance processes in itself does not guarantee knowledge democracy, especially when the use of scientific knowledge becomes a source of authority of some groups over others and an instrument of inequity in the distribution of power across participant groups (26, 57-59). For example, in Brazil, the use of technoscientific knowledge in the context of river basin committees, has shown that it can skew power within the group when it provides members with technical expertise with leverage vis-à-vis others without (60). Part of the problem is the ‘black box of technical knowledge’, that is, the obfuscation of the assumptions, values and methods embedded in the knowledge by those who create and/or employ it in the context of decision-making (26, 58). For example, in Denmark, a government organized citizen-experts dialogue conference focusing on expertise around environmental economics as a policy tool exposed dissent not just between experts and non-experts but between experts themselves when disagreements over assumptions and methods emerged (26). Moreover, in practice, it is also the case that postnormal science alone cannot counteract the role of politics in shaping critical issues within participatory/deliberative processes such as agenda building or the definition of who participates and who is doesn’t (for specific critiques of postnormal science see (61, 62); for a review of deliberative democracy and knowledge see (59)).

On the other hand, scholars have argued that participatory forms of knowledge production and use can avoid inequity often introduced by scientific expertise by being inclusive, transparent and integrating across different kinds of knowledge (e.g. scientific, lay and indigenous knowledge) (61, 63). Moreover, in the context of interaction, producers and users of scientific information can resolve conflicts and build consensus helping to overcome barriers for information use including issues of trust, communication and legitimacy, information accessibility, and lack of fit (26, 59, 60). The experience of interaction in a common social context is the core of social learning—defined as learning from others through observation and modeling (64). Through social learning, producers and users of different kinds of knowledge learn from each other (43), positively shaping common perceptions of problems and solutions, which in turn, may support collective action and effective management (56). However, implementing social learning as a methodology has its own set of challenges including reconciling the diversity of values, worldviews and epistemologies between all participants and the high level of human resources required to carry it out in practice (56).

2.3. Science-for-Policy Improvements: Boundary Organizations, Knowledge Systems, and Assessments

Boundary organizations. In the context of science-decision-making interactions, boundary organizations' function as both stabilizers and bridgers and/or brokers. First, they stabilize the knowledge production function by providing a protective layer against undue influence of extraneous factors such as politics. Second, they bridge and broker knowledge between the production side (universities, research institutes) and the use side (stakeholders, decision-makers). Early research on boundary organizations focused on their stabilizing function; more recently, scholars have attended increasingly to their role as an enabler of productive interactions between science and decision making.

In the first role, boundary organizations achieve stabilization by internalizing and collaboratively negotiating the contingent character of the science-policy boundary using boundary objects and standardized packages (55, 65, 66). Boundary objects (for example, a climate scenario) facilitate stabilization between two social worlds (for example, climate modeling and climate policy) both by fostering a sufficiently shared understanding to gain legitimacy in each world and by enabling negotiation to resolve mismatches in the overlaps (65). Boundary objects are most helpful when they are produced in a transparent fashion and when they are used to reshape and redefine meaning reflexively and iteratively (Carr and Wilkinson 2005). As stabilizers, boundary organizations provide a means for producers and users of knowledge to work together to form a common point of reference and shared understanding yet maintain their separate identities (55, 67). This is tricky work as “opposing pressures and accountability for the actors in the two social worlds… challenge efforts to stabilize the boundary” (68p. 222). The Office of Technology Assessment (OTA) and the Health Effects Institute (HEI) are exemplars of this sort of stabilizing function helping maintain stability when negotiating science production and use amidst fractious party politics, in the case of OTA, and an adversarial regulatory environment, in the case of HEI (18, 55).

In its second role, as a bridger and/or broker of knowledge, boundary organizations have at least three characteristics: 1) they create a legitimizing space and sometimes incentivize the production and use of boundary objects and standardized packages; 2) they involve both information producers and users and mediators; and, 3) they reside between the producer and user worlds with “lines of responsibility and accountability to each” (55, page 93), allowing both sides to pursue their own enterprises (44). In this sense, boundary organizations are institutional structures that contribute to the co-production of science and policy, first, by facilitating the collaboration between scientists and non-scientists (26); and, second, by creating a combined scientific and social order (44). Rather than merely being a conduit or a funnel, boundary organizations are a “forum where multiple perspectives participate and multiple knowledge systems converge” (69: page 261).

Further understanding of boundary organizations’ role as a bridger and broker of information has come about as scholars carried out in-depth empirical studies to examine both the interactions across epistemological and ontological boundaries, and the characteristics of organizations, producers and users that leads to increased usability (39). For example, Kirchhoff et al. found that in both the US and Brazil interaction in the context of a boundary organization improved the use of climate information by water managers (70). Similar improvements to climate information usability associated with interactions between producers and users have been observed across a variety of applications from sustainable land management (51) to disaster reduction (71) and urban sustainability (72). It is not just interaction between producers and users that matters. Building capacity for information uptake, integrating multiple forms of knowledge and managing the inequities in power between producers and users also improves usability (73).

Knowledge systems. In earlier usage, ‘knowledge systems’ referred to indigenous ways of knowing about the world encompassing nature, culture, and the environment and their interrelationships (see for example, (74)) and farmers’ knowledge of agricultural practices (see for example (75)). In their seminal paper, Cash et al. reframed knowledge systems to encompass programs and institutional arrangements that effectively harness science and technology to improve decision making for sustainable development (69). They argued that for knowledge systems to be effective, they must actively manage the boundary between expertise and decision making, enforce accountability of actors on both sides of the boundary, and jointly produce outputs (e.g., models, reports). For scientific information to be usable, decision-makers must perceive it to be credible, salient and legitimate (12). To be judged by these criteria, scientific knowledge needs to show distinctive characteristics decision-makers recognize (76). For instance, information is likely to be deemed credible if the science is accurate, valid, of high quality, supported by some form of peer review, and funded from one or more recognizable or established institutions. To ensure the information is legitimate, it must have been produced and disseminated in a transparent, open, and observable way that is free from political persuasion or bias. To be salient, information must be context sensitive and specific to the demands of a decision maker across ecological, spatial, temporal, and administrative scales (9, 12, 16, 77-79).

Empirical observations suggest salience, credibility, and legitimacy are often tightly coupled; improvement of one measure can result in a reduction in another (12). Hence, achieving these three criteria simultaneously maybe tricky as tradeoffs between them, may negatively influence the overall perception of information usability. Moreover, stakeholders may have different perceptions of what makes credible, legitimate, and salient information (7, 12). To try and reduce these tradeoffs, Cash et al. argue that knowledge systems need to have active, iterative, inclusive, and open communication and translation that promotes mutual understanding between participants (12). When all else fails, conflict across the three criteria may require active mediation to prevent the 'system' from collapsing. Here boundary organizations are critical in maintaining the integrity of the system since they can enhance communication, translation and mediation, routinize boundary spanning activities, and help to stabilize knowledge systems in a changing socio-political context (80).

The knowledge system criteria can be a valuable heuristic to assess stakeholders' perspectives of what constitutes usable science because it considers the entire process (from inception to dissemination) of the science in question. Indeed, credibility can be used to assess stakeholders' perceptions of the quality of science underpinning the disseminated information; legitimacy can assess stakeholders' perceptions of the level of transparency and bias of the individuals and institutions involved in its development; and saliency directly assesses stakeholders' perceptions of its relevancy to their needs and requirements. Proving its versatility, the knowledge systems framework has been applied to a diversity of research foci that range from understanding how The Global Fund to Fight AIDS, Tuberculosis, and Malaria contributes to support the global response to these diseases (81) to the investigation of how such systems support climate forecast use by farmers and water managers in Australia, water managers in Hawaii, natural resource managers in the Columbia River Basin and a range of users in the UK (76, 80, 82-84).

Integrated Scientific Assessments. Assessments organize, evaluate, and integrate expert knowledge to inform policy or decision making (85). They also interpret and reconcile information produced from disparate scientific domains making the information more useful for policy deliberations and for addressing an identified problem (86). For example, global environmental assessments have been undertaken to inform responses to pressing global environmental concerns including to climate change, biodiversity loss, and stratospheric ozone depletion (87-89). However, despite their designed intent (to be usable for policy or decision making), in practice their influence on national and international responses to environmental threats has been limited with ozone depletion and acid raid being notable exceptions (90, 91). In the US regional scale assessments like the Regional Integrated Sciences and Assessments (RISAs) have been relatively more successful in providing usable information for policymakers. This is partly because they reduce barriers to and leverage drivers of information use (14), and because, in many cases, they successfully reconcile the production of information with users' demand (9, 10, 25) through sustained and frequent interaction between scientists and stakeholders (14).

At the global level of environmental regimes, research applying the knowledge systems approach to evaluate scientific assessments finds that assessments perceived to be salient, credible, and legitimate are more successful (40, 85). In this case, success encompasses both the usability of the product and the process of information production. For example, Clark and Dickson found that more effective assessments achieve a balance of saliency, credibility and legitimacy, where saliency refers to the perceived relevance and credibility refers to the perceived authoritativeness of the process to the scientific community. Lastly, legitimacy captures the perceived fairness and openness of the assessment process to the mostly policy or political community who might reasonably use the assessment product (92).

Others have questioned the sufficiency of perceived salience, credibility and legitimacy to determine assessments' effectiveness, that is, their influence on the policy making process—particularly for those conducted at other than international scales (e.g., national, regional). For example, a number of researchers have found the US National Acid Precipitation Assessment Program (NAPAP) to be irrelevant to the policy-making process despite efforts to maintain credibility, saliency, and legitimacy (93-95). Similarly, despite efforts to ensure the credibility (e.g., peer reviewed), legitimacy and saliency (e.g., stakeholder participation) of the product and process of the first United States National Assessment of the Potential Impacts of Climate Change (USNA), limitations of assessment process itself (e.g. budget constraints) and political meddling effectively contributed to lessen its impact (L. Carter, personal interview, April 2, 2008) (96, 97).

At the regional scale, empirical research suggests that effective assessments are ongoing, interactive, iterative (8), match the scale of assessment with the relevant scale of decision making or management (98), and employ buffering and linking strategies (94). To be effective at producing usable information, regional assessments need to straddle the line between understanding complex problems and producing information that meets decision makers' perception of needs (8). Hence the early and continued involvement of stakeholders in the process of knowledge production is likely to positively influence the actual use of information in decision making (99, 100). Likewise, matching the scale of an assessment of a particular phenomenon of interest (e.g., climate change impacts) to the scale of a potential response (e.g., water management adaptation policies) improves assessment effectiveness (98). Finally, when assessments protect scientific work from bias and politicization (buffering) while maintaining ties to potential assessment information users who might rely on the outputs to inform policy decisions (linking), they are more effective (94).

3. WHAT INFLUENCES THE USE OF SCIENTIFIC INFORMATION FOR INDIVIDUAL USERS: EVIDENCE FROM CLIMATE KNOWLEDGE

3.1. Users' Perception of Risk

Attitudes towards risks vary across people, cultures, time and experience; these attitudes have a profound impact on the character and type of information sought and used (or not) in decision making. For example, O'Connor et al. found that risk perceptions were the strongest determinants of weather and climate forecast use amongst two eastern American states (101). Water managers who expect to face problems from weather events in the next decade are more likely to use forecasts than are water managers who expect few problems; their expectations of future problems are closely linked with past experience. Feeling at risk thus leads to a greater use of climate information. In her study of water managers in the US Pacific Northwest and Southwest, Kirchhoff points out that water managers' risk perceptions were strongly correlated with information seeking and collaborative behaviors, through which water managers gather and employ climate information as a strategy to manage risk and inform decision-making. These behaviors (seeking information and developing multiple collaborative relationships) help managers assemble a portfolio of information to manage both uncertainty related to their specific decision context and uncertainty embedded in the information that is ultimately used in decision making (14) (for a discussion of uncertainty in water decision making see also (102). Finally, different decision environments influence risk perception differently as well. In Australia, Power et al. discovered that water resource managers perceived the risk from public outcry over not using climate information in planning as more worrisome than the risk associated with using it (103).

Human cognition and experience also play a role in risk perceptions. Specifically, the ways in which people process information analytically (slowly, with "conscious awareness and knowledge of rules" such as logic and probabilities) or experientially (fast and relating to experiences and learning from them) affect their perception of risk and influence their use of information. Marx and Weber found that approaches that encourage users to employ a combination of these processes positively influence forecast use (104, 105). In terms of experience, worry stemming from personal experiences can influence risk perceptions and response. For example, individuals who are alarmed about a potential hazard or risk are more likely to take action informed by climate information while those who are not alarmed do not take precautions (106). Visualization can also improve the likelihood of taking action. For example, Weber found that interventions (e.g., visualizations) that help move future events closer in time and space raise individuals' visceral concern, which in turn, may lead to increased responsiveness (106).

3.2. Producer-user Interactions and Decision Environments

Within the broad scope of science-policy models, boundary organizations, knowledge systems, and assessments and their success (or failure) to produce usable information, a large body of literature has focused on understanding the factors that influence scientific information use in diverse areas of environmental decision making at both the producer-user interface and at the wider institutional context. In their review of this literature, Lemos et al. argued that usability is affected mainly by three interconnected factors: the level and quality of interaction between producers and users of climate information (*interaction*), how users perceive climate information meets their needs (*fit*) and how new knowledge interacts with other types of knowledge decision maker current use (*interplay*) (31).

At the producer-user interface, robust empirical evidence from the well developed literature focusing on the use of seasonal climate forecasts by different decision makers suggests that, first, two-way communication that improves mutual understanding and, second, long-term relationships that build trust between producers and users play a significant role in increasing scientific information uptake (107-114). In turn, trust building and accountability influence users' perceptions of information salience, credibility and legitimacy in particular decision contexts (14, 115). In addition, establishing convening, translating, mediating and collaborative processes that link producers and users increases the salience, legitimacy and credibility of information leading to improved usability (40). For example, in the US Pacific Islands and US Southwest (SW), ongoing collaboration between scientists and decision makers facilitated the production of information tailored to users' needs and context in the Islands case (40) and built the capacity of users to incorporate forecasts in decision making the SW case (116). Similarly, interactions and the long-term relationships they support can critically accelerate dissemination of new knowledge through the many networks to which users belong (114). Finally, usability is enhanced with interactions that help potential users understand, process and ultimately use information in decision making. By drawing on what is familiar to potential users and using holistic scenarios, especially those created using information visualization processes improve salience and facilitate more comprehensive understanding (117). Visualization has been used as an aid to local decision making across a range of applications from climate change impacts and responses (117, 118) to sustainable forest management (119) and landscape change (i.e., tourism, agriculture and forestry) (120).

What many of these in-depth studies have found is that interaction can help mitigate many of the barriers to information use, including users' perceptions that scientific information is too uncertain to use or that it lacks the perceived level of accuracy and reliability to be used in decision making. Interaction can help change users' minds by facilitating in-depth discussion, including potential trade-offs and risks in using information and their effect on decision making (14, 103, 121, 122). For instance, producer-user interactions over the course of a workshop helped users gain a more in-depth understanding of how streamflows are reconstructed from tree-rings and how this information can be used to extend what is known about the range of natural variability for individual streams to aid in long-term drought planning (123). Similarly, explaining decision-making tools in more depth positively influences users' willingness to deploy them. Users also benefit from producers' explanation of choices, tradeoffs and limitations of different kinds of knowledge/information. For example, disclosing data sources and assumptions underlying a water simulation model helped policy makers evaluate the salience and credibility of the model ultimately influencing its perceived usability (68). Interaction can also help users to better integrate information in their decision making. In their study of coastal managers Tribbia and Moser found they need more than just information when planning for climate change; they also need support in integrating and facilitating science knowledge into practical management (124). Finally, interaction may work to decrease mismatches between different kinds of knowledge and values such as explicit (e.g. facts and figures) and tacit knowledge (e.g. experience and context (106, 125). For example, interaction fosters learning, which in turn reduces conflicts between knowledge types by helping to transform one type of knowledge (e.g., explicit knowledge) into another (e.g., experiential or tacit knowledge).

Case studies in the US and around the world have shown that institutions and organizational culture matter to the usability of information (102, 109, 113, 126-133). For example, research found that organizations with more flexible decision-making frameworks (66) and those that insulate technocratic decision makers (134) are more likely to use information. Having sufficient human or technical capacity in-house or having access to relevant external expertise makes climate forecast use more likely (130, 135). Furthermore, a decision-making culture that views the use of climate information as a strategy to mitigate risk (14, 123, 136) rather than as a risky practice in itself (137) is more likely to promote integration of climate information in decision making. Finally, organizations that value research and provide incentives that promote incorporation of information into decision making also improve knowledge use (14, 110).

4. BROADENING USABLE CLIMATE SCIENCE

In our review, we have synthesized a wide range of research on science-policy models and empirical research on factors (institutional and organizational issues, risk attitudes and perceptions, etc.), processes (interaction, visualization, etc.), and structures (boundary organizations, knowledge systems, etc.) that influence information use. Regarding climate science, what this empirical research shows is that many of the strategies for increasing climate information usability focus on improving interactions between producers and users of information and obtaining a better fit of information to the specific user contexts (40, 80, 82, 107, 109). This makes sense given that most empirical examples of successful adoption have been driven by highly interactive and well-established relationships between producers and users of climate information brokered by mechanisms created specifically for that purpose (8, 9, 14, 42, 114, 123, 136). However, while effective in increasing usability, interaction focused approaches present their own set of challenges, not the least of which is the limited number of potential users that they can serve (14). Thus, as the need for climate information to inform policy increases (7, 31, 102, 138), there is a need to think beyond incremental improvements to existing processes of information production to new approaches capable of responding to increased levels of demand. Systemic change in the way we produce scientific information requires understanding how to improve usability not just for specific users in their particular decision contexts but for broad groups of users and scales of decision-making, especially those tasked with implementing different adaptation options and building adaptive capacity to respond to the impacts of climate variability and change. Hence, there is a critical need to better understand what is common and/or unique about information users and their decision environments both to inform the aggregation of users into groups and to aid in adapting climate information to meet the information needs and decision environments of a wide range of users. Aggregating user types helps information provisioning by guiding the range of potential strategies producers may choose to employ to those potentially more compatible with the target audience (once the characteristics of that target audience are known).

Our review of the empirical literature suggests two significant drivers of climate information use: a) behavior towards knowledge and innovation (i.e., how proactive users are in seeking new knowledge) and b) ability to use information in particular decision contexts (how supportive/flexible or inhibiting/inflexible is the user's decision environment). Across these two drivers, we propose a typology of users (illustrated in Figure 2), that can inform the design and implementation of climate information provisioning efforts both in terms of where and potentially how effort should be applied as well as where current levels of access to information may be in/adequate for current level of need.

Insert Figure 2 about here

The first type of user is the Early Adopter (upper right box, (a)), who has both a supportive decision environment (e.g., an organizational culture and institutional environment that supports using climate information in decision making, see, for example, (103)) and is highly proactive in obtaining and using information (i.e., they use many different pieces of information and have been proficient in adopting innovations in the past). This combination facilitates their use of climate information in decision making. Early adopters are on the leading edge of adaptation to climate variability and change and are likely among the most sophisticated information users (14). In considering aggregated approaches to the provision of climate information, starting with early adopters first, may help to pave the way for subsequent targeting of more tentative users, whose decision making environments also fosters uptake but they themselves may lack confidence in using climate information.

Tentative Users (lower right quadrant, (b)) have a supportive decision environment (making climate information use easier) but may exhibit a low level of initiative in obtaining and using information. This behavior maybe due to either individual users' risk averseness or a desire to stay out of the public eye or both (e.g., (109)). It may also be because of a negative perception about climate information or prior negative experience using climate information (134). Tentative users are thus likely to apply mostly prescribed, established, or routine information sources that they are familiar with rather than seeking new information or new information sources. While Tentative Users may not very proactively seek information, their decision environment maybe conducive to using climate information, especially in the context of decentralized decision environments (134) or with help from a boundary organization (70). Interaction with information producers may help groups of Tentative Users to become more confident with using climate information and to discover how adjusting their decision making to use available climate information may improve the climate-impacted decisions they make. For climate information producers, better understanding both users' reservations/limits to using climate information and the flexibility of their decision environments, will aid in retailing, value-adding and customizing information to be more accessible and usable.

The other intermediate user type are Proactive Users (upper left quadrant, (c)), who actively seek and use information beyond prescribed, established or routine information sources but, due to unsupportive/inflexible decision environments, may not presently use climate information. Drivers of inflexibility may include highly regulated environments and high levels of public accountability (109, 134), difficulty incorporating new information into existing decision processes (31, 123) or an unsupportive organizational culture (14). In this case, Proactive Users may want to use climate information and seek climate information to meet their perceived needs but may be unable to use it unless the information very easily integrates with the decision processes they currently use and with the decisions that they are already making. Hence, these users may increase their uptake of climate information if it meets their perceived information needs and fits their decision environment. Interaction can provide information producers with a better understanding of how to adjust information through customization or adding value to information to meet Proactive Users' perceived needs. Alternatively, proactive users may use climate information in planning but run into roadblocks by regulators not yet ready to approve its use. Interaction efforts could be designed to be more integrative spanning not just producers and users but involving regulators, upper management, or others who may impact uptake. Interaction in the context of a knowledge system could help in this regard since knowledge systems help span decision scales.

Finally, the penultimate user type, Laggards (lower left quadrant, (d)), have both a low level of proactivity of information adoption and an unsupportive decision context. Laggards are likely very difficult to reach out to because they do not want to use new information or information from sources that they are unfamiliar with and face decision environments that make incorporating new information difficult. While they might be more impervious to change in the short run, they may be good targets for awareness raising and broader education campaigns to build capacity for uptake of climate information in the longer term. In the sense that it aggregates users that inform different kinds of strategies to increase scientific information uptake, this simple matrix can be useful to the design of different strategies to amplify the availability and accessibility of climate information beyond close interaction and contribute to up-scaling the delivery of climate information that may be required with a growing number of users as the climate continues to change. It can also support the design of remote tools that seek to learn and emulate desirable characteristics of highly interactive processes and strategies of knowledge production and use.

5. **CONCLUSION**

There are an ever growing number of complex environmental problems that increasingly need science to support decision-making. Despite the growing availability of scientific information, there is a persistent gap between knowledge production and its use to inform decision making. Scholars have explored different ways to narrow this gap through better understanding society's relationship to science including how it both shapes the science that is produced and how that science is used (or not) to support decisions. These efforts have produced a rapid evolution of science-society models, ranging from the 1940's linear model, to more complex models of science production that embrace interdisciplinary approaches and involve users to help solve societal problems. Despite these efforts to re-think and restructure science production, current approaches have not been able to surmount the usability gap. This review advances this practical and scholarly inquiry by surveying a wide range of research on science-policy models and empirical research on factors, processes and structures that influence science usability highlighting the lessons that can both support the creation of new science/policy interfaces and inform the institutionalization of successful models. Our review of the empirical literature suggests two significant drivers of climate information use: a) behavior towards knowledge and innovation (i.e., level of proactivity of information adoption/knowledge seeking behavior) and b) ability to use information in particular decision contexts (how supportive/flexible or inhibiting/inflexible is the user's decision environment). We identify a typology of users—Early Adopters, Proactive Users, Tentative Users and Laggards—across these two drivers to inform the design and implementation of information provisioning efforts. The typology helps to identify concrete approaches that can support up-scaling information such as starting with early adopters to pave the way for subsequent targeting of more tentative users and designing integrative engagement efforts spanning not just producers and users but involving regulators, upper management, or others who may impact information uptake.

Although the typology has the potential to amplify the availability and accessibility of information beyond close interaction and contribute to up-scaling the delivery of information (including climate information) more broadly, there are potential constraints and challenges that need to be addressed in future research. One challenge concerns the constraints and disincentives that limit both the ability of scientists to engage with user communities and broker knowledge, and that limit users' ability to engage with scientists. Another challenge concerns overcoming the entrenched institutional roadblocks that can circumvent information uptake despite the establishment of successful information provisioning efforts between scientists and groups of users. Institutional change can be more difficult and much slower to change but finding ways to make even small gains in these areas (integrative, holistic strategies for interaction) can result in vast improvements in uptake when groups of users are targeted. Finally, up-scaling will be difficult to achieve if laggards and tentative users are not brought into the provisioning process. Finding creative ways to reach tentative users and increasing education and outreach across all user types, can get us part way there.

SUMMARY POINTS

- There has been a rapid evolution of increasingly complex science policy models to help understand science-society interaction and to aid in understanding how to provide information to solve societal problems
- Despite this advancement and attention to problem solving, there is a persistent gap between production and use of scientific knowledge
- Much of the work to bridge the gap has focused on individual users and their decision contexts
- We propose that to achieve more widespread uptake in information requires a shift in the way in which we approach information provisioning
- We suggest there is a need to better understand users in the aggregate and propose a typology of users using two drivers of information use: information seeking behavior and decision context
- Understanding types of users—Early Adopter, Proactive User, Tentative User, and Laggard—can inform the strategies producers use to reach potential users to advance more broad dissemination and use of information

FUTURE ISSUES

- Beyond understanding user types, there is a need to overcome institutional constraints that constrain information uptake despite best efforts at information provisioning
- There is a need to explore how interactions between producers and users that have increased usability in the past can be more integrative representing more of the users' decision context (e.g., institutions, regulators, etc.)

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGEMENTS

Suraje Dessai is supported by the European Research Council under the European Union's Seventh Framework Programme (FP7/2007- 2013)/ERC Grant agreement no. 284369 and Grant agreement no: 308291. Responsibility for any errors are with the authors.

LITERATURE CITED

1. Stokes DE. 1997. *Pasteur's quadrant: basic science and technological innovation*. Washington, DC: Brookings Institution, 180 p
2. Bush V. 1945. *Science The Endless Frontier*, United States Government Printing Office, Washington, DC
3. Cox B, Ince R. 2012. Politicians must not elevate mere opinion over science. In *New Statesman*
4. Feldman M. 1989. *Order Without Design: Information Production and Policymaking.* Palo Alto, CA: Stanford University Press
5. Meyer R. 2011. The Public Values Failures of Climate Science in the US. *Minerva* 49: 47-70
6. Dilling L. 2007. Towards science in support of decision making: characterizing the supply of carbon cycle science. *Environmental Science & Policy* 10: 48-61
7. Dilling L, Lemos MC. 2011. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Enviromental Change* 21: 680–89
8. Lemos MC, Morehouse B. 2005. The Co-Production of Science and Policy in Integrated Climate Assessments. *Global Environmental Change* 15: 57-68
9. McNie EC. 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental Science & Policy* 10: 17-38
10. Sarewitz D, Pielke RA, Jr. 2007. The neglected heart of science policy: reconciling supply of and demand for science. *Environmental Science & Policy* 10: 5–16
11. Eden S. 2011. Lessons on the generation of usable science from an assessment of decision support practices. *Environ. Sci. Policy* 14: 11–19
12. Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, et al. 2003. Knowledge systems for sustainable development. *Proceedings of the National Academy of Sciences of the United States of America* 100: 8086-91
13. Dilling L, Moser S. 2007. *Creating a Climate for Change: Communicating Climate Change and Facilitating Social Change. Cambridge, MA: Cambridge University Press*
14. Kirchhoff CJ. 2010. Integrating Science and Policy: Climate Change Assessments and Water Resources Management. *School of Natural Resources and Environment* PhD: 293
15. Klopper E, Vogel CH, Landman WA. 2996. Seasonal Climate Forecasts--Potential Agricultural-Risk Management Tools? . *Climatic Change* 76: 73–90
16. Hulme M, Dessai S. 2008. Negotiating future climates for public policy: a critical assessment of the development of climate scenarios for the UK. *Environmental Science & Policy* 11: 54-70
17. Gibbons M, Limoges C, Nowotny H, Schartzman S, Scott P, Trow M. 1994. *The New Production of Knowledge by*. London, UK: Sage Publications
18. Jasanoff S. 1990. *The Fifth Branch: Science Advisers as Policymakers*. Cambridge, MA: Harvard University Press
19. Latour B, Wolgar S. 1979. *Laboratory Life*. Beverly Hills, CA: Sage
20. Latour B. 1998. From the world of science to the world of research? *Science* 280 208–09
21. Jasanoff S. 2004. *States of knowledge: the co-production of science and social order*. New York, NY: Routledge

22. Ezrahi Y. 1990. *The Descent of Icarus: Science and the Transformation of Contemporary Democray*. Cambridge, MA: Harvard University Press
23. Jasanoff S, Wynne B. 1998. Science and decisionmaking. *Human Choice and Climate Change: The Societal Framework* 1: 1-88
24. Lovbrand E, Onberg G. 2005. Discussion: Comment on" How science makes environmental controversies worse" by Daniel Sarewitz. *Environmental Science and Policy* 7: 385-403
25. McNie E. 2008. *Co-Producing Useful Climate Science for Policy: Lessons from the RISA Program*. University of Colorado, Boulder, CO. 290 pp.
26. O'Mahony S, Bechky BA. 2008. Boundary Organizations: Enabling Collaboration among Unexpected Allies. *Administrative Science Quarterly* 53: 422-59
27. Tomich TP, Timmer DW, Velarde SJ, Alegre J, Areskoug V, et al. 2007. Integrative science in practice: process perspectives from ASB, the Partnership for the Tropical Forest Margins. *Agriculture, ecosystems & environment* 121: 269-86
28. Weiss CH. 1978. Improving the Linkage between Social Research and Public Policy. *Knowledge and Policy: The Uncertain Connection*: 23-81
29. Weiss C. 1995. The Haphazard Connection: Social Science and Public Policy. *International Journal of Educational Research* 23: 137-50
30. Funtowicz SO, Ravetz JR. 1993. The emergence of post-normal science. *Theory and Decision Library Series A Philosophy and Methodology of the Social Sciences; Science, politics and morality: Scientific uncertainty and decision making* 17
31. Lemos MC, Kirchhoff C, Ramparasad V. 2012. Narrowing the Climate Information Usability Gap. *Nature Climate Change* 2: 789-94
32. Pielke RA, Jr. 1995. Usable information for policy: An appraisal of the U.S. Global Change Research Program. *Policy Sciences* 28: 39-77
33. Gibbons M. 2000. Mode 2 society and the emergence of context-sensitive science. *Science and Public Policy* 27: 159-63
34. NRC. 2009. Restructuring Federal Climate Reserch to Meet the Challenges of Climate Change. Washington, DC: The National Academies Press
35. NRC. 2010. *America’s Climate Choices: Panel on Advancing the Science of Climate Change*, National Research Council of the National Academy of Science. Washington DC: The National Academies Press
36. Pereira AG, Raes F, Pedrosa TDS, Rosa P, Brodersen S, et al. 2009. Atmospheric composition change research: Time to go post-normal? *Atmospheric Environment* 43: 5423-5432
37. Turnpenny J, Jones M, Lorenzoni I. 2011. Where Now for Post-Normal Science?: A Critical Review of its Development, Definitions, and Uses. *Science, Technology & Human Values* 36: 287-306
38. Wolgar S. 2000. Social basis of interactive social science by. *Science and Public Policy* 27: 165-73
39. Kloprogge P, Van Der Sluijs JP. 2006. The inclusion of stakeholder knowledge and perspectives in integrated assessment of climate change. *Climatic Change* 75: 359-389
40. Cash DW, Borck JC, Patt AG. 2006. Countering the loading-dock approach to linking science and decision making. Comparative analysis of El Niño/Southern Oscillation (ENSO) Forecasting systems. *Science, Technology and Human Values* 31: 465-94

41. Cutts BB, White DD, Kinzig AP. 2011. Participatory geographic information systems for the co-production of science and policy in an emerging boundary organization. *Environmental Science & Policy* 14: 977-985
42. Feldman DL, Ingram HM. 2009. Making science useful to decision makers: Climate Forecasts, water management and knowledge networks. *Weather, Climate and Society* 1: 9-21
43. Folke C, Hahn T, Olsson P, Norberg J. 2005. Adaptive governance of social-ecological systems. *Annual Review of Environment and Resources* 30: 441-73
44. Guston DH. 2001. Boundary Organizations in Environmental Policy and Science: An Introduction. *Science, Technology and Human Values* 26: 399-408
45. Ingram H, Feldman DL, Jacobs KL, Mantua N, Lemos MC, et al. 2008. Looking Toward the Future. In: Decision-Support Experiments and Evaluations using Seasonal-to-Interannual Forecasts and Observational Data: A Focus on Water Resources. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. 141-54
46. Macleod CJA, Blackstock KL, Haygarth PM. 2008. Mechanisms to Improve Integrative Research at the Science-Policy Interface for Sustainable Catchment Management. *Ecology and Society* 13
47. McKinley DC, Briggs RD, Bartuska AM. 2012. When peer-reviewed publications are not enough! Delivering science for natural resource management. *Forest Policy and Economics* 21: 1-11
48. Meinke H, Howden SM, Struik PC, Nelson R, Rodriguez D, Chapman SC. 2009. Adaptation science for agriculture and natural resource management— urgency and theoretical basis. *Current Opinions in Environmental Sustainability* 1: 69–76
49. Robertson DP, Hull RB. 2003. Public ecology: an environmental science and policy for global society. *Environmental Science & Policy* 6: 399-410
50. Ravetz JR. 2006. Post-Normal Science and the complexity of transitions towards sustainability. *Ecological Complexity* 3: 275-284
51. Franks J. 2010. Boundary organizations for sustainable land management: The example of Dutch Environmental Co-operatives. *Ecological Economics* 70: 283-95
52. De Freitas DM, Tagliani PRA. 2009. The use of GIS for the integration of traditional and scientific knowledge in supporting artisanal fisheries management in southern Brazil. *Journal of Environmental Management* 90: 2071-2080
53. Lemos MC, Finan T, Fox R, Nelson D, Tucker J. 2002. The Use of seasonal climate forecasting in policymaking: lessons from Northeast Brazil. *Climatic Change* 55: 479-507
54. Gough M. 2003. *Politicizing Science*. Stanford, CA: Hoover Institution Press
55. Guston DH. 1999. Stabilizing the boundary between politics and science: the role of the office of technology transfer as a boundary organization. *Social Studies of Science 29*: 87–111
56. Ison R, Roling N, Watson D. 2007. Challenges to science and society in the sustainable management and use of water: investigating the role of social learning. *Environmetal Sciece and Policy* 10: 499–511
57. Lemos MC. 2008. Whose water is it anyway? Water management, knowledge, and equity in NE Brazil. *Water, Place and Equity*: 249-70

58. Taddei R. 2011. Watered-down democratization: modernization versus social participation in water management in Northeast Brazil. *Agriculture and Human Values* 28: 109-121
59. Pellizzoni L. 2010. Environmental Knowledge and Deliberative Democracy. In *Environmental Sociology: European Perspectives and Interdisciplinary Challenges.* Netherlands: Springer 159-182
60. Lemos MC, Bell A, Engle NE, Formiga-Johnsson RM, Nelson DR. 2010. Technical knowledge and water resources management: A comparative study of river basin councils, Brazil. *Water Resource Research* 46
61. Wesselink A, Hoppe R. 2011. If Post-Normal Science is the Solution, What is the Problem?: The Politics of Activist Environmental Science. *Science Technology & Human Values* 36: 389-412
62. Turnpenny J, Lorenzoni I, Jones M. 2009. Noisy and definitely not normal: responding to wicked issues in the environment, energy and health. *Environmental Science & Policy* 12: 347-58
63. Yearley S. 2000. Making systematic sense of public discontents with expert knowledge: two analytical approaches and a case study. *Public Understanding of Science* 9: 105–22
64. Bandura A. 1973. *Aggression: A social learning analysis.* Englewood Cliffs, NJ: Prentice-Hall
65. Star SL, Griesemer JR. 1989. Institutional ecology,translations' and boundary objects: Amateurs and professionals in Berkeley's Museum of Vertebrate Zoology, 1907-39. *Social Studies of Science* 19: 387-420
66. Guston DH. 2007. *Between Politics and Science: Assuring the Integrity and Productivity of Reseach.* Cambridge, MA: Cambridge University Press
67. Lynch AH, Tryhorn L, Abramson R. 2008. Working at the Boundary: Facilitating Interdisciplinarity in Climate Change Adaptation Research. *Bulletin of the American Meteorological Society* February: 169-79
68. White DD, Wutich A, Larson KL, Gober P, Lant T, Senneville C. 2010. Credibility, salience, and legitimacy of boundary objects: water managers' assessment of a simulation model in an immersive decision theater. *Science and Public Policy* 37: 219–232
69. Carr A, Wilkinson R. 2005. Beyond participation: Boundary organizations as a new space for farmers and scientists to interact. *Society and Natural Resources* 18: 255-65
70. Kirchhoff CJ, Lemos MC, Engle NL. 2013. What influences climate information use in water management? The role of boundary organizations and governance regimes in Brazil and the US. *Environmental Science & Policy* 26: 6-18
71. Kasperson RE. 2010. Science and disaster risk reduction. *International Journal of Disaster Risk Science* 1: 3-9
72. Owens S, Petts J, Bulkeley H. 2006. Boundary work: knowledge, policy, and the urban environment. *Environment and Planning C: Government and Policy* 24: 633-43
73. Clark WC, Tomich TP, Noordwijk Mv, Guston D, Catacutan D, et al. 2011. Boundary work for sustainable development: Natural resource management at the Consultative Group on International Agricultural Research (CGIAR). *Proceedings of the National Academy of Sciences*
74. Dei GJS. 1993. Indigineous African knowledge systems: local traditions of sustainable forestry. *Singapore Journal of Tropical Geography* 14: 28-41

75. Pingali PL, Hossain M, Pandey S, Price LL. 1998. Economics of nutrient management in Asian rice systems: towards increasing knowledge intensity. *Field Crops Research* 56: 157-76
76. Tang S, Dessai S. 2012. Usable Science? The U.K. Climate Projections 2009 and Decision Support for Adaptation Planning. *Weather, Climate, and Society* 4: 300-13
77. Hegger D, Lamers M, Van Zeijl-Rozema A, Dieperink C. 2012. Conceptualising joint knowledge production in regional climate change adaptation projects: success conditions and levers for action. *Environmental Science & Policy* 18: 52–65
78. Meinke H, Nelson R, Kokic P, Stone R, Selvaraju R, Baethgen W. 2006. Actionable climate knowledge: from analysis to synthesis. *Climate Research* 33: 101-110
79. Munang R, Rivington M, Takle ES, Mackey B, Thiaw I, Liu J. 2010. Climate Information and Capacity Needs for Ecosystem Management under a Changing Climate. *Procedia Environmental Sciences* 1: 206-27
80. Buizer J, Jacobs K, Cash D. 2010. Making short-term climate forecasts useful: Linking science and Action. *Proc. Nat. Acad. Sciences*
81. van Kerkhoff L, Szlezak NA. 2010. The role of innovative global institutions in linking knowledge and action. *Proceedings of the National Academy of Sciences*
82. Jacobs K, Lebel L, Buizer J, Addams L, Matson P, et al. 2010. Linking knowledge with action in the pursuit of sustainable water-resources management. *Proceedings of the National Academy of Sciences*
83. van Kerkhoff L, Lebel L. 2006. Linking Knowledge and Action for Sustainable Development. *Annual Review of Environment and Resources* 31: 445-77
84. Wallington T, Maclean K, Darbas T, Robinson C. 2010. *Knowledge – Action Systems for Integrated Water Management: National and International Experiences, and Implications for South East Queensland*, CSIRO
85. Farrell A, Jager J. 2006. *Assessments Of Regional And Global Environmental Risks: Designing Processes For The Effective Use Of Science In Decisionmaking*: Resources for the Future
86. Parson EA. 1995. Integrated Assessment and Environmental Policy Making in Pursuit of Usefulness. *Energy Policy* 23: 463-75
87. IPCC. 2007. Climate Change 2007: The Physical Science Basis. Summary for Policymakers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. 18
88. MEA. 2003. *Millennium ecosystem assessment*
89. WMO. 2011. *Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project*, World Meteorological Organization, Geneva, Switzerland
90. Reis S, Grennfelt P, Klimont Z, Amann M, ApSimon H, et al. 2012. Atmospheric science: From acid rain to climate change. *Science* 338: 1153-54
91. Parson EA. 2003. *Protecting the ozone layer: Science and strategy*. New York: Oxford University Press
92. Clark W, Dickson N. 1999. The Global Environmental Assessment Project: Learning from efforts to link science and policy in an interdependent world. *Acclimations* 8: 6-7
93. Herrick C, Jamieson D. 1995. The social construction of acid rain: some implications for science/policy assessment. *Global Environmental Change* 5: 105-12

94. Keller AC. 2010. Credibility and relevance in environmental policy: Measuring strategies and performance among science assessment organizations. *Journal of Public Administration Research and Theory* 20: 357-86
95. Rubin ES, Lave LB, Morgan MG. 1991. Keeping climate research relevant. *Issues in Science and Technology;(United States)* 8: 47-55
96. Mooney C. 2007. An inconvenient assessment. *Bulletin of the Atomic Scientists* 63: 40-47
97. Morgan MG, Cantor R, Clark WC, Fisher A, Jacoby HD, et al. 2005. Learning from the US national assessment of climate change impacts. *Environmental Science & Technology* 39: 9023-32
98. Cash DW, Moser SC. 2000. Linking global and local scales: designing dynamic assessment and management processes. *Global Environmental Change-Human and Policy Dimensions* 10: 109-120
99. NRC. 2005. *Decision making for the environment: Social and behavioral science research priorities*. Washington DC: National Academy Press
100. Pielke RA. 1994. Scientific information and global change policymaking. *Climatic Change* 28: 315-19
101. O'Connor RE, Yarnal B, Dow K, Jocoy CL, Carbonne GJ. 2005. Feeling at Risk Matters: Water Managers and the Decision to Use Forecasts. *Risk Analysis* 5: 1265-75
102. Kiparsky M, Milman A, Vicuña S. 2012. Climate and Water: Knowledge of Impacts to Action on Adaptation. *Annual Review of Environment and Resources* 37: 163-194
103. Power S, Sadler B, Nicholls N. 2005. The Influence of Climate Science on Water Management in Western Australia: Lessons for Climate Scientists. *Bulletin of the American Meteorological Society* 86: 839-44
104. Marx S, Weber EU. in press. Decision making under climate uncertainty: The power of understanding judgment and decision processes. In *Climate change in the Great Lakes region: Decision making under uncertainty*, ed. T Dietz, DC Bidwell. East Lansing, MI: Michigan State University Press
105. Marx SM, Weber EU, Orlove BS, Leiserowitz A, Krantz DH, et al. 2007. Communication and mental processes: Experiential and analytic processing of uncertain climate information. *Global Environmental Change* 17: 47-58
106. Weber EU. 2006. Experience-based and description-based perceptions of long-term risk: Why global warming does not scare us (yet). *Climatic Change* 77: 103-20
107. Carbone GJ, Dow K. 2005. Water Resources and Drought Forecasts in South Carolina. *Journal of the American Water Resources Association* February: 145-55
108. Pagano TC, Hartmann HC, Sorooshian S. 2002. Factors affecting seasonal forecast use in Arizona water management: a case study of the 1997-98 El Niño. *Climate Research* 21: 259-69
109. Rayner S, Lach D, Ingram H. 2005. Weather forecasts are for wimps*: why water resource managers do not use climate forecasts. *Climatic Change* 69: 197-227
110. Engle NL. 2010. *Adaptation to Extreme Droughts in Arizona, Georgia, and South Carolina: Evaluating Adaptive Capacity and Innovative Planning and Management Approaches for States and Their Community Water Systems*. University of Michigan, Ann Arbor, MI
111. Pagano TC, Hartmann HC, Sorooshian S. 2001. Using climate forecasts for water management. *Journal of the American Water Resources Association* 37: 1139-53

112. Moser S. 2009. Making a difference on the ground: the challenge of demonstrating the effectiveness of decision support. *Climatic Change* 95: 11-21
113. Nelson RA, Holzworth DP, Hammer GL, Hayman PT. 2002. Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. *Agricultural Systems* 74: 393-414
114. Roncoli C, Jost C, Kirshen P, Sanon M, Ingram KT, et al. 2009. From accessing to assessing forecasts: an end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). *Climatic Change* 92: 433-60
115. Cash D, Buizer J. 2005. Knowledge-Action Systems for Seasonal to Interannual Climate Forecasting: Summary of a Workshop. *Roundtable on Science and Technology for Sustainability, Policy and Global Affairs*
116. Ray AJ, Garfin GM, Wilder M, Vásquez-León M, Lenart M, Comrie AC. 2007. Applications of monsoon research: Opportunities to inform decision making and reduce regional vulnerability. *Journal of Climate* 20: 1608-27
117. Sheppard SRJ, Shaw A, Flanders D, Burch S, Wiek A, et al. 2011. Future visioning of local climate change: A framework for community engagement and planning with scenarios and visualisation. *Futures* 43: 400-12
118. Cohen SJ, Sheppard S, Shaw A, Flanders D, Burch S, et al. 2012. Downscaling and visioning of mountain snow packs and other climate change implications in North Vancouver, British Columbia. *Mitig Adapt Strateg Glob Change* 17: 25–49
119. Sheppard SRJ. 2005. Participatory decision support for sustainable forest management: a framework for planning with local communities at the landscape level. *Canadian Journal of Forest Research* 35: 1515–26
120. Schroth O, Hayek UW, Lange E, Sheppard SRJ. 2011. Multiple-Case Study of Landscape Visualizations as a Tool in Transdisciplinary Planning Workshops. *Landscape Journal* 30: 53-71
121. Changnon SA. 2004. Changing uses of climate predictions in agriculture: implications for prediction research, providers, and users. *Weather Forecasting* 19: 606-13
122. Cobon D, Bell K, Park J, Keogh D. 2008. Summative evaluation of climate application activities with pastoralists in western Queensland. *Rangeland Journal* 30: 361-74
123. Rice JL, Woodhouse CA, Lukas JL. 2009. Science and decision making: water management and tree-ring data in the western United States. *Journal of the American Water Resources Association* 45: 1248-59
124. Tribbia J, Moser SC. 2008. More than information: what coastal managers need to plan for climate change. *Environmental Science & Policy* 11: 315-28
125. Nonaka I. 1994. A Dynamic Theory of Organizational Knowledge Creation. *Organization Science* 5: 14-37
126. Ingram KT, Roncoli C, Kirshen PH. 2002. Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. *Agricultural Systems* 74: 331-49
127. Ranis G. 2005. *The evolution of development thinking: Theory and policy*. Presented at 16th Annual World Bank Conference on Development Economics, Washington, DC
128. Lemos MC, Dilling L. 2007. Equity in forecasting climate: can science save the world's poor? *Science and Public Policy* 34: 109-116

129. Broad K, Pfaff A, Taddei R, Sankarasubramanian A, Lall U, de Souza FD. 2007. Climate, stream flow prediction and water management in northeast Brazil: societal trends and forecast value. *Climatic Change* 84: 217-39
130. Callahan B, Miles E, Fluharty D. 1999. Policy implications of climate forecasts for water resources management in the Pacific Northwest. *Policy Sciences* 32: 269-93
131. Goddard L, Aitchellouche Y, Baethgen W, Dettinger M, Graham R, et al. 2010. Providing seasonal-to-interannual climate information for risk management and decision-making. *Procedia Environmental Sciences* 1: 81-101
132. Meinke H, Nelson R, Kokic P, Stone R, Selvaraju R, Baethgen W. 2008. Actionable Climate Knowledge: from analysis to synthesis. *Climate Research* 33: 101-10
133. Morss R, Wilhelmi O, Downton M, Gruntfest E. 2005. Flood Risk Uncertainty & Scientific Information for Decision-making: Lessons from an interdisciplinary project. *Bull. Am. Met. Soc.* 86: 1594-1601
134. Lemos MC. 2008. What influences innovation adoption by water managers? Climate information use in Brazil and the US. *Journal of the American Water Resources Association* 44: 1388-96
135. Snover AK, Hamlet AF, November DPL. 2003. Climate-change scenarios for water planning studies: Pilot applications in the Pacific Northwest. *Bulletin of the American Meteorological Society* November: 1513-18
136. Lowrey J, Ray A, Webb R. 2009. Factors influencing the use of climate information by Colorado municipal water managers. *Climate Research* 40: 103-19
137. Broad K, Pfaff ASP, Glantz MH. 2002. Effective and equitable dissemination of seasonal-to-interannual climate forecasts: Policy implications from the Peruvian fishery during El Nino 1997-98. *Climatic Change* 54: 415-38
138. NRC. 2009. Informing Decisions in a Changing Climate--Panel on Strategies and Methods for Climate-Related Decision Support. Washington, DC: National Academies Press

ACRONYMS

GFCS	Global Framework for Climate Services
HEI	Health Effects Institute
IPCC	Intergovernmental Panel on Climate Change
MEA	Millennium ecosystem assessment.
NAPAP	United States National Acid Precipitation Assessment Program
OTA	Office of Technology Assessment
RISA	Regional Integrated Sciences and Assessment
USNA	United States National Assessment of the Potential Impacts of Climate Change

GLOSSARY

Science-policy model: conceptual means to simplify and explain the interactions and boundaries of science production and society or policy-/decision-making

Postnormal science: postnormal science is both a framework (Funtowicz and Ravetz 1993) and a practical approach (Turnpenny, Jones et al. 2011) for problem situations in which stakes are high and science uncertain. In postnormal science, scientific knowledge alone is not enough to solve societal problems and constituents need their own forms of knowing to better evaluate their risk situation

Boundary organization: organizations that facilitate the interaction between science producers and users

Knowledge system: encompass programs and institutional arrangements that effectively harness science and technology to improve decision making

Scientific assessment: organize, evaluate, and integrate expert knowledge to inform policy or decision making

Figure Captions

Figure 1 The evolution in the complexity in knowledge production and user participation. On the vertical access, the complexity of knowledge production increases from low (where production is predominately focused on increasing our fundamental knowledge) to high complexity (where production aims to help solve societal problems). On the horizontal axis, the complexity of user participation changes from low to high as users become increasingly active agents in the knowledge creation process.

Figure 2 Matrix of user types as a function of proactivity for obtaining and using information and users' decision environment.