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Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy

Lisa Dilling [a,*], Maria Carmen Lemos [b]

[a] Center for Science and Technology Policy Research, CIRES, and Environmental Studies Program, University of Colorado, 1333 Grandview Ave., UCB 0488, Boulder, CO 80309, United States

[b] School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109, United States

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ABSTRACT

In the past several decades, decision makers in the United States have increasingly called upon publicly funded science to provide "usable" information for policy making, whether in the case of acid rain, famine prevention or climate change policy. As demands for usability become more prevalent for publicly accountable scientific programs, there is a need to better understand opportunities and constraints to science use in order to inform policy design and implementation. Motivated by recent critique of the decision support function of the US Global Change Research Program, this paper seeks to address this issue by specifically examining the production and use of climate science. It reviews empirical evidence from the rich scholarship focused on climate science use, particularly seasonal climate forecasts, to identify factors that constrain or foster usability. It finds, first, that climate science usability is a function both of the context of potential use and of the process of scientific knowledge production itself. Second, nearly every case of successful use of climate knowledge involved some kind of iteration between knowledge producers and users. The paper argues that, rather than an automatic outcome of the call for the production of usable science, iterativity is the result of the action of specific actors and organizations who 'own' the task of building the conditions and mechanisms fostering its creation. Several different types of institutional arrangements can accomplish this task, depending on the needs and resources available. While not all of the factors that enhance usability of science for decision making are within the realm of the scientific enterprise itself, many do offer opportunities for improvement. Science policy mechanisms such as the level of flexibility afforded to research projects and the metrics used to evaluate the outcomes of research investment can be critical to providing the necessary foundation for iterativity and production of usable science to occur.

1. Introduction

As the problem of climate change rises in public policy agendas around the world, the need for robust science to inform policy design also increases. And while the production of climate science has steadily grown (NRC, 2007, p. 94; IPCC, 2007), in the United States, its usability remains relatively limited in terms of decision support and policy design (NRC, 2009a,b). For example, in 1990, the United States Congress established in law the U.S. Global Change Research Program (USGCRP) and called for the provision of "usable information on which to base policy decisions relating to global change" (US Congress, 1990). The law referred to usable information as knowledge that could be "readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change" (Ibid.). However in both provisions, the US Congress did not specify what it meant by usable, nor did the law suggest how the program should evaluate its effectiveness in terms of usability (Pielke, 1995).

Funded by the federal government through 13 different agencies,[1] through the years, the USGCRP[2] has mostly focused on fundamental science. Until 2009, the Program's implementation was organized around seven main scientific priorities (climate dynamics, ecosystems, atmospheric composition, the water cycle, the carbon cycle, land use change, and human dimensions) and operationalized by seven interagency working groups (one for each element).[3]

* Corresponding author. Tel.: +1 303 735 3678; fax: +1 303 735 1576.
E-mail address: ldilling@colorado.edu (L. Dilling).

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[1] For example, National Oceanographic and Atmospheric Administration (NOAA), Environmental Protection Agency (EPA), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), etc. For a complete list of agencies and working groups see, Our Changing Planet 2010, the budget document accompanying the President's budget request for the program from 1989 to the present.

[2] Also known as the US Climate Change Science Program—CCSP from 2002–2008.

[3] These categories can be found in the annual report *Our Changing Planet*.

A committee—chaired by a high level member of one of the participating agencies and under the auspices of the Executive Office of the President (EOP)—guides the program and a small integration office coordinates its activities. The budget for the USGCRP is allocated to each agency independently, although there is some effort to coordinate activities through the EOP, the interagency working groups, and the Coordination and Integration office. Although the level of emphasis on the scientific themes has changed over time (for example to expand the scope of human dimensions of climate change or to boost research focusing on decision-making tools), research focusing on physical and environmental aspects of climate has overwhelmingly dominated the program's budget (NRC, 2009b; Dilling, 2007). And with the exception of the National Climate Assessment completed in 2000, the input of potential users of the information in shaping the USGCRP research agenda has been limited (NRC, 2007).

While the scientific accomplishments of the USGCRP in understanding the climate system have been amply acknowledged (NRC, 2007, 2010), in recent years, the Program has come under greater scrutiny both from those who first created it (the U.S. Congress) and from scholars who have analyzed different aspects of its design and implementation (Lambright, 1997; NRC, 2009b, 2010; Pielke, 1995). In 1992 and 2002, Congress critiqued the USGCRP for being "less than successful at developing information that is useful to policy-makers and resource managers in making informed decisions" (Pielke, 1995, HCS, 2002, p. 5). Five years later, a review from the National Research Council of the US National Academy of Sciences (NRC/NAS), found that "inadequate progress has been made in synthesizing research results, assessing impacts on human systems, or "*providing knowledge to support decision making and risk analysis*" (emphasis added, NRC, 2007, p. 34). In 2009, two other NRC/NAS reviews have reiterated that the program has fallen short from the goal of supporting policy and decisions on the ground (NRC, 2009a,b).

Central to this critique is how one evaluates the usability of science, that is, what it means for science to be usable in the context of decision-making. While basic science may become applied science in the future, or eventually support whole new industries or technologies that we cannot even imagine today (Stokes, 1997), we argue that its function differs from that implied by the call for usable science for decision making. Alternatively, usable science is that produced to contribute directly to the design of policy or the solution of a problem (Lemos and Morehouse, 2005; NRC, 2009a,b; Weiss, 1978). This implies a much more specific, time sensitive role for science to be used in supporting decisions as they exist today or in the near future, and appears consistent with the US Congress' intent that the USGCRP provide information "readily usable by policymakers attempting to formulate effective strategies." In this context, it is not about which science is more important or about usable science replacing basic science—both are necessary and many times complement each other (Lemos and Morehouse, 2005; NRC, 2010). Rather, we focus particularly on usable science for decision making as stated by the Global Change Research Act, and the USGCRP (whose mission includes research, education, communication and *decision support* [emphasis added]).[4]

In this paper, we suggest that usability exists within a range in which each use is defined by a perception of usefulness and the actual capacity (e.g. human and financial resources, institutional and organization support, political opportunity) to use different kinds of information. In a recent paper, Lemos and Rood (2010, p. 673) describe this range by arguing that

> (...) different actors perceive the usefulness of scientific information differently. Scientists, for example, when choosing the focus of their research, may make an assumption of what they think decision makers need and hope their work will meet that need. Users, in turn, may define their need differently. However, scientists and users do not uniformly make the same assumption about what they think is useful and what they know is usable. Thus, some scientists' assumptions may be closer to users' definition of need, while others' may be farther away. In this sense, there is a range of perceptions of usefulness and usability.

Providing information that is "readily usable" for decision making must therefore navigate and bridge any differences that might exist between what scientists might think is useful, and what is actually usable in practice. This entails establishing a shared vision of what knowledge is usable in a given decision process. We can think of the production and uptake of scientific knowledge as a pull–push process in which different conditions, mechanisms and institutions shape ultimate usability. Here we argue that usability is a function of both how science is produced (the push side) and how it is needed (the pull side) in different decision contexts. We further suggest usability is most effectively pursued through deliberate science policy design and implementation, or "reconciling supply and demand," as needs for information are often not well met through the independent production of scientific knowledge alone (Sarewitz and Pielke, 2007). One critical aspect of this design is the creation of the conditions and mechanisms that enable iterativity, that is, the purposeful and strategic interaction between climate knowledge producers and users so as to increase knowledge usability (Lemos and Morehouse, 2005). In this article, we contend that the creation of these conditions and mechanisms is predicated on the action of organizations and actors that take upon themselves the responsibility to build them. In other words, these actors and organizations 'own' the task of fostering iterativity rather than expecting it to fall on someone else's shoulders or to be a consequential outcome of the call for the creation of usable science alone. And whereas in some cases factors constraining or fostering use of climate information may be outside the purview of what the scientific enterprise can influence and control (e.g. organizational constraints, lack of human resources, lack of political support), in other cases, they might be within the scope of what science policy can effect. Hence, to produce usable science, effective science policy should foster iterativity not only by purposefully incentivizing producers and users to own the task of creating it but also by eliminating the constraints that inhibit it.

In the next few sections, we explore opportunities and constraints for science use both in the way science is produced as well as in the way it is needed and used. We rely on evidence from different areas of climate information use but especially seasonal climate forecasting (SCF), about which there is a rich empirical literature. We aim at exploring evidence-based assumptions of different factors that influence the likelihood of climate science being used in decision making and policy. First, we synthesize 'lessons learned' from the literature—both from a more general perspective and from the perspective of climate science—seeking to understand the factors that shape information use; second, we explore how these lessons can inform climate science policy. In section two, we briefly discuss different modes of science production and illustrate the models that inform this analysis. Section three summarizes the factors constraining and fostering climate science use based on the empirical literature. In section four, we speculate how lessons learned from empirical cases can inform the design of science policy to foster the usability of climate science for decision-making.

[4] USGCRP Program Website: http://www.globalchange.gov/about/overview (last accessed October 29, 2010).

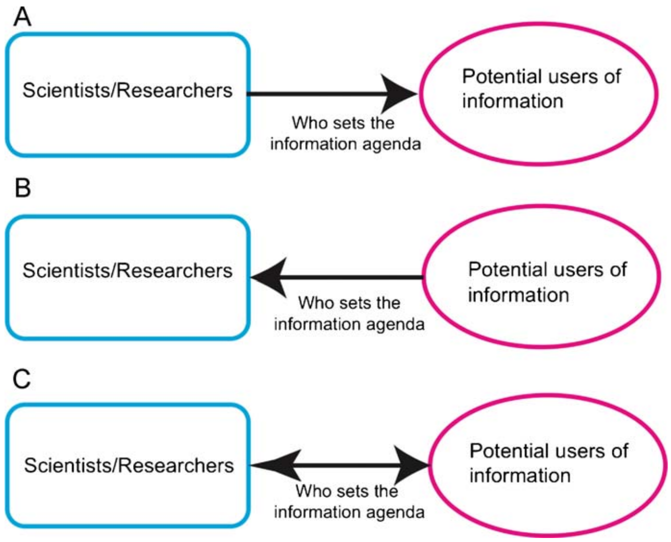

Fig. 1. (A) Science "Push." Researchers and information providers set the agenda for what type of science is produced and disseminated. (B) Demand "Pull." Priorities in the generation of new knowledge are set by those making decisions outside of the scientific community. (C) Co-production of knowledge requires iterativity between scientists and potential users/stakeholders.

2. Modes of science production

There is a long tradition of scholarship focusing on different models of science creation and its applicability to the solution of problems or the design of public policy.[5] In general, scholars identify three main modes of science–policy interaction. The first model is characterized by a "science push", that is, the pursuit of knowledge itself drives scientific production and the applicability of this knowledge in the solution of problems, while desirable, is not always assumed nor a necessary condition for its funding (Stokes, 1997). A second approach is characterized by the emergence of a "demand pull", that is, in pursuit of a solution to problem, science is commissioned or sought out by stakeholders. In these cases, the expectation that the science produced is more readily applicable is higher, even if use is not straightforward (Weiss, 1978). The downside of purely a "demand pull" model is that stakeholders may demand information which is not feasible to produce or scientifically robust (Sarewitz and Pielke, 2007). A third mode combines "science push" and "demand pull", in a co-production model where the research agenda is shaped in an ongoing, iterative fashion between knowledge producers and users (Agrawala et al., 2001; Lemos and Morehouse, 2005). In this model, although the initial impetus from information production often comes from the science community, through close iterativity with potential users, knowledge is co-produced. This knowledge, in many cases, better fits users' needs than that produced by more traditional models. A critical issue in these models is who drives the agenda for what knowledge is produced (Fig. 1). In the science push model, for example, information may be seen as *useful* by scientists, but ultimately not *usable* by users. This first model represents the "loading dock" approach, where information that may or not be relevant, is simply released and may not ever be "picked up" due to a range of factors (Cash et al., 2006).

3. The elements of usable climate science for decision making

The usability of science for decision-making has been the focus of research for many years (see for example, Clark and Majone, 1985; Jasanoff and Wynne, 1998; Sarewitz, 1996; Stokes, 1997; Weiss, 1978). The use of seasonal climate information in particular has been studied across regions in many different sectors, including agriculture, water, and disaster response. In the past twenty years, great advances in the ability to predict El Nino Southern Oscillation (ENSO) events up to a year ahead of time led to growing expectations that these forecasts would be useful and usable for decision making in a number of climate-sensitive sectors (Glantz, 1996; Ropelewski and Lyon, 2003; Zebiak and Cane, 1987; Agrawala et al., 2001; Ropelewski and Halpert, 1987). Yet, in most of the cases documented in the literature, while the use and interest in forecasts has increased over the last decade (Cobon et al., 2008; Hartmann et al., 2002; Beller-Simms et al., 2008; Changnon, 2004; Steinemann, 2006; Lowrey et al., 2009), constraints to forecast use abound. This has generated widespread disappointment; as expressed by Ed Miles and his colleagues "every empirical study conducted to date has shown that climate forecasts are not used to their full potential" (Miles et al., 2006, p. 19616).

Overall, the empirical literature focusing on climate forecast use finds that usability is influenced by many factors. We separate these factors into *contextual* to refer to the context where information is needed and used and *intrinsic* to refer to the conditions shaping the production of information itself. While we recognize that these factors often intersect and influence each other, we separate them for analytical purposes. For our analysis we reviewed over 30 empirical studies focusing on seasonal climate forecast use for the past twenty years (Table 1).

3.1. Contextual factors

Across the cases reviewed, we find that the institutional or organizational setting shaping information use is critical to usability. Institutional barriers to information use can be formal and informal. Examples of formal institutional barriers include inflexible institutional decision rules, such as those found in water allocation practices in the U.S. Pacific Northwest, wildland fire mitigation, and flood risk decision making in the US (e.g. Callahan et al., 1999; Corringham et al., 2008; Morss et al., 2005; Pulwarty and Redmond, 1997). Informal institutional barriers include preference for established and tested practices instead of unproven innovations such as seasonal forecasts. In Zimbabwe, subsistence farmers who depended on external institutions for obtaining seed each year did not use forecasts, preferring instead to rely on traditional methods and seed combinations, planting the same selection of varieties every year, or planting more of whatever variety did best in the previous year (Patt and Gwata, 2002).[6] In contrast, where forecasts have been used successfully in organizations, it has been due to (i) specific interventions such as the creation of fora or networks where forecasters and potential users come together; (ii) users' perception of specific benefits such as cost savings; (iii) the existence of organizational resources such as technical capacity to understand climate information (Beller-Simms et al., 2008; Everingham et al., 2008; Feldman and Ingram, 2009; Hartmann et al., 2002; Pagano et al., 2002; Lowrey et al., 2009; Pagano et al., 2001); or (iv) the presence of institutional support for incorporation of climate considerations in planning (e.g. in the water sector) (Kirchhoff, 2010; Lemos, 2008).

[5] For a thorough review of this scholarship, especially related to climate science, see Jasanoff and Wynne (1998).

[6] Patt and Gwata (2002) did note one exception when forecasts might have been more useful to a decision—when the price of seed rose so much that farmers were forced to choose a pathway outside of their normal practice.

Table 1
Empirically based literature reviewed on the use of seasonal climate forecasts.

Study	Region	Use of SCFs
Agrawala et al. (2001)	International Research Institute—several regions and sectors	Often not used, multiple constraints
Blench (1999)	Farmers in Southern Africa	Often not used
Broad and Agrawala (2000)	Famine prevention in Ethiopia	Underutilized
Broad et al. (2002)	Various sectors in Peru	Selective use, unequal outcomes
Callahan et al. (1999)	US Pacific Northwest	Only used as background information
Carbone and Dow (2005)	Community water system managers, US	Rare use, many barriers
Cash et al. (2006)	Southern Africa and Pacific Islands	Southern Africa, not well used; Pacific Islands, well used
Changnon and Changnon in Leetmaa (2003)	Agribusiness in US	Not used to full benefit
Changnon and Vonnahme (2003)	Water and Agriculture in US	Used, but forecaster credibility suffered b/c incorrect forecast
Changnon (2004)	Agribusiness in United States	Some use, some barriers
Changnon and Changnon (2010)	US Weather Derivatives and Risk Models	Successful use
Cobon et al. (2008)	Pastoralists in Australia	Some use, some barriers
Corringham et al. (2008)	Fire management in US	Rare use, accuracy questioned
Everingham et al. 2008	Farmers in Australia	Yes with participatory methods
Feldman et al. (2008)	Cases across the US	Yes, different sectors
Hartmann et al. (2002)	Various sectors, Western US	Some use, much skepticism
Ingram et al. (2002)	Farmers in Burkina Faso	Limited, but interested
Lemos et al. (2002), Lemos (2003)	Drought response in Northeast Brazil	Yes, but not always beneficial
Lemos and Morehouse (2005)	Multiple sectors in Southwest U.S.	Yes, if co-production effort is expended
Letson et al. (2001)	Farmers in Argentina	Some use but obstacles such as scale and reliability exist
Lowrey et al. (2009)	Water managers in the US mountain West	Increasing use with ongoing co-production
Orlove et al. (2004)	Multiple sectors in Peru	Yes, with differences among groups
Pagano et al. (2001)	ENSO in Southwest U.S.	Yes, but not to full potential
Pagano et al. (2002)	Southwest U.S.	Yes, with a number of barriers
Patt and Gwata (2002)	Farmers in Zimbabwe	Not directly useful
Power et al. (2005)	Water managers in Australia	Yes
Pulwarty and Melis (2001)	Water management in the US	Yes, successful
Pulwarty and Redmond (1997)	Water managers in U.S.	No
Rayner et al. 2005	Water managers in US	Very limited, many constraints
Sonka et al. (1992)	U.S. agribusiness	Qualified yes, only as background information
Steinemann (2006)	Water managers in US	Yes with translation assistance
Tarhule and Lamb (2003)	Farmers in West Africa	No, or very limited
Vogel and O'Brien (2006)	Farmers in Southern Africa	Very limited, many constraints

Second, in many cases, information might seem relevant in a general sense, but be less usable as it competes with many other factors shaping the decision context. In these cases, information might be germane, but ultimately is not used, either because forecasts are less important than other kinds of information given certain decision goals or because it does not 'fit' policy goals (Skolnikoff, 1999). For example, in the Ethiopian food crisis in 2000, even though donor countries were warned in advance of a potential pending famine due to forecasted drought in the region, they were slow to promise food aid because they hoped to use aid as leverage to quell an ongoing armed conflict in the region (Broad and Agrawala, 2000). In this case, information regarding the impending drought was clearly relevant, but ultimately other goals, i.e. maintaining leverage over the situation, prevented effective use of the information to mitigate large-scale famine. For some water managers in the US Pacific Northwest and US Southwest, other kinds of information and planning priorities edge out climate information use (Kirchhoff, 2010). In contrast, high levels of interaction between water managers and paleoclimate scientists created an increasing demand for this kind of information from managers planning for longterm drought response in the US Southwest (Engle, 2010; Kirchhoff, 2010).

Third, organizational culture and individual reward structures can play a large role in whether or not decision-makers will use climate knowledge to inform their decisions (Carbone and Dow, 2005; Lemos, 2008; Pagano et al., 2001; Rayner et al., 2005). For example, Rayner et al. (2005) found that water managers in three different U.S. cities were not interested in using forecasts because of a combination of conservatism toward new ideas, the potential for public criticism, and the perception that forecasts were not relevant to improving ultimate outcomes. In the US Southwest, operational water managers resisted asking for additional resources to respond to an El Niño forecast because they feared that resources would be reduced in non-El Niño years, or that they would appear unprepared by comparison in other years (Pagano et al., 2001).

Fourth, the cultural context of information use critically shapes its adoption (Lemos, 2008; Rogers, 1995). Take for example the issue of forecast uncertainty. Despite advances in forecasting, predictions still carry high degrees of uncertainty depending on the variable that is forecast, the time of year the forecast is issued, the region, and the length of lead-time (Lemos and Rood, 2010). In Australian water management and in US agribusiness, decision makers were quite aware of the uncertainty of information and yet able to accept it as part of using the information in their decision making (Changnon, 2004; Cobon et al., 2008; Power et al., 2005). In contrast, those who are risk averse and vulnerable may prefer not to use forecasts (but see Orlove et al., 2004). In Burkina Faso, individuals were not interested in relying on forecasts "until they have proven themselves reliable" (Ingram et al., 2002). In NE Brazil, farmers many times prefer to rely on traditional rain prophets forecasts than on the ones released by the state meteorological agency (Lemos et al., 2002).

Finally, the availability of realistic alternative courses of action is a critical factor shaping usability. In this case, even if information is theoretically useful, it may not be usable if potential users lack the material means to implement alternatives that seasonal climate forecasting supports (Lemos et al., 2002). For example, in the Sahel, use is still constrained by lack of access to information, but, more importantly, by the ability of potential users to respond to forecast information (Glantz, 1977; Tarhule and Lamb, 2003). In Burkina Faso, farmers were limited in their ability to respond to seasonal forecasts in the absence of additional basic agricultural technologies, such as plows, new crop varieties, and fertilizers (Ingram et al., 2002).

3.2. Intrinsic factors

On the scientific production side, other factors are documented to influence usability. First, although scientists cannot (and should not be expected to) control the decision context in which their information will be used, across case studies, one common factor that influenced usability was the fact that information producers were sensitive to understanding the specific decision contexts they were targeting (Broad et al., 2007; Cash et al., 2003; Lemos and Dilling, 2007; Morss et al., 2005; Steinemann, 2006; Stern and Easterling, 1999; Vogel and O'Brien, 2006). Equally important are the users' perspectives of the utility of the science for their own decision processes. One way this mutual understanding is enhanced is through repeated interactions between researchers and potential information users (Hammer, 2000; Lemos and Morehouse, 2005). For example, among water managers in the US Pacific Northwest and US Southwest regions, higher levels of interaction between producers and users significantly increased rates of use of climate science (Kirchhoff, 2010).

Second, issues of spatial and time scales and level of skill of climate information production also influence its usability. While most seasonal forecasting has better skill at larger scales, users perceive lower scales (regional, local) as much more useful (Broad and Agrawala, 2000; Broad et al., 2002; Leetmaa, 2003; Patt and Gwata, 2002; Rayner et al., 2005; Letson et al., 2001; Jagtap et al., 2002). And beyond scale, decision-makers often want information that is not only specific to their own region but also delivered in the context of what is happening in their surrounding area (Dow et al., 2009). The timing of climate information release can also be critical for whether or not it is usable (Cash et al., 2006; Changnon and Vonnahme, 2003; Corringham et al., 2008; Hartmann et al., 2002; Lemos et al., 2002; Orlove et al., 2004; Rayner et al., 2005; Ray et al., 2007). For example, in the South Pacific, forecasters were able to release warnings about an impending El Niño to the local authorities and vulnerable groups with enough lead-time to prepare, but not so much time that people became complacent or forgot the information (Cash et al., 2006). The time of the year in which the forecast is delivered can also shape usability (Hartmann et al., 2002; Pulwarty and Redmond, 1997; Ray et al., 2007). The skill of a SCF itself can vary depending on the season of the year. For example, between March and June climate variability is difficult to predict, even while its effects might be extreme (e.g. Barnston et al., 1999). Moreover, users often mention the level of skill of forecast as a perceived barrier to use, meaning how accurate the forecast is in predicting what happens in a season (Carbone and Dow, 2005; Changnon, 2004; Corringham et al., 2008; Letson et al., 2001; Ritchie et al., 2004). For example, in the US Southwest, forecasters found that potential users were as interested in evaluations of the skill of the forecast as in the forecasts themselves (Hartmann et al., 2002; Pagano et al., 2002). Moreover, the very meaning of forecast accuracy differs between scientists (who are interested in forecast "skill") and decision makers (who are interested in how well the forecast performs for variables of interest to them (Ritchie et al., 2004; Steinemann, 2006). In addition, better forecast skill does not necessarily mean better forecast use as policy agendas can influence use much more strongly than skill (Lemos, 2003). Some studies have found that even a SCF with perfect skill may not be useful because of other constraints in the context such as institutional barriers (e.g. Pulwarty and Redmond, 1997).

Third, the level of trust of users in the forecasts and their perception of how legitimate they are can be critical to foster usability (Broad et al., 2002; Callahan et al., 1999; Carbone and Dow, 2005; Cash et al., 2003; Lemos et al., 2002; Letson et al., 2001; Patt and Gwata, 2002; Pulwarty and Redmond, 1997). In Peru, forecast reports issued from multiple sources conflicted, thus reducing the confidence of decision makers in using any of the information (Broad et al., 2002). In contrast, factors such as distrust, misunderstanding, and perceived irrelevance can be countered by developing processes that build relationships and social capital among the different parties involved (McNie, 2007; Patt and Gwata, 2002). In their thorough review of climate information use in integrated assessments, Cash et al. (2003) found that credibility, legitimacy and salience were strong determinants of information use.

Finally, information needs to be accessible. There are many dimensions to accessibility, including availability (i.e. users can obtain the forecasts), language/communication, graphical representations and format (Dow et al., 2009; Hartmann et al., 2002; Pagano et al., 2001), and understanding and comprehension (Lemos et al., 2010). Empirical research shows that users have difficulty understanding and translating probabilistic information into action (Nicholls, 1999; Hammer, 2000). In NE Brazil, forecasters tried different formats of information release until settling for geoclimatic maps that avoided deterministic simplifications of the forecast (Lemos et al., 2002). In the US Southeast, forecasters found that "translating" forecasts into specific probabilities for specific crops made them more user-friendly (Carbone and Dow, 2005).

4. Expanding the options for creating usable science

What the rich literature reviewed above suggests is that many of the constraints and limitations of SCF use originate in the lack of a broader understanding of the decision-making environments where climate information is supposed to be used. It also shows that in many of the cases of successful use of SCF, interaction between producers and users of information played a positive role. In this context, the influence of iterativity in increasing usability is twofold. First, by improving producers' understanding of the decision-context of users, iteration allows for better customization of knowledge to meet specific needs. Second, through iteration, producers and users may uncover new uses for climate knowledge that might not have been identified before. And while many constraints and opportunities for knowledge use maybe beyond the control of the science production enterprise, a better understanding of users' decision contexts may critically influence the ability of producers to meet users' expectations of climate knowledge as decision support information. In the next sections, we explore a few factors and mechanisms we suggest may enhance the ability of producers and users to increase the usability of climate science in different contexts.

4.1. Owning the problem and setting common goals

As suggested above, iterativity between producers and users matters. However, many times, the conditions and mechanisms necessary for iterativity to happen are simply not there. We argue that part of the problem is that, in most cases, neither knowledge producers nor users are interested or equipped to create and implement these conditions. Indeed, the institutional spaces or actual organizations available to make the link between producers and potential consumers of science are often lacking (Tarhule and Lamb, 2003; Vogel and O'Brien, 2006). In other words, neither producers nor users "own the problem" of producing usable knowledge. For example, the scientific enterprise often sees its job as producing knowledge only, rather than producing information that is useful in decision-making. As one senior official of the committee leading the USGCRP put it, "whether that [knowledge] can translate into actions ... is not really the business of the Subcommittee on Global Change Research. That is where our job ends, and, thank God, in some sense, other people's job starts"

(HCSST, 1992; p. 93). However, if no-one owns the job of creating usable science, the delivery of effective decision support will be inadequate, as observed by several National Research Council/ National Academy studies (NRC, 2009a,b). In this context, the connection or institutional space to understand what decision makers need, and what researchers are able to provide, simply may not exist. One of the key challenges to producing usable science may therefore be to determine who or what organization needs to take on the process of connecting science to decision-making.

In some of the cases reviewed, this role was played by the private sector, which created the linkages between climate knowledge and decision-making. For example, the use of SCFs in agribusiness and weather derivatives demonstrates that when private interests see a benefit and can afford to invest in personnel, SCFs are incorporated into business decisions through sophisticated modeling and interpretation of climate data (Changnon and Kunkel, 1999; Changnon and Changnon, 2010). Private sector ownership of creating use from science is of course one successful model that is motivated by the goal of making a profit or even the risk of high losses.

Experiences in the public sector are mixed. In several of the cases reviewed, academic and scientific organizations have been funded specifically to improve the use of SCFs and other climate-related data in societal decision processes in different sectors such water management utilities, meteorological services, state agencies, and the like (e.g. Hartmann et al., 2002; Kirchhoff, 2010; Jagtap et al., 2002; Lemos and Morehouse, 2005; Lowrey et al., 2009; Miles et al., 2006; Pagano et al., 2001; Steinemann, 2006). In some cases, this long-term commitment resulted in increasing trust, increasing use of SCFs and an overall positive assessment of usable science from the researchers involved (e.g. Cash et al., 2006; Everingham et al., 2008; Kirchhoff, 2010; Lowrey et al., 2009; Steinemann, 2006).

Other evidence shows that there can be resistance to utilizing SCFs within the potential user community for a wide variety of reasons, including lack of trust, perceived lack of relevance, perverse incentives, and perceived lack of skill (e.g. Carbone and Dow, 2005; Cobon et al., 2008; Corringham et al., 2008; Lemos and Rood, 2010; Letson et al., 2001; Pagano et al., 2001). In all these cases, studies concluded that some form of collaboration and cooperative work would be necessary to design and tailor information to fully take advantage of the opportunities that SCFs represent. Without a sense of ownership of the process of creating usable science, and accountability for outcomes on both the scientific production side and the user community side, it is likely that opportunities will continue to be missed (Corringham et al., 2008; Pagano et al., 2001).

Finally, empirical evidence suggests that both users and producers should be tackling the ownership of usable science production. Even the most useful science cannot be foisted upon an unwilling organization or user. One option to make programs more effective at generating usable science is to involve stakeholders and decision makers from the start in helping to generate priorities for research and metrics for success. For example, many of the US Regional Integrated Sciences and Assessment (RISA) projects funded by NOAA actively involve stakeholders in setting research directions, either through participating in workshops, conversations with researchers, or requiring stakeholder consultation as part of the proposal process (Lemos and Morehouse, 2005; McNie, 2008). In certain areas such as water management, the level of iteration and interaction with users has been found to be critical to increase usability (Kirchhoff, 2010).

4.2. Establishing innovative mechanisms to foster iterativity

As reviewed above, empirical evidence shows that most successful SCF use is mediated, translated and/or co-produced between potential users and producers of forecasts. It also suggests that ongoing, iterative relationships critically shape the usability of science. The USGCRP has been critiqued for lacking adequate mechanisms to facilitate these relationships, and indeed, the appropriate mechanisms for that program to develop have been said to be a matter for empirical research (NRC, 2009b). A wide range of means to accomplish this connection between producers and users of climate science exists in the SCF experience. Here we document the main institutional arrangements and mechanisms that have been shown to be able to do the job. These arrangements have varying degrees to which they might affect how the scientific information itself is created and how information is shared and disseminated. What is common between all of them, however, is that they connect users and producers albeit with different levels of iterativity, that is, the degree to which this connection affects how science is produced and used.

- *Information brokers*: Rather than a producer of climate knowledge, the broker is an intermediary between the users and the scientists, and is fluent in both worlds. Brokers have been very successful in the U.S. Pacific Island region where they have worked in the intersection of climate knowledge producers (at the University) and users (often public officials) to increase the usability of SCFs in planning and decision-making (Cash et al., 2006; McNie, 2007). The role played by brokers bridging science and use suggest the need to foster the education and training of a new kind of professional that is at least literate but ideally fluent in what it takes to understand both contexts (that is, of knowledge production and use) (Jacobs et al., 2005). It also suggests the need for science policy to build capacity in this intersection both through the creation of conditions for these professionals to emerge (e.g. through the support of interdisciplinary education programs or funding of science–policy integrated research) and through the design of institutional incentives for the creation of jobs for these professionals (e.g. through the support of co-production organizations such as the RISAs in the U.S.).
- *Collaborative group processes*: In some cases, where decision-making is highly distributed, with many groups vested in the outcome of a particular high stakes and complex process, climate information such as SCFs can be used to bring together disparate interests and organizations. Water allocation in the U.S. West is one such process. Fire management is another. For example, in the US, SCFs have been successfully used as part of a process established to bring together vested partners, such as the Glen Canyon Dam Adaptive Management Program (GCDAMP) (Pulwarty and Melis, 2001). In Australia, SCFs have been used as an element of the discussions in the scope of the Indian Ocean Climate Initiative (IOCI) (Power et al., 2005).
- *Embedded capacity*: In some cases, organizational capacities such as human resources, technical capacity, and leadership critically shaped usability of climate knowledge. For example, within some US Southwest water management organizations, ongoing relationships between scientists and operational managers in water management led both to the emergence of internal 'champions' or to the hiring of new people explicitly for the task of incorporating climate information into decision making (Lowrey et al., 2009; Pagano et al., 2001). Because managers often place higher confidence on internal products (i.e. forecasts) than externally generated ones, this strategy may be one of the most successful in institutionalizing the use of forecasts (Pagano et al., 2001). Similarly to information brokers, the role of these champions suggests a need to encourage the emergence and training of such professionals.
- *Boundary organizations*: Akin to an information broker, a boundary organization serves the function of working between

the worlds of research and use of science. However, through their size and capacity, they may have more resources to tailor information and produce value-added products than individual brokers (Guston, 2001; Cash, 2001). For example, a critical service such organizations can provide is the translation and customization of climate information to specific users. While working with water managers in the US Southeast, Steinemann (2006) showed that the translation of previously unusable NOAA-CPC issued forecasts into a "forecast precipitation index" by her organization resulted in information that could be used successfully and credibly in state drought decision making. Many of the RISA organizations have functioned as boundary organizations and served to connect decision makers with relevant science (Buizer et al., 2010; McNie, 2007). For example, in the U.S. Pacific Northwest, 15 years of research and relationship building have resulted in increased awareness of the impact of climate variability on various resources and incorporation of climate information into water management and coastal emergency preparedness (Buizer et al., 2010). What the literature on RISAs suggests is that the deliberate creation of boundary organizations driven by users needs critically influences usability in two main ways. First, it increases rates of use by producing and customizing information to those expressed needs. In this case, knowledge producers interact with potential users to solicit and understand their needs as they build their research agenda. Second, it influences usability by developing a new clientele for climate science. In this case, through interaction, science producers expose potential users to the possibilities of different kinds of science to inform different decisions (e.g. as in the case of paleoclimate science) even if the knowledge seems to not 'fit' needs at first (Kirchhoff, 2010; Lemos and Morehouse, 2005; McNie, 2008). In some cases, an existing organization emerges as the connection between research and potential users of SCFs. Meteorological agencies, for example, would seem to be a natural home for this activity, but in some cases, they have been less than effective (Cash et al., 2006; Lemos et al., 2002; Tarhule and Lamb, 2003; Vogel and O'Brien, 2006). Depending on their approach, they may perpetuate the "loading dock" mentality, rather than work to break down barriers between producers and users of science.

- *Knowledge networks*: Knowledge networks are comprised of policy makers, scientists, government agencies and non-governmental organizations that communicate with one another and share information across areas of practice, such as the network between land grant colleges, water irrigation districts and agricultural extension offices in the United States (Feldman and Ingram, 2009). These networks operate informally and can intersect with more formal boundary organizations. They may play a role in connecting different communities of practice and expanding the usability of different kinds of climate information.

4.3. Institutionalizing incentives for usable science in science policy practice

Owning the problem of creating usable science and establishing innovative mechanisms to foster iterativity has implications for science policies, that is, how we organize and carry out research. There may also be implications for how user communities and organizations evolve and change with respect to incorporating climate science (e.g. as in the case of water managers who have been working steadily with RISAs for several years). While many of the issues influencing the usability of science fall outside of the purview of science policy, we argue that others may be well within the scope of the things science policy can encourage, induce or create.

4.3.1. Acknowledging the need for flexible research agendas

In order to co-produce knowledge in an iterative fashion, research agendas (and researchers) need to be flexible to better meet the needs of decision-makers (Lemos and Morehouse, 2005). Creating usable science may therefore require adaptive research agendas that encourage risk taking and are a better match to the changing nature of problems and needs on the ground (NRC, 2009b, 2010; Pulwarty et al., 2009). Overall, analysts find the process of producing scientific knowledge to be fairly conservative, rewarding predetermined methods and incremental efforts rather than risky, unproven, innovative strategies (Travis and Collins, 1991; Wessely, 1998). While this system has proven sound for knowledge-driven science (science push), it may act as a constraint to co-produced science where flexibility and risk-taking both in agenda setting and personnel may be necessary. The USGCRP itself has been critiqued for its "entrenched" organizational barriers to expanding research agendas into the areas of human dimensions and informing decision making (NRC, 2009b). Expertise needs may change over the course of a project, and indeed, the very nature of the research itself may change with the evolution of problem definition and potential solutions. Finally, some projects would potentially need to be longer than the usual two or three year cycle favored by U.S. funding agencies in order to accommodate the length of time it takes to establish relationships with stakeholders and build trust (Miles et al., 2006; NRC, 2006).

4.3.2. Identifying success—the essential role of metrics

Currently, metrics for many science programs, even those targeted at producing usable science, focus on production of peer-reviewed papers or citations as the main metric of success (NRC, 2005). In this context, engaging stakeholders often represent an undue burden rather than an incentive to produce usable science since it does take additional time and skill (Lemos and Morehouse, 2005). Academic and government scientists in climate change science are generally encouraged to produce peer-reviewed papers, to increase citations, and to conduct fundamental science to reduce uncertainties. However, peer-reviewed papers are often not accessed directly by decision makers (e.g. Tarhule and Lamb, 2003). Depending on the context of use, usable science that seeks to meet users' needs may not be at the cutting edge of disciplinary science, but as Stokes (1997) argues, use-inspired basic research also can result in fundamental scientific breakthroughs (Stokes, 1997; Kammen and Dove, 1997). For example, in the SCF experience, a new climate mode was discovered as a result of a research path followed from a question posed by climate-affected stakeholders (Miles et al., 2006). Within academia, while many universities are increasingly encouraging outreach activities such as working with stakeholders and outside organizations, overall reward of these kinds of activities remains low.

While scientific merit is paramount as evaluation criteria of any research activity, it may be necessary to add a second dimension in the case of co-produced science. If usable science is indeed a goal, evaluating success in terms of usability and use may encourage science producers and users to engage in co-production. In this case, metrics need to also focus on other outcomes such as relationships with stakeholders, accessibility of knowledge, and especially, progress on specific societal outcomes. For the past decade, the USGCRP has focused on the reducing uncertainty in the fundamental science as a metric of success, but the limitations of this approach are well known (NRC, 2005). A recent NRC report (2005, p. 94) suggests that a broader suite of metrics evaluated in consultation with stakeholders could be "a valuable tool ... for further increasing [the program's] usefulness to society." In another example, one climate program at NOAA is refining its performance measures to include a focus on the percent of use of various types of research, and indicators of the Quality of

Relationship between those tasked with supporting decision making and potential users (Christerson, personal communication). Whereas these are more difficult to measure and do not map well to metrics for academic achievement, they can potentially be more useful in helping programs move in the right direction (Lemos and Morehouse, 2005; NRC, 2005, 2007). And where it may be difficult to judge whether usable science or decision support has been effective (Moser, 2009; Romsdahl and Pyke, 2009), it is critical to consider the question of what constitutes success in decision support up front when designing such programs (Moser, 2009).

5. Conclusion

Twenty years after its initiation, the USGCRP stands at a crossroads of opportunity. On the one hand, the Program has been critiqued in the recent past for providing inadequate decision support and for lacking the appropriate mechanisms to fully engage in research that might illuminate how to best rectify that deficiency. On the other hand, there have been some real advances made in understanding how to create usable science for decision making and how science policies can support such efforts effectively, particularly in the area of seasonal climate forecast use. The factors that enable or constrain the emergence of usable science can be thought of as either contextual, that is within the context of where the information is needed, or intrinsic, that is within the process of the production of science itself. Favorable conditions on both sides can critically influence the usability of science for decision making.

Empirical evidence from the use of seasonal climate forecasts suggests that iterativity between scientists and users of knowledge is critical to the successful production of usable science. Without a deliberate effort to create opportunities for iterativity, acknowledge user needs and orient programs accordingly, scientific organizations risk being ineffective "loading dock" style programs and potential users will continue to lack critical knowledge to inform their decisions.

However, one cannot assume that the job of connecting or co-producing scientific knowledge with users will happen automatically. Rather we argue that there needs to be a concerted effort to own the problem of producing usable science. Ownership of the problem of creating usable science rests both on scientific organizations and those organizations that might benefit from the knowledge produced. There are a wide variety of institutional arrangements and mechanisms, requiring different degrees of capacity and resources, that can help better connect scientific knowledge to users. They range from an embedded expert within a user organization to a full-fledged boundary organization that both carries out research and mediates between the world of science and users.

Finally, addressing the details of policies for usable science means we need to examine how the process of science works and whether it is conducive to fostering usable science. As the empirical literature suggests, simply identifying a potential use, or hoping that information might be useful, is not enough to ensure usability. Attention to the process of selecting and conducting projects, including the flexibility of the research agenda and of the research team can improve the responsiveness of research to user needs. Also of critical importance are the longevity and continuity of research projects and the metrics by which usable science programs are evaluated. Programs such as the USGCRP may want to consider metrics that more accurately reflect the importance of the co-production process and the perception of usability as judged by decision makers. Without considering how science policies enable or constrain the production of usable science, climate research programs will likely miss further opportunities to more effectively support climate-related decision making.

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