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Narrowing the climate information usability gap

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Climate-change-related risks pose serious threats to the management of a wide range of social, economic and ecological systems. Managing these risks requires knowledge-intensive adaptive management and policy-making actively informed by scientific knowledge, especially climate science[1]. However, potentially useful climate information often goes unused[1,2]. This suggests a gap between what scientists understand as useful information and what users recognize as usable in their decision-making. We propose a dynamic conceptual model to address this gap and highlight strategies to move information from useful to usable to reduce climate-related risks.

Worldwide, the complexity of environmental problems and their increasing negative effects on social and ecological systems have heightened the stakes for research that both increases understanding and informs potential solutions. Climate change is perhaps the most important of these problems, with potentially unprecedented damaging impacts on a wide range of systems and sectors[3]. In this context, even if a lack of climate information has not necessarily precluded decision-making in this area (see, for example, refs 4,5), scholars from different fields have suggested the need for urgent policy responses and adaptive management grounded by science[1]. However, despite both the considerable amount of climate change research made available in the past thirty years[6] and evidence that decision-makers at the local and resource management level (for example, agriculture, water, disaster response and urban planning) are actively seeking to increase their climate information uptake[7,8], there is a persistent gap between knowledge production and use[1,2].

In this Review, we argue that to narrow this gap we need to delve deeper into understanding the processes and mechanisms that move information from what producers of climate information ('producers' henceforth) hope is useful, to what users of climate information ('users' henceforth) know can be applied in their decision-making. In his now classic study, Stokes[9] defined both use-inspired basic research (in which consideration of both use and advancing fundamental understanding are high) and applied research (in which consideration of use is high and advancing fundamental understanding low) as useful because they tend to users' needs. In our conceptualization, we revisit Stokes to argue, theoretically and practically, for a distinction between useful and usable information that reflects the different ways that producers and users perceive scientific information. Indeed, producers may make the assumption that knowledge is useful when they engage in research they think users need (in Stokes's sense), but because they do not completely understand or know potential users' decision-making processes and contexts, the knowledge produced remains 'on the shelf'. Users, in turn, may not know or may have unrealistic expectations of how knowledge fits their decision-making and choose to ignore it, despite its usefulness. We recognize that producers and users are far from homogeneous in the way that they produce and use climate information, and suggest that it is precisely these different perceptions and understandings of useful and usable[5] that create the usability gap reflected in the low level of climate information use in the real world. Indeed, although all forms of user-inspired knowledge are in principle useful, they are not always usable, unless users and producers take specific steps to make them so[10].

Many scholars have tackled the usability gap from different and overlapping perspectives[11–17]. Some have focused on the push and pull factors of science production and decision-making, and others have examined institutions and processes at different scales that foster or constrain scientific information use (for example, politics, national organization of research and development, public engagement, stakeholder participation and deliberation). Scholars have shown that the level of interaction — or co-production of science and decision-making — between information producers and information users critically affects the rate of climate information use[8,11,18–19]. A series of studies has focused on how different factors (organizational, cultural, institutional, political, cognitive, behavioural and so on) characterizing knowledge, and those who use it, influence climate information uptake in specific contexts[8,20–25]. In their influential article, Cash *et al.* argue that information is usable only if perceived by users as salient, credible and legitimate[26]. Others have shown how organizations and different forms of information communication and dissemination (for example, boundary organizations and knowledge systems) influence how science fails or succeeds in supporting decision-making[15,26,27]. For example, in advocating for a new form of climate adaptation science that influences decision-making, Meinke *et al.* emphasize the role of highly participatory, context-specific dialogues aided by modelling approaches that bring together producers and users of knowledge across disciplines, and define climate impact as one of many stressors shaping users' decisions[28]. Finally, research has also focused on the role of uncertainty in decision-making and on the negative effect of the highly politicized context of climate policy-making on the use and public value of climate science[29,30].

Although we recognize the strength of this rich literature in elucidating different aspects of the usability gap and build on its constructs to inform our own model, we contend that so far there has been relatively little effort to explain how perceptions, willingness and ability to use information change through time, and how a particular piece of information goes from being useful to usable. In our model, we focus on the factors and actions that change users, producers and the character of information to increase use. We argue that usability depends on three interconnected factors: users' perception of information fit; how new knowledge interplays with other kinds of knowledge that are currently used by users; and the level and quality of interaction between producers and users. We propose different strategies to narrow the usability gap, including varying levels of interaction, value-adding, customization, and retailing and wholesaling of existing knowledge to meet users' needs.

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Table 1 | Summary of opportunities and barriers that affect usability derived from the literature.

	Barriers identified in the literature		Opportunities identified in the literature	
Fit	Not accurate and reliable Not credible Not salient	Not timely Not useful; not usable Excessive uncertainty	Accurate and reliable Credible Salient	Timely Useful; usable
Interplay	Professional background Previous negative experience Value routine, established practices, local knowledge Low or no perceived risk Difficulty incorporating information	Insufficient technical capacity (for example lack of models) Culture of risk aversion Insufficient human or financial capacity Legal or similar Lack of discretion	Previous positive experience Threat of public outcry; public pressure Perception of climate vulnerability Sufficient human or technical capacity More flexible decision framework	Technocratic insulation Water scarcity In-house expertise Triggering event/crisis (drought, El Niño and so on) Organizational incentives Value research; information seeking
Interaction	Not legitimate One-way communication	Infrequent interaction End-user relationship	Legitimate Two-way communication Iterative	Trust Long-term relationship Co-production

Adapted from ref. 8 © Univ. of Michigan.

The promise of climate information

Much of what we know empirically about the use of climate information comes from the literature focusing on the application of seasonal climate forecasts (SCF) around the world. Although SCF deal with shorter temporal scales (climate variability), they have often been used as an analogue to understand information uptake and response to climate-driven effects, including climate change[5,31]. In this Review, we rely heavily on the well-developed literature examining the opportunities and constraints of SCF application (Table 1) to inform our model. We use the term climate information to refer both to SCF knowledge and to other kinds of climate-related information such as paleoclimate reconstructions and climate change projections, although empirical evaluation of their use is relatively scarce (but see ref. 8).

Regarding perception of fit and how it affects the application of climate information in decision-making, empirical research finds that different factors influence knowledge uptake and dissemination. First, users are more likely to deploy climate information products that they perceive to be accurate[32,33], credible[26], salient[11,25,26,33–35] and timely[11,33,34,36,37]. Usability is bolstered when users perceive climate information as useful to their decision-making needs[11,19,32,33,35,38,39]. Not surprisingly, decision-makers are less likely to use inaccurate, ill-timed information as well as that which they perceive to be lacking relevance or credibility[22,25,32,34,40–42].

Regarding interplay, problems emerge when current uses of different kinds of knowledge make the introduction of new ones difficult[22,23,39,43]. For example, Rayner *et al.* found that many US water resource managers resisted using new knowledge because of the perceived risk posed by deviating from more established knowledge use practices[43]. These managers feared that using climate information might expose them to undue criticism in case of negative outcomes. In the US southwest, Rice *et al.* found that customized climate information integrated into water system models went unused because users relied on more established routines and knowledge such as those embedded in environmental impact statements[22].

Institutions and organizational culture play critical roles in making interplay better or worse in different sectors[21,40,44–53]. For example, research found that organizations with more flexible decision-making frameworks are more likely to use information[54]. Having sufficient human or technical capacity in-house or access to external relevant expertise makes climate forecast use more likely[23,39,41], as does previous positive experience with innovation[41,55,56]. In contrast, for wealthy and poor nations alike, the lack of institutional capacity to respond to, for example, improved scientific predictions of stream flow and seasonal weather patterns, constrains information use[25,43,45,57]. Furthermore, a decision-making culture that views the use of climate information as a strategy to mitigate risk[8,19,22] rather than as a risky practice in itself[58] is more likely to promote integration of climate information in decision-making. External influences such as public pressure, the perception of vulnerability[41,59,60] or actual water scarcity[22] can help overcome resistance to using novel information. For instance, because of intense water-supply challenges, water resource managers in Australia perceived themselves to be at greater risk from not using available climate information than from using it[38]. They believed that many in their constituency would find it unacceptable "if a known risk to supply was ignored in earlier planning"(ref. 38). Finally, knowledge-seeking behaviour among potential users, valuing research, and organizational incentives also shape knowledge use[7,8]. Table 1 summarizes the opportunities and barriers that affect usability as a function of fit, interplay and interaction that are well documented in the literature (see also recently published reviews focusing on different areas of climate information application[10,17,46,48,61]).

Interaction and usability dynamics. How users obtain, receive and participate in the production of climate information affects decision-makers' willingness to use that information. Moreover, moving from production to use requires bridging gaps created by cognitive, emotional and behavioural influences that shape both public and private decisions. Empirical evidence from in-depth case studies shows that two-way communication and establishing an ongoing relationship are important to usability in many ways. First, they build trust between producers and users of information[8,11,33,41,43,49,59,62]. In turn, trust building and accountability modulate fit by influencing users' perceptions of information salience, credibility and legitimacy in particular decision contexts[8,12]. In the Pacific Northwest, because water resource managers have been able to follow the evolution of climate modelling over time, they trust the information and perceive the process as credible[8]. In some contexts, salience and interplay become more important in driving usability. For example, in a study of climate information use in the context of a boundary organization, it was found that credibility and trust were established quickly allowing interactions to focus primarily on improving information fit and promoting positive interplay[8].
Second, trust and two-way communication establish long-term relationships between producers and users, and promote better understanding of each others' contexts, needs and limitations[7,8,11,33,41,43,49]. In the Pacific Islands, ongoing collaboration between scientists and decision-makers facilitated the production of information tailored to user needs and operation context[12]. In the US southwest, scientist–stakeholder interactions played a significant role in building

capacity to use forecasts in decision-making, thereby enhancing information use[63]. These interactions and long-term relationships can critically accelerate dissemination of new knowledge through the many networks to which users belong[49].

Third, interaction can contribute to address barriers to climate information use such as levels of uncertainty and perceptions of accuracy and reliability. Here, interaction can help change users' minds by facilitating in-depth discussion of these issues and how they may affect decision-making, including potential trade-offs and risks[8,33,38,64,65]. For instance, better understanding of how climate information is produced and how it can be used for long-term drought planning critically increases usability[22]. Furthermore, White *et al.* found that explaining decision-making tools in more depth positively influences users' willingness to deploy them[66]. Finally, interaction may work to decrease mismatches between different forms of knowledge such as tacit (knowledge that is unarticulated and tied to senses, movement skills, physical experiences, intuition and implicit rules of thumb), and explicit (knowledge uttered and captured in writings and drawings)[67]. When the two kinds of knowledge are at odds, fit may become a problem, as in the case when explicit knowledge is rejected because it does not match expectations from users informed by their tacit knowledge. Here, interaction between users and producers may help to bring these two knowledge types closer together. For example, in the US southwest case described above, interaction around climate knowledge and long-term drought planning (explicit knowledge) brings scientists and managers closer together, allowing for better understanding of their specific jobs and of their experience[20], way of thinking, and intuitions (tacit knowledge). And because most people use a combination of tacit and explicit knowledge in their day-to-day decision-making, iteration coupled with reinforcing feedback loops as they get to know each other better may help ensure that these forms of knowledge synergize in positive rather than negative ways.

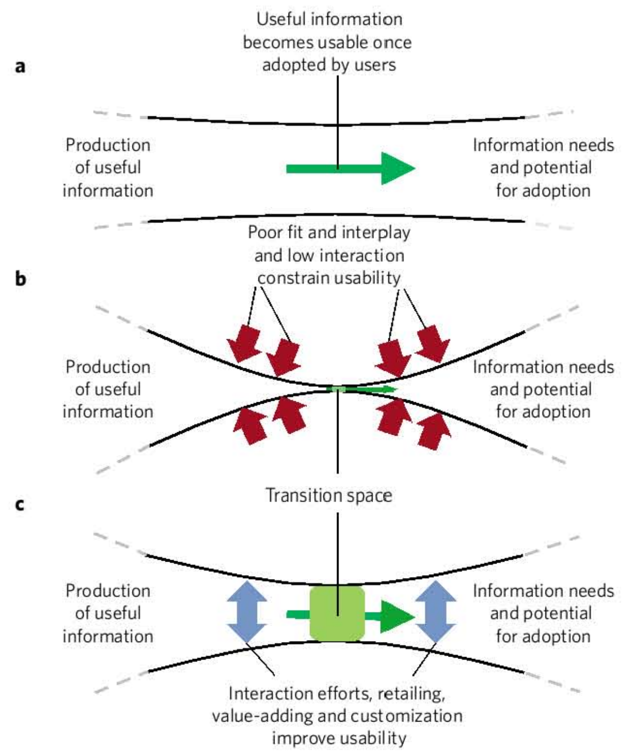

Figure 1 | The conceptual model. a, In principle, information moves from useful to usable by being deployed by users in decision-making. **b**, From a producers' perspective all information produced is potentially useful; information needs, fit, interplay and lack of interaction may restrict usability constraining the amount of information that moves from useful to usable. **c**, Interaction, retailing, customization and value-adding improve fit and interplay by changing users and producers' perceptions both of the information and the character of the information itself, widening the transition space and pushing information from useful to usable.

A conceptual model for usability

Drawing on the literature as a foundation, we propose a dynamic conceptual model to understand the path between usefulness and usability. The production and use of information in the model is akin to a market place where all available information is potentially useful as produced (hence where usefulness is a necessary but not sufficient condition), but will only be usable as users 'pick it,' that is, as users effectively incorporate specific information into a decision process. At each point in the range, information can go from useful to usable as it is translated, communicated and/or transformed to approach users' perceived needs. However, the point in the range where this transformation happens is not the same for all users, decisions, types of information or information production processes.

In our model, rather than operating independently, fit, interplay and interaction critically shape each other to increase or constrain usability of climate information. Hence fit, or the way users perceive their information needs and their ability to deploy knowledge, influences their willingness to use information. How users obtain information (for example, forms of communication, accessibility and format) and information characteristics — such as levels of uncertainty, reliability and accuracy — in turn influence users' perception of fit. However, fit is not static. Many factors and processes shape how perceptions of fit emerge and evolve: (1) new leadership or organizational shifts, focal events (for example, a crisis or unprecedented extreme event) or active learning through formal or informal interactions within a group or a network may alter how users perceive information fit; (2) improved formatting, better translation and communication of information and trust built through interaction can also change how users perceive and evaluate climate information; and (3) by interacting with producers, users may improve their understanding of how different kinds of knowledge fit their decision process in ways that they would not have imagined before.

Second, the model accounts for interplay between new information and information already routinely used in decision-making. Users' behaviour, past experiences and culture influence interplay[8,20,56,68,69]. On the one hand, existing established routines, the way people access information, and the way they perceive risk may create path dependencies that make seeking and deploying new information harder[43]. Interplay may be particularly critical in cases where users build their professional identity around established practices and where users are particularly vulnerable to public accountability processes[56]. On the other hand, interplay can be positive when new knowledge complements and creates positive synergies with old knowledge, adding value to the whole decision-making process.

Third, as mentioned in many of the examples above, usability depends on the level and quality of interaction between information producers and users. In the model, interaction acts in two ways: as an independent variable when trust building in the process of knowledge generation improves usability, or as a moderating variable when interaction alters perceptions of fit or affects interplay. For example, through interaction users may better understand the current limitations of modelling efforts or the level of uncertainty germane to these efforts[5,29]. Producers may also improve their understanding of how different pieces of knowledge may be better employed in different decision environments (for example, improving users' access to specific kinds of data or information) or get a better feeling of the type and format of information users prefer in the context of specific decisions[7,8,66]. In this interactive context, climate information is tailored (formatted, translated and communicated) to meet specific user needs at the same time that trust building and accountability between producers and users is improving perceptions of information salience, credibility and legitimacy[12,70]. Here, interaction benefits usability not only by modulating fit as participants 'talk' and exchange explicit knowledge but also when their collective experience (tacit knowledge) positively influences the process of knowledge production and use[11]. Figure 1 depicts the conceptual model.

Strategies to improve usability. Now, we consider different strategies that narrow the gap between information production and use. We know from the literature that iterativity and co-production models of science production and use effectively increase usability, but are costly in terms of human, financial and technical resources, and are difficult to sustain in the long term without specific financial and institutional resources and incentives[11]. Creating boundary organizations that translate, mediate and communicate information into more useful and usable forms partly ameliorates these constraints[26,27,71–73]. Highly iterative modes of knowledge production are also limited in their ability to reach a large audience because of the disparity in size between the knowledge producer and user communities. To enhance reach and rates of adoption beyond these intense and dedicated producer–user relationships, innovation theory suggests creating systems of interacting actors/organizations (for example, private and public firms, universities and government agencies) that initiate, modify, import and diffuse science and technology[74]. This requires creating linkages (for example, joint research and personnel exchanges) between actors to support knowledge creation and technological innovation, and also maintaining flows of financial, legal, technological and scientific support to facilitate use and diffusion of those advancements. Alternatively, identifying the paths of information flow and institutional elements through which knowledge production, innovation and use occurs, and developing cross-chain interactions between them, creates synergies amongst old and new knowledge[75]. In either case, usability improves by structuring a knowledge production environment interconnected with and sustained by financial, legal, technical and information flows.

We know from cognitive research that the way users process information, analytically or experientially, is important to their understanding and use of that information[69]. For example, relating new information to ensembles of relevant past experience and statistical constructs taps into an individual's analytical processing. On the other hand, relating new information to personal or others' experiences and memories engages one's experiential processing. Attending to these two kinds of processing equally during producer–user interactions improves communication of information, highlight relevant personal experience, elicit affective responses, and provide contextual meaning[20,69] to information, thereby fostering usability.

Value-adding. Adding value to available information to better meet users' needs can positively influence usability[76]. In the context of information systems, value-adding refers to formal processes through which producers enhance the usefulness of a specific message[77]. In this case, producers, through a process of selection and analysis, convert data to information that can inform and educate users (that is, informed knowledge). In turn, synthesis and evaluation transform informed knowledge to decision-oriented (that is, productive) knowledge. For example, producers might add crop insurance data and planting and harvest patterns to climate information (that is, downscaled climate change impacts information and SCF), therefore increasing the advantages and value of using climate information for agricultural production or disaster prevention efforts. One disadvantage of value-adding, especially in traditional new-product-development processes, is the prohibitive costs for catering to 'markets of one'. To mitigate this challenge, von Hippel and Katz suggest deploying 'tool-kits' for user-driven innovation in situations where coordinated sets of 'end-user friendly' design tools enable users to develop need-related, low-cost product innovations for themselves[78]. Thus, climate knowledge producers can cater to heterogeneous users by producing science products that can be easily understood and customized by users themselves through toolkits tailored to specific sectors. However, the enabling institutional conditions and costs that make either of these mechanisms functional need further research[78].

Retailing, wholesaling and customization. In a knowledge producer–user context, retailing and wholesaling refers to supplying a subset of the original climate information products (for example, climate change model outputs and SCF) to groups of users with similar information requirements in a manner that is easily taken up by the end user. Whereas retailing serves users with individualized decision-making processes at a more localized scale (for example, farmers and water managers), wholesaling serves users at a broader scale who themselves influence other potential information users (for example, water or agriculture agencies and interest groups). Both strategies require that knowledge producers (or brokers) understand user information needs and how to appropriately package, contextualize and communicate subsets of existing information in an easy, user-friendly manner. In climate information systems, retailing and wholesaling could have significant advantages over one-size-fits-all climate information provision efforts, given not all climate information produced is usable to everyone. Examples of retailing climate information are evident in SCF application, where boundary organizations, traditional agricultural extension agencies, and urban planning agencies provide subsets of information based on user needs. For example, in Victoria, Australia, the Department of Primary Industries provides climate change and seasonal risk information via training programmes, conferences, and steering groups to help farm foresters manage climate risks. In these examples, retailing helps cater to the needs of multiple users, moderate perceptions of poor fit (for example, lack of salience), and increase participation of users in climate information uptake[79].

Lastly, customization refers to adjustments to meet an individual user's needs made at the end of the knowledge production process. Framing uncertainties of generic climate information such as 'percent chance of an event occurring (or not occurring)' is an example of customizing climate information to probability of events. This customization generates information more usable for decision-making such as influencing budgetary decisions or helping risk managers to conduct rapid assessments[80]. Taken together, these transforming strategies (interaction, value-adding, retailing, wholesaling and customization) act in the model to expand the amount of useful information that becomes usable in decision-making (Fig. 1c).

Conclusions and limitations

Climate-related risks pose serious threats to our social and ecological systems. As climate change is prioritized in societal and political agendas, we can reasonably expect that the need and demand for climate information will grow. However, the application of climate information in decision-making is neither easy nor straightforward. Some information is picked up easily and integrated into decision-making processes whereas other information — in principle useful information — does not make it into decision-making. In this Review, we identified and summarized the myriad factors influencing usability including institutional and organizational factors and individuals' perceptions, cognition, beliefs, values and experiences. Additionally, we highlight the critical role of interaction between producers and users in helping to overcome barriers to usability. In this model, usability depends on three interconnected factors: fit, interplay and interaction. By describing how information moves from useful to usable, the model helps to identify concrete actions that can improve usability such as varying levels of interaction, customization, value-adding, retailing and wholesaling.

Although improving fit and interplay through interaction has great potential to increase the usability of climate information, especially at the local and resource-management levels, there are limitations to the implementation of the model and other challenges that need to be addressed in future research. One challenge is the critical mismatch between the size of the producer and user communities. If the demand for climate information grows, that demand could critically outstrip the ability of producers to establish highly interactive relationships to increase usability. Producers can address this mismatch both by establishing remote relationships that learn from face-to-face ones and by increasingly relying on boundary organizations and objects to disseminate information. For example, the creation of highly interactive web-based mechanisms (for example, tool-kits) can potentially emulate some of the more desirable aspects of face-to-face interaction allowing for relatively high levels of customization and value-adding. Also, through boundary organizations, producers can both learn about overlapping needs and contextual constraints that different classes of users face using climate knowledge and enhance the range of products being offered (for example, retailing and wholesaling) to facilitate more widespread dissemination and uptake of information.

Another challenge is that whereas high levels of iteration critically influence usability, in practice, human, organizational and material limitations constrain both sides of the science–policy interface. For science production, the evidence suggests that we must rethink the ways in which we design and promote use-inspired basic and applied research programmes if we aim to produce usable climate information to meet societal risk and adaptive management needs. For users of climate information, it suggests the need for policy change to increase the range of incentives for the use of climate information and the need to build and sustain capacity for facilitating use.

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References

1. National Research Council *America's Climate Choices: Panel on Advancing the Science of Climate Change* (NRC, 2010).
2. National Research Council *Informing Decisions in a Changing Climate — Panel on Strategies and Methods for Climate-Related Decision Support* (NRC, 2009).
3. Rockstrom, J. *et al.* A safe operating space for humanity. *Nature* **461,** 472–475 (2009).
4. Sarewitz, D. World view: Tomorrow never knows. *Nature* **463,** 24 (2010).
5. Lemos, M. C. & Rood, R. Climate projections and their impact on policy and practice. *WIRes. Clim. Change* **1,** 670–682 (2010).
6. National Research Council *Evaluating Progress of the U.S. Climate Change Science Program: Methods and Preliminary Results — Committee on Strategic Advice on the U.S. Climate Change Science Program* (NRC, 2007).
7. Engle, N. L. *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* PhD thesis, Univ. of Michigan (2010).
8. Kirchhoff, C. J. *Integrating Science and Policy: Climate Change Assessments and Water Resources Management* PhD thesis, Univ. Michigan (2010).
9. Stokes, D. E. *Pasteur's Quadrant: Basic Science And Technological Innovation* (Brookings Institution, 1997).
10. Dilling, L. & Lemos, M. C. Creating usable science: Opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environ. Change* **21,** 680–689 (2011).
11. Lemos, M. C. & Morehouse, B. The co-production of science and policy in integrated climate assessments. *Global Environ. Change* **15,** 57–68 (2005).
12. Cash, D. W., Borck, J. C. & Patt, A. G. Countering the loading-dock approach to linking science and decision making. Comparative analysis of El Niño/Southern Oscillation (ENSO) Forecasting systems. *Sci. Technol. Hum. Val.* **31,** 465–494 (2006).
13. McNie, E. C. Reconciling the supply of scientific information with user demands: An analysis of the problem and review of the literature. *Environ. Sci.Policy* **10,** 17–38 (2007).
14. Jasanoff, S. & Wynne, B. in *Human Choice and Climate Change: The Societal Framework* Vol. 1 (eds Rayner, S. & Malone, E. L) 1–88 (Batelle, 1998).
15. Buizer, J., Jacobs, K. & Cash, D. Making short-term climate forecasts useful: Linking science and Action. *Proc.Natl Acad. Sci. USA* http://dx.doi.org/10.1073/pnas.0900518107 (2010).
16. Jacobs, K. *et al.* Linking knowledge with action in the pursuit of sustainable water-resources management. *Proc.Natl Acad. Sci. USA* http://dx.doi.org/10.1073/pnas.0813125107 (2010).
17. Van Kerkhoff, L. & Lebel, L. linking knowledge and action for sustainable development. *Annu. Rev. Env. Resour.* **31,** 445–477 (2006).
18. Feldman, D. L. & Ingram, H. M. Making science useful to decision makers: Climate Forecasts, water management and knowledge networks. *Weather Clim. Soc.* **1,** 9–21 (2009).
19. Lowrey, J., Ray, A. & Webb, R. Factors influencing the use of climate information by Colorado municipal water managers. *Climate Res.* **40,** 103–119 (2009).
20. Weber, E. U. Experience-based and description-based perceptions of long-term risk: Why global warming does not scare us (yet). *Climatic Change* **77,** 103–120 (2006).
21. Patt, A. & Gwata, C. Effective seasonal climate forecast applications: Examining constraints for subsistence farmers in Zimbabwe. *Global Environ. Change* **12,** 185–195 (2002).
22. Rice, J. L., Woodhouse, C. A. & Lukas, J. L. Science and decision making: Water management and tree-ring data in the western United States. *J. Am. Water Resour. Assoc.* **45,** 1248–1259 (2009).
23. Callahan, B., Miles, E. & Fluharty, D. Policy implications of climate forecasts for water resources management in the Pacific Northwest. *Policy Sci.* **32,** 269–293 (1999).
24. Corringham, T. W., Westerling, A. L. & Morehouse, B. J. Exploring use of climate information in wildland fire management: A decision calendar study. *J. Forest.* **106,** 71–77 (2008).
25. Pulwarty, R. S. & Redmond, K. T. Climate and salmon restoration in the Columbia River Basin: The role and usability of seasonal forecasts. *B. Am. Meteorol. Soc.* **78,** 381–396 (1997).
26. Cash, D. W. *et al.* Knowledge systems for sustainable development. *Proc. Natl Acad. Sci. USA* **100,** 8086–8091 (2003).
27. Jacobs, K., Garfin, G. & Lenart, M. More than just talk: Connecting science and decision making. *Environment* **47,** 6–21 (2005).
28. Meinke, H. *et al.* Adaptation science for agriculture and natural resource management— urgency and theoretical basis. *Curr. Opin. Environ. Sustain.* **1,** 69–76 (2009).
29. Mearns, L. O. The drama of uncertainty. *Climatic Change* **100,** 77–85 (2010).
30. Meyer, R. The public values failures of climate science in the US. *Minerva* **49,** 47–70 (2011).
31. Adger, W. N., Huq, S., Brown, K., Conway, D. & Hulme, M. Adaptation to climate change in the developing world. *Prog. Dev. Studies* **3,** 179–195 (2003).
32. Changnon, S. A. & Kunkel, K. E. Rapidly expanding uses of climate data and information in agriculture and water resources: Causes and characteristics of new applications. *Bull. Am. Meteorol. Soc.* **80,** 821–830 (1999).
33. Pagano, T. C., Hartmann, H. C. & Sorooshian, S. Factors affecting seasonal forecast use in Arizona water management: A case study of the 1997–98 El Niño. *Clim. Res.* **21,** 259–269 (2002).
34. Stern, P. & Easterling, W. E. *Making Climate Forecasts Matter* (National Academy, 1999).
35. Wilbanks, T. & Kates, R. W. Global change in local places: How scale matters. *Climatic Change* **43,** 601–628 (1999).
36. Changnon, S. A. & Vonnahme, D. R. Impact of spring 2000 drought forecasts on Midwestern water management. *J. Water Resour. Plan. Manag.* **129,** 18–25 (2003).
37. Orlove, B. S., Broad, K. & Petty, A. M. Factors that influence the use of climate forecasts — Evidence from the 1997/98 El Niño event in Peru. *Bull. Am. Meteorol. Soc.* **85,** 1735–1743 (2004).
38. Power, S., Sadler, B. & Nicholls, N. The influence of climate science on water management in western Australia: Lessons for climate scientists. *Bull. Am. Meteorol. Soc.* **86,** 839–844 (2005).
39. Snover, A. K., Hamlet, A. F. & November, D. P. L. Climate-change scenarios for water planning studies: Pilot applications in the Pacific Northwest. *Bull. Am. Meteorol. Soc.* **84,** 1513–1518 (2003).
40. Lemos, M. C., Finan, T., Fox, R., Nelson, D. & Tucker, J. The Use of seasonal climate forecasting in policymaking: Lessons from Northeast Brazil. *Climatic Change* **55,** 479–507 (2002).
41. Pagano, T. C., Hartmann, H. C. & Sorooshian, S. Using climate forecasts for water management. *J. Am. Water Resour. Assoc.* **37,** 1139–1153 (2001).
42. Yarnal, B., Heasley, A. L., O'Connor, R. E., Dow, K. & Jocoy, C. L. The potential use of climate forecasts by community water system managers. *Land Use Water Resour. Res.* **6,** 1–38 (2006).
43. Rayner, S., Lach, D. & Ingram, H. Weather forecasts are for wimps: Why water resource managers do not use climate forecasts. *Climatic Change* **69,** 197–227 (2005).

44. Archer, E. R. M. Identifying underserved end-user groups in the provision of climate information. *Bull. Am. Meteorol. Soc.* **84,** 1525–1532 (2003).
45. Ingram, K. T., Roncoli, C. & Kirshen, P. H. Opportunities and constraints for farmers of west Africa to use seasonal precipitation forecasts with Burkina Faso as a case study. *Agr. Syst.* **74,** 331–349 (2002).
46. Meinke, H. *et al*. Actionable climate knowledge: From analysis to synthesis. *Climate Res.* **33,** 101–110 (2008).
47. Nelson, R. A., Holzworth, D. P., Hammer, G. L. & Hayman, P. T. Infusing the use of seasonal climate forecasting into crop management practice in North East Australia using discussion support software. *Agr. Syst.* **74,** 393–414 (2002).
48. Roncoli, C. Ethnographic and participatory approaches to research on farmers' responses to climate predictions. *Climate Res.***33,** 81–99 (2006).
49. Roncoli, C. *et al.* From accessing to assessing forecasts: An end-to-end study of participatory climate forecast dissemination in Burkina Faso (West Africa). *Climatic Change* **92,** 433–460 (2009).
50. Ziervogel, G. & Calder, R. Climate variability and rural livelihoods: Assessing the impact of seasonal climate forecasts. *Area* **35,** 403–417 (2003).
51. Lemos, M. C. & Dilling, L. Equity in forecasting climate: Can science save the world's poor? *Sci. Publ. Pol.* **34** (2007).
52. Van Kerkhoff, L. & Szlezák, N. A. The role of innovative global institutions in linking knowledge and action *Proc.Natl Acad. Sci. USA* http://dx.doi.org/10.1073/pnas.0900541107 (2010).
53. Morss, R., Wilhelmi, O., Downton, M. & Gruntfest, E. Flood risk, uncertainty and scientific information for decision making: Lessons from an interdisciplinary project. *Bull. Am. Meteotol. Soc.* **86,** 1593–1601 (2005).
54. Beller-Simms, N. *et al. Decision-Support Experiments and Evaluations Using Seasonal to Interannual Forecasts and Observational Data: A Focus on Water Resources* (United States Climate Change Science Program, 2008).
55. Glantz, M. H. Consequences and responsibilities in drought forecasting: The Case of Yakima, 1977. *Water Resour. Res.* **18,** 3–13 (1982).
56. Lemos, M. C. What influences innovation adoption by water managers? Climate information use in Brazil and the US. *J. Am. Water Resour. Assoc.* **44,** 1388–1396 (2008).
57. Tarhule, A. & Lamb, P. J. Climate research and seasonal forecasting for West Africans: Perceptions, dissemination, and use. *Bull. Am. Meteorol. Soc.* **84,** 1741–1759 (2003).
58. Broad, K., Pfaff, A. S. P. & Glantz, M. H. Effective and equitable dissemination of seasonal-to-interannual climate forecasts: Policy implications from the peruvian fishery during El Niño 1997–98. *Climatic Change* **54,** 415–438 (2002).
59. Carbone, G. J. & Dow, K. Water resources and drought forecasts in South Carolina. *J. Am. Water Resour. Assoc.* **41,** 145–155 (2005).
60. O'Connor, R. E., Yarnal, B., Dow, K., Jocoy, C. L. & Carbonne, G. J. Feeling at risk matters: Water managers and the decision to use forecasts. *Risk Anal.* **5,** 1265–1275 (2005).
61. Ropelewski, C. F. & Lyon, B. in *Global Climate: Current Research And Uncertainties In The Climate System* (eds Rodó, X. & Comín, F. A) Ch. 4, 41–54 (Springer, 2003).
62. Hedger, M., Connell, R. & Bramwell, P. Bridging the gap: Empowering decision-making for adaptation through the UK Climate Impacts Programme. *Clim. Policy* **6,** 201–215 (2006).
63. Ray, A. J. *et al.* Applications of monsoon research: Opportunities to inform decision making and reduce regional vulnerability. *J. Climate* **20,** 1608–1627 (2007).
64. Changnon, S. A. Changing uses of climate predictions in agriculture: Implications for prediction research, providers, and users. *Weather Forecast* **19,** 606–613 (2004).
65. Cobon, D., Bell, K., Park, J. & Keogh, D. Summative evaluation of climate application activities with pastoralists in western Queensland. *Rangeland J.* **30,** 361–374 (2008).
66. White, D. D. *et al.* Credibility, salience, and legitimacy of boundary objects: Water managers' assessment of a simulation model in an immersive decision theater. *Sci. Publ. Policy* **37,** 219–232 (2010).
67. Nonaka, I. A dynamic theory of organizational knowledge creation. *Organ. Sci.* **5,** 14–37 (1994).
68. Lemos, M. C. A Tale of two policies: The politics of seasonal climate forecast use in Ceará, Brazil. *Policy Sci.* **32,** 101–123 (2003).
69. Marx, S. M. *et al.* Communication and mental processes: Experiential and analytic processing of uncertain climate information. *Global Environ. Change* **17,** 47–58 (2007).
70. Hartmann, H. C., Pagano, T. C., Sorooshian, S. & Bales, R. Confidence builders: Evaluating seasonal climate forecasts from user perspectives. *Bull. Am. Meteorol. Soc.* **8,** 683–698 (2002).
71. Guston, D. H. Boundary organizations in environmental policy and science: An introduction. *Sci.Technol. Hum. Val.* **26,** 399–408 (2001).
72. Sarewitz, D. & Pielke, R. A. Jr The neglected heart of science policy: Reconciling supply of and demand for science. *Environ. Sci. Policy* **10,** 5–16 (2007).
73. Beyer, J. M. & Trice, H. M. The utilization process — a conceptual framework and synthesis of empirical findings. *Admin. Sci. Quart.* **27,** 591–622 (1982).
74. Lundvall, B. A., Johnson, B., Andersen, E. S. & Dalum, B. National systems of production, innovation and competence building. *Res. Policy* **31,** 213–231 (2002).
75. Kline, S. J. & Rosenberg, N. in *The Positive Sum Strategy: Harnessing Technology for Economic Growth* (ed Rosenberg, N. & Landau, R.) 275–305 (National Academy, 1986).
76. Prahalad, C. K. & Ramaswamy, V. Co-creation experiences: The next practice in value creation. *J. Interact. Mark.* **18,** 5–14 (2004).
77. Taylor, R. S. Value-added processes in the information life-cycle. *J. Am. Soc. Inf. Sci.* **33,** 341–346 (1982).
78. Von Hippel, E. & Katz, R. Shifting innovation to users via toolkits. *Manage. Sci.* **48,** 821–833 (2002).
79. Department of Primary Industries *DPI Services to farm foresters* (2011); available via http://go.nature.com/1IEZUO
80. Goddard, L. *et al.* Providing seasonal-to-interannual climate information for risk management and decision-making. *Procedia Environ. Sci.* **1,** 81–101 (2010).

Author contributions
All authors contributed extensively to the work presented in this paper.

Additional information
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