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Bridging the gap between end user needs and science capability: decision making under uncertainty

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ABSTRACT: There is a recognised gap between what climate science can currently provide and what end users of that information require to make robust adaptation decisions about their climate-related risks. This issue has been identified as a major barrier to successful climate change adaptation outcomes and is emphasised within the water resource management and agricultural sectors because of high uncertainty surrounding precipitation projections. This paper details the outcomes of a survey and workshop aimed at better understanding this gap. To bridge the gap, it is recommended that communication and packaging of climate information be improved via a formalised 'knowledge broker'. It is also suggested that a 'terms of reference' for key climate change-related terms be developed and agreed upon by both climate science providers and end users to reduce the misuse of terminology and subsequent confusion. Further, it is recommended that additional research be conducted into natural variability and baseline risk to provide a realistic background on which climate change projections and associated uncertainties are assessed. Finally, for successful climate change adaptation, new tools and methods are needed that deal explicitly with end user needs and the practical limitations end users face (e.g. time, funding, human resources, politics) when attempting to make robust decisions under climate change-related uncertainty.

KEY WORDS: Climate change · Adaptation · Decision making · Communication · Knowledge broker

1. INTRODUCTION

Successful adaptation outcomes are supported by decision making that is informed by the best available climate science (e.g. Sarewitz & Pielke 1999, Patt & Dessai 2005, Power et al. 2005, Burton 2009, Meinke et al. 2009). However, a fundamental gap exists between the information that climate science provides and the information that is practically useful for (and needed by) end users and decision makers (e.g. Jacobs et al. 2005, Kiem & Austin 2013a,b). In some cases, it appears that the information is simply too 'uncertain' to be of any practical use, or that the uncertainty is not adequately quantified and communicated. Further, even if the climate information does exist and the uncertainty is properly communicated, often decision makers are unaware of it or cannot access it in a format they can readily use (i.e. the right information may exist, but it is inaccessible for end users because of time, expertise and/or technological constraints).

Traditionally, in carrying out research on human-induced climate change and its impacts, scientists have followed a linear pathway of activity, starting from the specification of greenhouse gas emissions and ending with impacts and possible response strategies. From the perspectives of those working in the adaptation field through to policy and decision makers, the problem is that each step in this pathway has an associated uncertainty. More importantly, these uncertainties compound at each step, so that by the time the stage of projecting climate change impacts at spatial scales relevant for decision making is reached, the uncertainties have exploded (e.g. Jones 2000).

Several recent studies have reviewed the uncertainties associated with general circulation models

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(e.g. Parry et al. 2007, Randall et al. 2007, Stainforth et al. 2007, Koutsoyiannis et al. 2008, 2009, Blöschl & Montanari 2010, Montanari et al. 2010) and the implications of those uncertainties for climate change impact assessments in Australia (e.g. Pitman & Perkins 2008, Verdon-Kidd & Kiem 2010, Kiem & Verdon-Kidd 2011). These studies demonstrate that while climate models may represent the 'best available science' in terms of our understanding of global climate processes and projecting future climate, the inherent limitations and uncertainties mean that climate model outputs do not necessarily represent useful information or meet the needs of end users when planning for and making decisions about the future. This is especially the case for precipitation in regions with highly variable climates (e.g. Australia). The uncertainty in these circumstances is often so high that projections of future hydrologic risk, on either the short term (seasonal up to 5 yr) or long term (>10 yr into the future), currently have limited practical usefulness for decision makers (Kiem & Verdon-Kidd 2011). Compounding this is our lack of understanding into the relationship between the climate (e.g. rainfall, temperature) and the hydroclimate (e.g. evaporation, runoff, streamflow, soil moisture). For climate models to be useful for water resource management, they need to provide projections that simulate important land surface–ocean–atmosphere interactions. However, there are significant hurdles to overcome, including: (1) these interactions are complex and currently imperfectly understood and (2) there are added difficulties and computational limitations associated with integrating land surface models and climate models.

While uncertainties exist in relation to the generation of climate information, there is also uncertainty when attempting to define the differing and varied needs across the range of diverse end users. End user needs vary considerably because of location, sector, resources, existing knowledge, climate risks and the decision being made (e.g. Maraun et al. 2010, Kiem & Verdon-Kidd 2011). The capability, capacity to act (i.e. budget and time constraints), awareness of science information and attitudes of end users also vary markedly across locations and sectors (e.g. Kiem et al. 2010a,b, Rickards 2012, Kiem & Austin 2013a,b), meaning that even if uncertainty in the science is dealt with, effort is still needed in addressing uncertainty in the way that science is viewed and implemented by end users.

Climate science and its related uncertainties are often not the only, or even the most important, considerations in making climate-sensitive decisions (Power et al. 2005). There is increasing support for the suggestion that the gap is not just between the science and the decision makers, rather it is that the decision has to be socially, politically, economically and environmentally acceptable for it to be implemented (e.g. Adger et al. 2005, Füssel 2007, Kiem & Austin 2013b). Even in a perfect world where scientists provide useful information to end users and end users subsequently make robust climate change adaptation decisions based on that science, if the decision is not supported by the community (e.g. because of a lack of community engagement), there will always be difficulty in getting that decision implemented (e.g. when a desalination plant or reservoir is proposed, when water trading or allocation schemes are introduced, when sea level inundation or flood management policies are changed).

Science is uncertain and always will be, but decision making under uncertainty is not new (e.g. the precautionary principle, Foster et al. 2000). Decisions are regularly made under uncertainty or with only partial knowledge about likely consequences (e.g. investment decisions, career decisions, decisions concerning our health). However, when it comes to climate science, many are reluctant to consider climate change adaptation until the science is more certain (e.g. Jacobs et al. 2005, Kiem & Austin 2013b). Unfortunately, uncertainty in science, especially climate science, will not disappear, and novel frameworks for climate adaptation decision making under uncertainty are urgently required. Much can be learned from the economics and investment literature (e.g. Dixit & Pindyck 1994, Pindyck 2007, Bammer & Smithson 2008, Randall 2011) and the extensive body of knowledge relating to assessing and dealing with climate risks in general, as opposed to impacts and risks associated with anthropogenic climate change, much of which pre-dates the emphasis on climate change adaptation (e.g. Hammer et al. 2000, Hayman 2000, Cash et al. 2003, McKeon et al. 2004, Adger et al. 2005, Meinke et al. 2006, 2009, Hayman et al. 2007).

This issue of decision making under uncertainty was investigated during a project conducted for the Australian government's National Climate Change Adaptation Research Facility (NCCARF, www.nccarf.edu.au/publications/decision-making-under-uncertainty) via an online survey (targeted to providers of climate information and end users), a workshop (where both providers and end users came together to discuss key issues) and a focus group (where some of the key issues identified during the workshop were further explored). This study presents the results of the online survey and workshop findings.

2. METHODS

2.1. Online survey

An online survey was conducted to obtain participation from a large number of respondents with a diverse range of backgrounds. The survey was specifically designed to answer the following questions: (1) How has climate information been used to date, and what is the source of the climate information? (2) How do people rate the existing climate information (i.e. what are the strengths and weaknesses of the information)? (3) What do people understand uncertainty to mean, and how well do they think uncertainty is communicated? (4) What will be the major advances in climate modelling over the next 5 to 10 yr, and will these advances reduce uncertainty?

Survey participants were obtained through authors' personal networks, associations and email contacts; personal communications at conferences where participants provided their contact details voluntarily; previous research (e.g. interviewees and workshop participants in Kiem et al. [2010a] and Kiem & Austin [2013b]); publicly available contact information such as websites; and distribution of the survey to respondents' own contacts and networks.

Survey questions (see www.nccarf.edu.au/publications/decision-making-under-uncertainty for full survey) were designed to facilitate a quantitative analysis of the gap between science capability and end user needs, with a particular focus on water resource management and agriculture. The survey required participants to initially identify as 'providers' or 'end users' of climate information. The survey then tailored subsequent questions according to this selection. While the survey was open to everybody, participants were asked questions to establish their background, which enabled the survey results to be stratified into 'provider' and 'end user' groupings and provided insights into which responses would be relevant to or not relevant to water resource management and agriculture.

2.2. Workshop

Climate scientists (i.e. providers) and high-level decision makers (i.e. end users) were brought together over a 2 day workshop in Canberra, Australia (12–13 April 2012), to discuss decision making under uncertainty and the gap that currently exists between the information that climate science provides and the information that is practically useful for (and needed by) end users and decision makers (a list of workshop participants is provided in Table 1). The objective of the workshop was to give both providers of climate information and end users 'a voice' where concerns, issues and beliefs could be raised and challenged in an organised forum. Specifically, the overall aims of the workshop were to (1) improve climate scientists' understanding about what climate information is required by decision makers and in what format the information should be provided (particularly regarding uncertainty); (2) improve end users' (particularly in the water resources sector) understanding of what information climate science can currently provide, the limitations of the science and the uncertainties associated with the outputs; (3) develop a better understanding of what climate science can realistically be expected to provide over the next 5 to 10 yr and what will probably never be possible; and (4) learn about the decision-making process (particularly in the water resources sector) and how uncertainty is currently dealt with.

Workshop presenters and participants (Table 1) were carefully considered and selected to provide a comprehensive background on the state of current climate science in Australia, while also providing a succinct summary of the perspective of end users. Participants were selected because of their prominence in their particular field of climate science, their specific role as a decision maker (e.g. representing a particular sector or level of government) or their representation of one of the following 3 case study regions: (1) City of Melbourne, representing a highly developed urban city with recent experience in water shortages and large expenditure on climate change adaptation (e.g. the Wonthaggi desalination plant); (2) Hunter Region, representing a rapidly growing coastal region with potential water shortages in the future, issues relating to sea level rise for established development and appropriate infrastructure planning around climate change; and (3) Central West Catchment of the Murray-Darling Basin, representing a diverse region west of the Great Divide that supports a variety of towns, cities and industries and is also an area that has numerous natural resource assets such as national parks, culturally significant areas and the internationally recognised Macquarie Marshes.

To ensure independence and remove any potential biases, the workshop was conducted primarily by professional and experienced facilitators from Global Learning (for more information, see www.globallearning.com.au/). This style of facilitation ensured that all participants were given the opportunity to voice their concerns, but had the added benefit of

Table 1. Workshop participant list

Name	Organisation
Alan Randall	University of Sydney
Alice Howe	Lake Macquarie City Council (LMCC)
Andrew Davidson	New South Wales Office of Water (NOW)
Anthony Kiem	University of Newcastle (UoN)
Anthony Swirepik	Department of Climate Change & Energy Efficiency (DCCEE)
Bertrand Timbal	Centre for Australian Weather and Climate Research (CAWCR)
Brendan Berghout	Hunter Water
Bruce Rhodes	Melbourne Water
Bryson Bates	Commonwealth Scientific and Industrial Research Organisation (CSIRO)
Chris Lee	New South Wales Office of Environment & Heritage (OEH)
Danielle Verdon-Kidd	University of Newcastle (UoN)
David Griggs	Monash University
David Post	CSIRO Land and Water
David Rissik	National Climate Change Adaptation Research Facility (NCCARF)
Eleanor McKeough	Melbourne Water
Francis Chiew	CSIRO Land and Water
Frank Stadler	National Climate Change Adaptation Research Facility (NCCARF)
Greg Hertzler	University of Sydney
James Ward	University of South Australia
Jane Chrystal	Central West Catchment Management Authority (CMA)
Jason Alexandra	Murray-Darling Basin Authority (MDBA)
Jason Crean	New South Wales Department of Trade & Investment
Jason Evans	University of New South Wales (UNSW)
Jean Palutikof	National Climate Change Adaptation Research Facility (NCCARF)
Ken Day	Queensland Climate Change Centre of Excellence
Mike Roderick	Australian National University (ANU)
Neville Nicholls	Monash University
Penny Whetton	CSIRO Marine and Atmospheric Research
Peter Hayman	South Australian Research and Development Institute (SARDI)
Rae Moran	Victoria Department of Sustainability and Environment (DSE)
Rod McInnes	Sydney Catchment Authority (SCA)
Sam Capon	National Climate Change Adaptation Research Facility (NCCARF)
Shahadat Chowdhury	New South Wales Office of Water (NOW)
Tim Capon	University of Sydney
Todd Sanderson	University of Sydney

keeping discussions directed. The computer software iMEET! (www.imeet.com.au/public/) was also used at the workshop to increase productivity and to increase the efficient use of time during the workshop and afterwards when reporting. The iMEET! software captures discussions and allows groups to quickly analyse, organise and evaluate ideas. All data were captured and available immediately, allowing instant discussion and clarification, and rapid evolution of ideas.

The first day of the workshop and the first session of the second day covered both end users' experience in using climate information and the 'state of the science' (the workshop program is presented in Table 2). A hypothetical case study exercise was carried out on the second day that required all participants to engage in an interactive exercise that highlighted the information required and the different methods that end users rely on when forced to make decisions under uncertainty (for further details, see authors unpubl.). This was followed by a wrap-up session, where the key themes emerging from the workshop were discussed and given priority rankings.

3. RESULTS

3.1. Online survey

A total of 210 respondents commenced the survey, with 70% completing all questions. This low response and completion rate was anticipated and is symptomatic of 'research fatigue' (e.g. Kiem et al. 2010a, Rickards 2012, Kiem & Austin 2013a,b). 'Research fatigue' is experienced by end users and providers who are exposed to similar surveys, workshops or requests

Table 2. Workshop program, 12–13 April 2012, Hyatt Hotel, Canberra. See Table 1 for organisation abbreviations

SESSION 1: USING CLIMATE CHANGE INFORMATION IN PRACTICE — THE DECISION MAKER'S EXPERIENCE
Case study: City of Melbourne — Rae Moran (Victorian DSE), Bruce Rhodes (Melbourne Water)
Case study: Hunter Region — Brendan Berghout (Hunter Water), Alice Howe (Lake Macquarie City Council)
Case study: Murray-Darling Basin — Jane Chrystal (Central West CMA)
Facilitated group discussion session
SESSION 2: THE CURRENT STATE OF CLIMATE SCIENCE
General overview of the current state of the science — David Griggs (Monash University)
Lessons learnt from South Eastern Australian Climate Initiative: how to bridge the gap between climate science and end users — David Post (CSIRO)
Regional climate change projections: dynamical downscaling — Jason Evans (UNSW)
Regional climate change projections: statistical downscaling — Bertrand Timbal (CAWCR)
Facilitated group discussion session
SESSION 3: UNCERTAINTIES IN CLIMATE MODELLING
Climate change and hydrological modelling — Francis Chiew (CSIRO)
Emission scenarios — James Ward (University of South Australia)
Extremes — Neville Nicholls (Monash University)
Temperature and evaporation — Mike Roderick (ANU)
Baseline climate and natural variability — Anthony Kiem (UoN)
Facilitated group discussion session
SESSION 4: THE FUTURE OF CLIMATE SCIENCE AND ADAPTATION
Future advances in climate change science: what can we realistically expect in the next 5 to 10 years? — Penny Whetton (CSIRO)
Adaptation under climate uncertainty: an update — Bryson Bates (CSIRO)
Facilitated group discussion session
SESSION 5: HYPOTHETICAL CASE STUDY ACTIVITY
Facilitated activity in small groups using iMEET!
Wrap up and discussion
SESSION 6: DECISION-MAKING FRAMEWORKS
Linking science and decision making: using time series and probability wheels — Peter Hayman (SARDI)
Decision support tools and frameworks — University of Sydney
WRAP-UP: LESSONS LEARNT AND KNOWLEDGE GAPS
Wrap-up from the workshop and where to go from here — UoN

for interviews (particularly related to climate change) on at least a monthly basis with no apparent practical outcomes or return for effort. It may also be that some respondents did not feel that they could adequately respond to some or all of the questions or that the questions were not applicable to them. This experience also supports the key finding from Kiem et al. (2010a) that research needs to be conducted in a way that is respectful of stakeholders and coordinated to avoid unnecessary overlap and repetition. The following sections discuss the survey results obtained.

3.1.1. Respondent cohort

End users were defined as 'people who are in a position where it is necessary for them to make decisions (business/operational or policy-related) or recommendations to manage climate-related risks. This may include practitioners, decision makers and policy roles'. Providers were defined as 'people who are in a position where they are directly involved in climate modelling (e.g. developing, running and/or testing climate models) or use climate modelling outputs to provide information on climate impacts and risks'. Approximately 70% of respondents identified themselves as end users, while approximately 30% identified as providers of climate information. Verbal feedback and free-text responses indicated that some respondents found it difficult to categorise themselves into just 1 group, and felt that they belonged to both groups. This was noted as a limitation of the survey, but could not be avoided, as the aim was to compare the thoughts and experiences of the 2 groups. Respondents worked within a range of Australian organisations, with government and university organisations particularly well represented (Fig. 1a). Various end user sectors, including the water supply/availability and primary industry sectors, were also well represented (Fig. 1b), with 75% of end users stating that their decisions directly related to these industries.

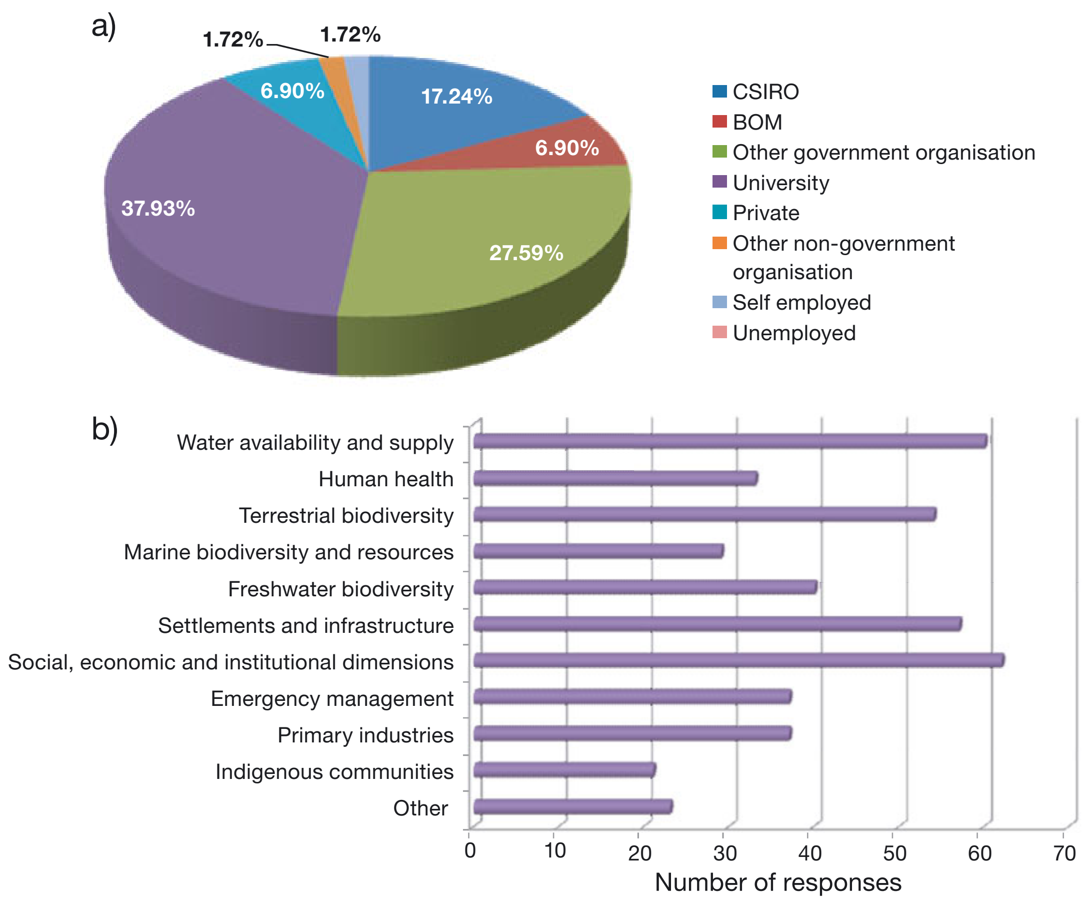

Fig. 1. (a) Employment institution or type of respondents who are providers (no providers identified as being unemployed); (b) sectors and industries that end user decisions relate to (categories are based on National Climate Change Adaptation Research Facility networks). Respondents were able to select multiple responses. BOM: Bureau of Meteorology; CSIRO: Commonwealth Scientific and Industrial Research Organisation. Options that do not appear in the chart received 0% response

Respondents that identified as providers of climate information were asked what type of climate information they provide (respondents could choose more than 1 climate product). Close to 80% of providers stated that they produce information on long-term climate change, while 50% also produce information on historical data sets. Close to 20% produce seasonal climate forecasts, while only 10% of respondents produce weather-related forecasts. Further, only ~17% of providers were directly involved in climate modelling, with the majority of providers using climate model outputs to provide information on climate impacts and risks.

End users were asked if they currently use climate information in their role and if not, why not. Only 6% of the end user group stated that they do not use climate information in their role, and this was for a variety of reasons (a common theme in the free-text responses was a lack of relevance of the available climate information for an end user's specific purpose).

3.1.2. What respondents told us about available climate information

End users and providers were queried about the sources of climate information (Fig. 2). Both sets of participants were given the same set of responses to choose from. The difference was that providers were asked where they think end users source climate information from, whereas end users were asked where they source climate information from. From Fig. 2, it is seen that end users regularly source information from Australian organisations including the Australian Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), state government websites and international agencies. It is also clear that twice as many end users source information from journals and peer-reviewed literature as the number of providers who expect that end users utilise this source. Further, providers think that end users source

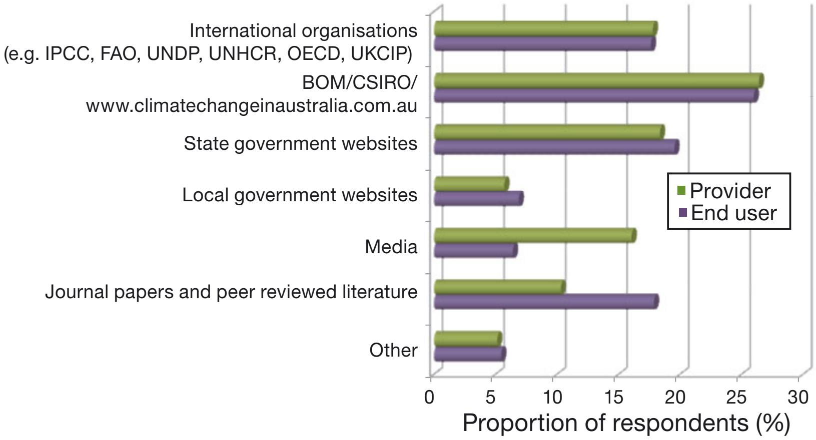

Fig. 2. End users' sources of climate information: providers' perception compared to actual sources (percentages indicate the proportion of respondents who identified as providers and end users rather than the proportion of total respondents). BOM: Bureau of Meteorology; CSIRO: Commonwealth Scientific and Industrial Research Organisation; FAO: Food and Agriculture Organization of the United Nations; IPCC: Intergovernmental Panel on Climate Change; OECD: Organisation for Economic Co-operation and Development; UKCIP: UK Climate Impacts Programme; UNDP: United Nations Development Programme; UNHCR: United Nations High Commissioner for Refugees

information from the media much more frequently than end users do in reality. These results indicate that end users (at least those that were surveyed here) are more educated on the issue of climate change information and source their information from 'higher levels' than providers are aware of.

The next 2 questions of the survey were aimed at determining if climate change information needs to be accurate (i.e. free from error) to make informed decisions (Fig. 3a) and also how useful existing climate change information is to end users in their role as a decision maker (Fig. 3b). Most end users and providers surveyed were in agreement that the accuracy of climate information is important/very important (as shown by Fig. 3a). However, their opinions were polarised at the more extreme ends of the scale, in that more end users felt that accuracy is crucial compared to providers, while more providers felt that accuracy is only somewhat important. Interestingly, and difficult to explain, is that some providers responded that it is not important at all to have accurate information to make informed decisions. Fig. 3b shows that there is not much difference in the way that providers and end users view the usefulness of climate information. However, the disparity between responses for 'useful' and 'somewhat useful' suggest that more investigation is required. In particular, it is not clear from the survey responses whether providers properly understand what end users use the information for (i.e. providers may not be in a position to know what is and what is not useful). Also unclear is whether end users who rate the usefulness of climate information highly are aware of the limitations and uncertainties associated with the climate information and/or are using the climate information correctly (see further discussion on this related to the difference between precise and accurate information at the end of Section 3.1.3).

Following Austin (2011) and Kiem & Austin (2013b), respondents were asked to rate 9 characteristics of climate information (Fig. 4): (1) availability of climate information in terms of what end users require; (2) end user level of knowledge of what climate information actually exists; (3) end user level of understanding of the available climate information; (4) end user awareness of where to find avail-

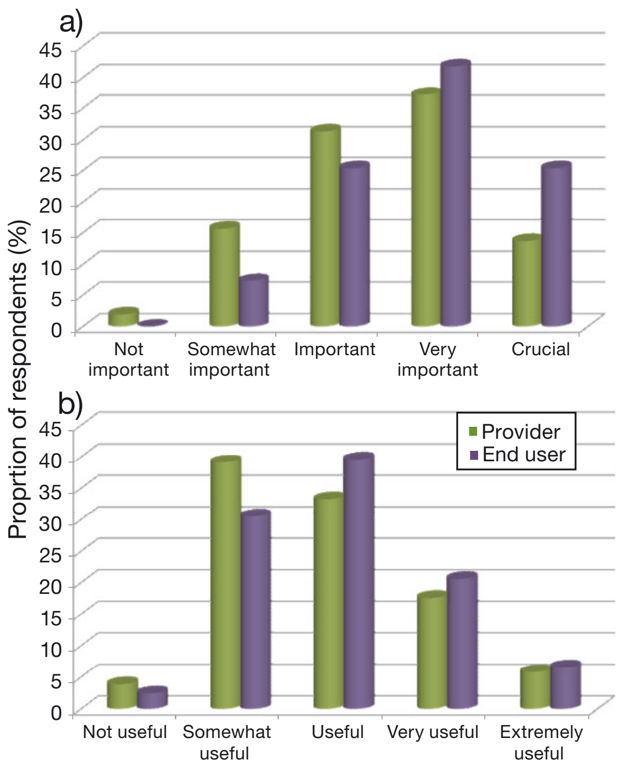

Fig. 3. (a) Provider and end user perspectives on how important it is for end users to have accurate information when making informed decisions; (b) provider and end user perspectives on how useful existing climate information is (for example, whether existing information helps end users make informed decisions). Percentages indicate the proportion of respondents who identified as providers and end users rather than the proportion of total respondents

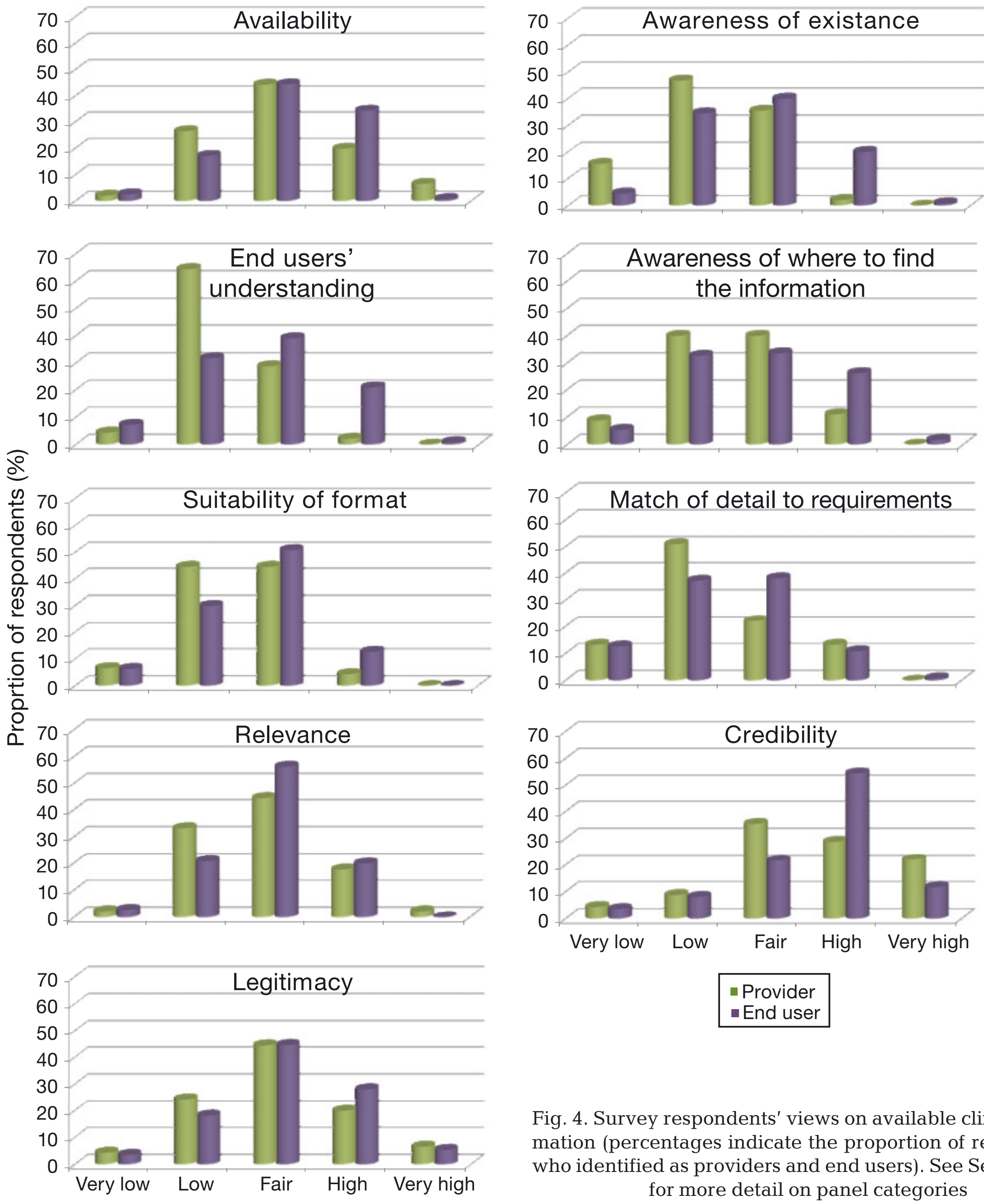

Fig. 4. Survey respondents' views on available climate information (percentages indicate the proportion of respondents who identified as providers and end users). See Section 3.1.2 for more detail on panel categories

able climate information; (5) how well the format of available climate information meets end user needs; (6) how well available climate information matches the level of detail end users require; (7) relevance of available climate information to end user needs; (8) credibility of available climate information (for the purpose of this study, credibility refers to the scientific adequacy of the evidence and arguments presented); and (9) legitimacy of available climate information refers to whether the production of information is based on accepted standards and logical reasoning, particularly with respect to how the information represents and satisfies the needs of all stakeholders.

Of the 9 characteristics, the question that resulted in the greatest gap between providers and end users was around 'end users' understanding', as shown in Fig. 4. In particular, end users rated their level of understanding about climate information much higher than providers rated end user understanding.

This is consistent with previous results showing that some end users are more highly educated about climate change and obtain their information from higher level sources than providers give them credit for. It may also be that end users think they have a better understanding of climate information than they do in reality (since we are only testing here for perceived understanding). Either way, there is a clear gap between how providers and end users rate the understanding of end users.

Fig. 4 also shows that there is a bias in responses around the question relating to end user knowledge of what climate information exists and the credibility of that information, whereby end users rate their understanding of what information exists higher than the providers, and end users also believe the information is more credible than the actual providers of that information. A common theme among both end users and providers is the problem that available climate information does not match the format, level of detail and relevance that end users require, with both groups rating these aspects as low/fair.

3.1.3. Dealing with uncertainty in climate information

One of the key focuses of the survey was to determine how providers and end users deal with uncertainty. A fundamental question in the survey aimed to assess what respondents understood uncertainty to mean (in relation to climate information). Word clouds produced from the free-text responses are shown in Fig. 5. Word clouds are used to allow researchers using different methodologies and approaches to identify common ground and, hence, points of intersection within their research (e.g. Rubin & Fornari 2011, Kiem & Austin 2013b). The font size of individual words is indicative of the number of times they were used in the responses (i.e. larger font size implies more frequent usage), and this is assumed to give some indication as to what is and what is not important. Word clouds have several limitations, however, such as determining context, and hence it is not possible to tell whether a word or phrase is being used from a positive or negative perspective. Limitations also include the potential for inaccuracies because of spelling mistakes and the use of several derivatives of the same word. Nevertheless, in this study word clouds are a useful tool for quickly analysing the large amounts of text that emerged from the survey to get an initial understanding of what respondents understood uncertainty to mean (in relation to climate information).

There were clear commonalities between the 2 groups in their definition of uncertainty, with the words 'models', 'future' and 'range' featuring in both sets of answers as shown in Fig. 5. However, there was also a distinction between the terminology of the 2 groups in terms of the word 'projections' versus 'predictions' (which have 2 very different meanings; projections are what could happen, while predictions are what is thought will happen). Providers also use terms like 'accuracy' and 'error' when describing uncertainty, whereas end users favoured terms such as 'confidence', 'quality', 'variability/variance' and 'spread'. It appears that end users mainly think of uncertainty in terms of the ability of the model to accurately simulate reality; however, providers think about uncertainty in a broader sense, encompassing the range of model projections and variability between simulations. This difference in terminology is further evidence that there is a gap, and it is suggested that this is because end users focus more on practically dealing with the actual conditions they are faced with (i.e. reality), while climate science providers focus more on model simulations, projections and scenarios that might happen.

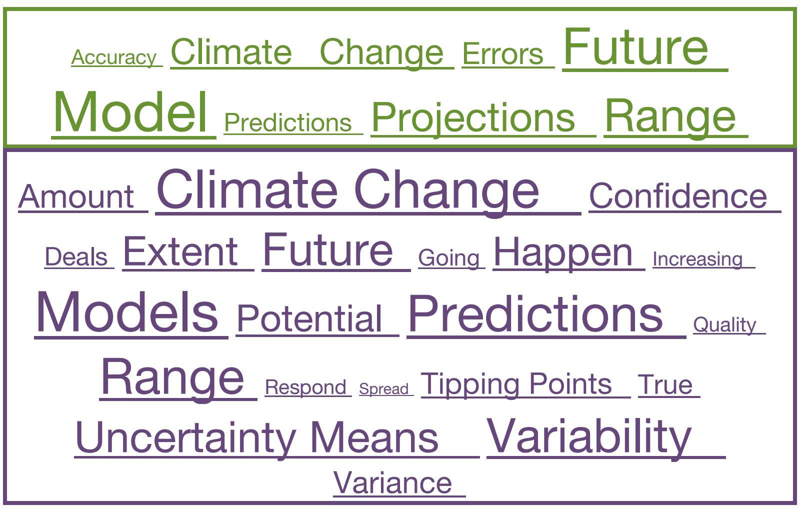

Fig. 5. Understanding of what uncertainty means in terms of climate information as reported by providers (green) and end users (purple). Font size indicates the number of times a word was used in survey responses (i.e. larger font implies higher importance)

The consensus is that uncertainty in climate science is not well communicated to end users (Fig. 6a). This

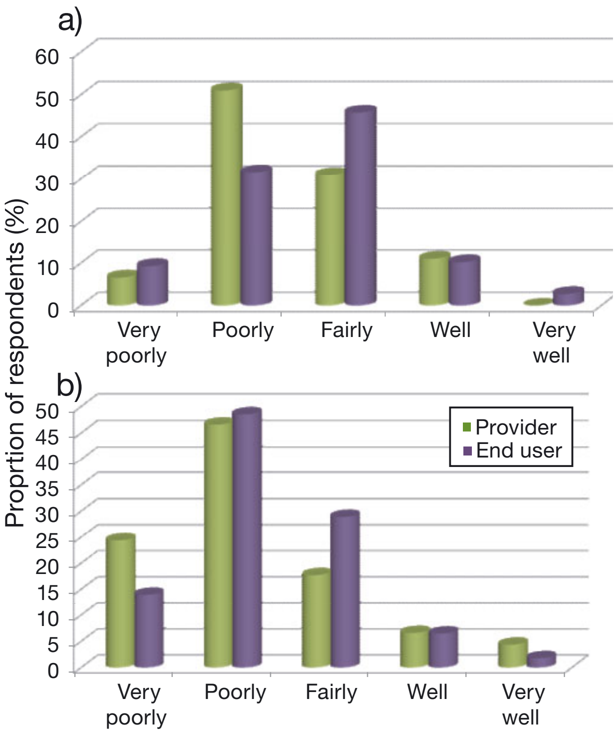

Fig. 6. (a) Provider and end user perspectives on how well uncertainty in climate information is communicated by the providers of that information; (b) provider and end user perspectives on the capabilities of end users to deal with uncertainty in climate information

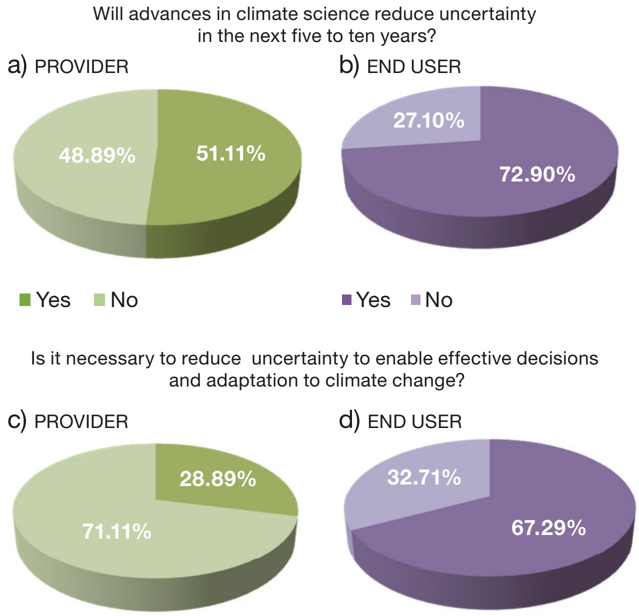

Fig. 7. (a) Provider and (b) end user views on whether advances in climate science will reduce uncertainty over the next 5 to 10 yr; (c) provider and (d) end user opinions on whether it is necessary to reduce uncertainty to enable effective decisions and adaptation to climate change

result is supported by literature (e.g. Cash et al. 2003, Dow & Carbone 2007, Tang & Dessai 2012) as well as by the survey conducted in this study, with most respondents choosing 'poor' or 'fair' when asked how well uncertainty in climate information is communicated. Indeed, >50% of providers believe that uncertainty is poorly or very poorly communicated, and <15% of respondents (irrespective of whether they are providers or end users) think that uncertainty is well or very well communicated. Fig. 6b highlights the gap between provider and end user perceptions around the capabilities of end users to deal with uncertain climate information, whereby providers appear to underestimate end users' capacity to deal with uncertainty, or end users overestimate their ability in this area.

Providers listed models, resolution, downscaling, understanding and uncertainty as major areas of advancement in climate science over the next 5 to 10 yr. However, only 51% of providers believe that these advances in climate science will lead to a reduction in uncertainty (Fig. 7a), compared with 73% of end users who have expectations that uncertainty in climate science will reduce over this timeframe (Fig. 7b). This result shows that there is a significant lack of communication around what end users should realistically expect over the next 5 to 10 yr in terms of improvements in the science. Perhaps the most striking result is the differing opinions among providers and end users about whether reduced uncertainty (assuming it is possible) enables more effective decisions and adaptation to climate change, with over 67% of end users seeing reduced uncertainty as necessary (Fig. 7d), while only 29% of providers agreed (Fig. 7c). This is an important result given that some end users may delay long-term adaptation planning while they wait for more certain climate projections that may never eventuate. The question over whether uncertainty needs to be reduced to make effective decisions was further explored in the workshop (Section 3.2).

The survey revealed that the majority of providers believe that the greatest contribution they could make to improve decision making around climate change (Fig. 8a) is more location- and variable-specific information (i.e. regional information). Approximately 30% believe that more confidence in future projections is required, while only 16% reported that they feel that end users already have sufficient information. Fig. 8b shows that this result was matched by end users, with 68% reporting that they need more specific information for locations where their decisions apply, but as discovered at the work-

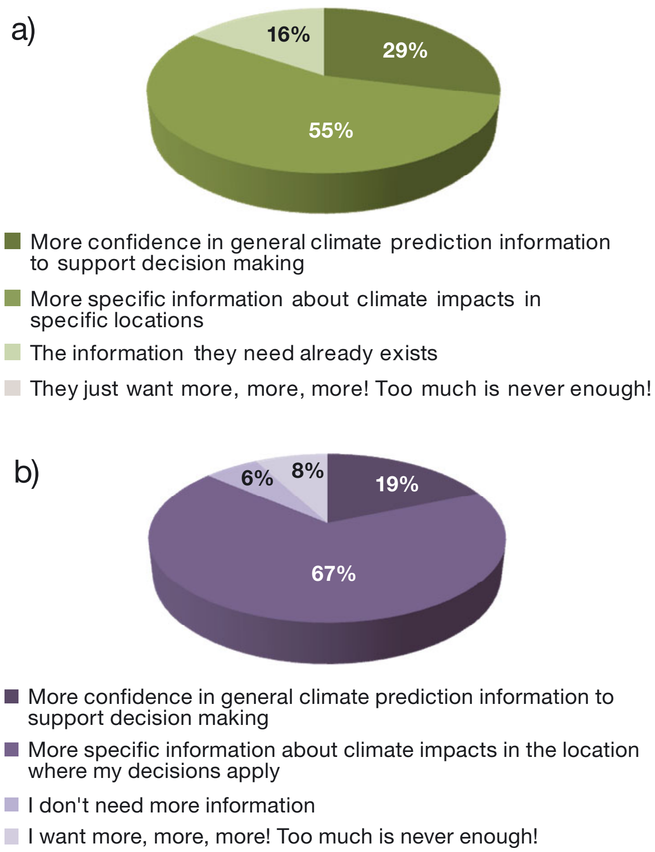

Fig. 8. (a) What providers think they need to provide to end users to improve their decision-making process; (b) end user responses when asked what they most need from the providers of climate information to improve their decision-making processes. Options that do not appear in the chart received 0% response

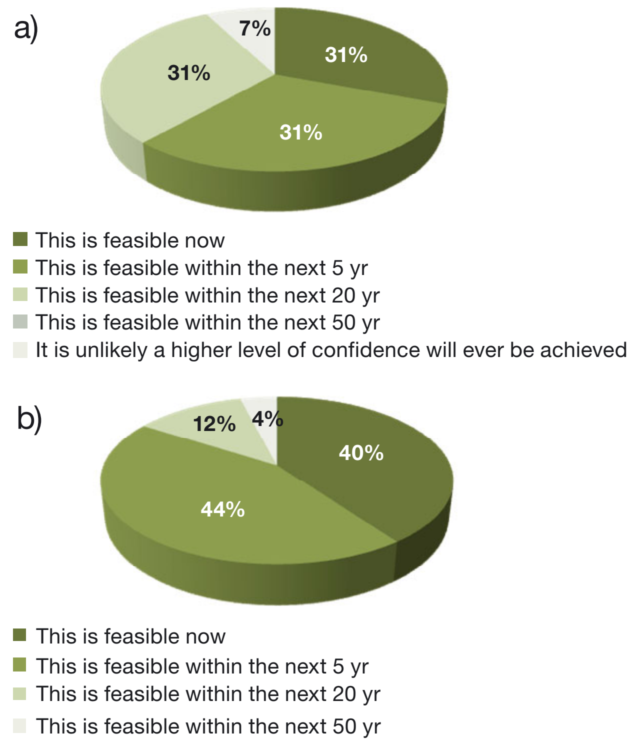

Fig. 9. (a) Provider opinion on feasibility of significant improvement in the confidence of climate information; (b) provider opinion on feasibility of providing more specific information about climate impacts in specific locations and how feasible this is. Options that do not appear in the chart received 0% response

shop (Section 3.2), this should not necessarily be interpreted as a need for more downscaling.

Fig. 9a shows that there is little consensus among providers about when there may be significant improvement in the confidence (i.e. accuracy) of climate information. An equal amount of providers (31% each) felt that this achievable in the short-term (i.e. feasible now or feasible within 5 years). However, the same amount (31%) felt that this was more of a long-term goal (i.e. feasible within 20 yr) and the remaining (7%) felt it was not feasible at all. This is a finding that conflicts with the expectation of end users (see Fig. 7d), who feel that this information is necessary now to enable effective adaptation to climate change. If the providers of this information cannot agree on this issue, how can end users take the likelihood of future improvements in climate information into account in their planning? By contrast, when asked about the feasibility of providing specific information about climate impacts in specific locations (Fig. 9b), providers were more in agreement that this is a feasible short-term goal (84% agreed that this is possible within 5 yr). This is likely to be a reflection of the increased investment (both academically and financially) into the downscaling of climate models in Australia and, indeed, around the world. However, Fig. 9a,b also highlights a critical point that many (both providers and users of climate information) do not appreciate. That is, with increasing computing power and funding, the feasibility of more specific or precise climate information will increase (as suggested by Fig. 9b). However, this does not necessarily mean that the information produced is more accurate or useful (as suggested by Fig. 9a).

3.2. Workshop

3.2.1. End user accounts of dealing with uncertainty in decision making

It was clear that the end user presenters from each case study region had different levels of experience, methods and ideas about dealing with uncertainty in decision making with respect to climate change. Even within the case study regions, the approach varied between representative organisations. However, there was clear consistency around the approach of planning for a wide range of plausible futures by developing robust and adaptive responses that are consistently reviewed moving forward in time.

The end user presenters' expectations for the use of future climate information were insightful given that they were united in their belief that uncertainty would remain no matter how good the climate science is or becomes—a finding that seems to contradict the survey results presented in Fig. 7b. However, discussion revealed that while end users do expect uncertainty in climate science to reduce over the next 5 to 10 yr (Fig. 7b), they definitely understand that significant uncertainty will remain, both in the climate science and in decision making because of other sources (e.g. politics, population growth, economics, social and community issues). This issue of irreducible climate uncertainty and uncertainty associated with non-climatic influences is well documented (e.g. Randall et al. 2007, Stainforth et al. 2007, Koutsoyiannis et al. 2008, 2009, Pitman & Perkins 2008, Blöschl & Montanari 2010, Montanari et al. 2010, Kiem & Verdon-Kidd 2011) and is further discussed in Section 3.4.

The end user presenters commented that uncertainty in climate science may be reduced by model improvements (e.g. in their ability to replicate large-scale climate modes that drive Australian climatic variability). However, the major advances are likely to be in ways to better define plausible scenarios that holistically capture drivers and impacts associated with both climate variability and change, and the development of decision support systems to enable interpretation of uncertainty and non-stationarity, and to aid in planning for low-probability/high-consequence events (i.e. the 'black swans'). This is also different from the survey results that identified more specific information at specific locations as the most likely major advancement in the science, which again suggests confusion between precision (i.e. more specific) and accuracy (i.e. more realistic). Some interesting quotes from both provider and end user participants when reflecting on this session in the workshop are included below:

> 'Need more understanding of climate variability, not just projections'

> 'Focus should be on robust solutions rather than certainty in projections'

> 'The speaker mentioned that uncertainty of predictions was a problem when communicating with the community and seemed to infer that it was scientists' problem. I am wondering if it is because as a community we are unaware of the level of uncertainty in which we exist? And as part of climate change conversations, we need to be educated as a community about uncertainty'

3.3. Scientists' views on the state of the climate science

The second workshop session aimed to provide participants with an up-to-date account of the 'state of climate science' (see Table 2 for workshop program). Again, at the end of the information session, participants were asked to reflect on the themes arising from the session and, in particular, if they felt that the gap had widened or narrowed following the discussions. There was some disagreement between tables as to whether the gap had widened or narrowed. Tables that were predominantly end users actually commented that they felt the gap had narrowed because of their improved understanding of the scientific issues. Two comments reflect the overall consensus that while it was unclear whether the gap had widened or narrowed, the workshop had, at the very least, helped improve awareness of the gap (both real and perceived), which is the first step towards bridging the gap.

> 'I don't think the gap has widened. I think that people's awareness of the size of the gap has improved'

> 'There is a difference between the REAL and PERCEIVED gap. The outcome of a meeting such as this must be a narrowing of the real gap; however, depending on one's starting point, the perceived gap may appear wider as more complex information comes to light!'

3.4. Reflections on the workshop

At the start of the workshop, participants were asked to reflect on the following: (1) what they understood uncertainty to mean; and (2) if they thought it was possible to effectively adapt and manage climate risk under uncertainty given the current tools and information available and if so, why, and if not, why not.

During the last session of the workshop, participants were once again asked to reflect on these 2 questions, along with the additional question 'What are the take-home messages and priority actions from the workshop?' The aim of this exercise was to assess the success of the workshop as a tool for bridging the gap (i.e. bring scientists and decisions makers together to facilitate knowledge transfer between the 2 groups).

Despite the fact that uncertainty is a well-defined concept (e.g. https://www.ipcc.ch/pdf/glossary/ar4-wg1.pdf), workshop participants referred to uncertainty in very different ways when they were asked at the start of the workshop what it meant to them (Table 3); the same occurred in the survey (Fig. 5). This demonstrates that even though uncertainty may be well defined in the scientific community, it still means different things to different people. This points to reasons for the gap between end users and scientists (and even between different groups of end users or different disciplines of science) but also to opportunities to bridge the gap via education or further research (e.g. educate end users on the scientific definition of uncertainty; conduct research into why people do not know what uncertainty is and whether or not the scientific definition of uncertainty is relevant or agreeable to end users). By the end of the workshop, scientist and end user understanding of uncertainty did not change significantly. However, it was agreed that 'better clarity through technical definitions' had been gained, especially for end users, and that the importance of uncertainty not related to climate was reinforced, especially from a climate scientist perspective. This is a very satisfactory result, as prior to the workshop end users said that one thing that would make the workshop valuable is 'an appreciation that climate change adaptation and decision making is based on more than just climate'. Based on the following comments given by scientists after the workshop, it seems that this was achieved:

> 'The workshop reinforced my view on uncertainty and reinforced that climate change uncertainty is not the only uncertainty and not always the most important.'

> 'I still tend to view uncertainty the same as before the workshop with respect to climate change projections; however, I now recognise that there are political, social and demographic issues affecting decision makers that may be of equal or greater magnitude than scientific uncertainty.'

Participants were asked prior to the workshop if they thought it was possible to effectively adapt and manage climate risk under uncertainty given the current tools and information available (responses provided in Table 4). The typical response was 'yes', evidenced by the fact that people already are generating and implementing adaptation plans. Scientists thought that 'there is enough information to make effective adaptation possible'; however, it was identified that effective adaptation and management of risk is exposed to barriers (e.g. 'social and behavioural') and that success is dependent on the 'climate variable and the system in question'. One group that included a mix of scientists and end users identified that 'the context and the technical and socioeconomic implications of the decision to be made' influences the effectiveness of current tools and information. When asked the same question at the conclusion of the workshop, responses were consistent with pre-workshop opinions. End users felt that although a range of information, processes and tools are already in use to inform decisions under current levels of uncertainty, these tools require improvement. Responses from scientists reiterated that the effectiveness of current information and tools is situation dependent, indicating again that a more holistic approach is required.

Table 3. Participants' responses on what uncertainty meant to them at the start of the workshop

What do you currently understand uncertainty to mean?	Response
	Unresolvable, inherent unpredictability
	Uncertainty in future regional climate change
	In terms of climate change, it means we do not know what might happen, e.g. whether water supply reliability to urban consumers will rise or fall
	The future will be one of several plausible outcomes
	Recognition that there are many possible outcomes
	It means different things to different people
	'We were certainly uncertain, least I'm pretty sure I am'
	'There are known knowns, known unknowns (the things we know that we don't know), but there are also unknown unknowns' (approx.)
	Common usage = uncertainty is variability and risk is variability with possible negative consequences
	Classical uncertainty is when you know the outcomes but you don't know the probabilities; we should be so lucky
	Difference between model result and reality
	Range of potential futures
	Uncertainty is not the same thing as precision and accuracy

To determine the key take-home messages and priority actions emerging from the workshop, participants were presented with a list of issues that arose throughout the workshop and were asked to vote on what they felt were the most important to

Table 4. Participants' views on the effectiveness of adaptation given current uncertainty

Do you think it is possible to effectively adapt and manage climate risk under uncertainty given the current tools and information available?	Response
	Yes, because understanding vulnerability and sensitivity is a sound basis for adaptation under uncertainty
	There is enough information to make effective adaptation possible, but there are barriers (e.g. social, behavioural) that may be difficult or impossible to overcome
	To some degree, yes, because even without climate change, we do manage for large climate variability already
	A bit: depends on the context and the technical and socioeconomic implications of the decision to be made
	Yes; uncertainty should not be an excuse not to act, and uncertainty will always be there
	Yes, because people already are; adaptation is a messy business, and we can be messy
	Current information allows risks to be identified but problematic for making investment decisions
	Current uncertainty generally drives us towards robust solutions that may not be optimal for what actually eventuates
	Yes, but it depends on the climate variable and the system in question

address to bridge the gap and enable better decision making under uncertainty; 1 vote per person was allowed, with votes submitted confidentially through iMEET!. Table 5 lists the issues that were voted on, sorted to indicate the highest priority issues (i.e. the ones that received the most votes) at the top.

Table 5 shows that there were 3 primary issues that participants felt were the most important:

(1) Improved communication and packaging of climate information (highlighted in red in Table 5). Participants commented that this was not just more glossy brochures and presentations by climate scientists; rather, the role of a 'knowledge broker' that could operate in the space between the 2 parties was identified. The role of the 'knowledge broker' would be to package, translate (both ways) and transform climate information (see authors unpubl. for further details on the proposed 'knowledge broker').

(2) A better understanding and quantification of baseline risk, natural variability and non-stationarity (comments related to this are highlighted in green in Table 5). This issue arose on multiple occasions throughout the workshop, and it is clear that guidance needs to be developed for end users to integrate this into their climate impact assessment and adaptation processes and, in particular, how the natural variability might change.

(3) Development of tools and methods to integrate between projections and decision making (comments related to this are highlighted in blue in Table 5). This issue is the focus of a parallel project, funded by NCCARF, entitled 'Understanding end user decisions and the value of climate information under the risks and uncertainties of future climates' (refer to www.nccarf.edu.au/content/decisions-under-climate-risks for further information)

4. CONCLUSIONS

Uncertainty in climate science is often seen as a key barrier to adaptation. As demonstrated by this project, the issue of uncertainty is multi-faceted, with issues identified in terms of communication of uncertainty, misunderstanding of uncertainty and the lack of tools/methods to deal with uncertainty. The findings of the survey revealed that both the providers of climate information and end users, mostly from the water resources or agriculture sectors, felt that uncertainty was not well communicated, and this was noted as an area where significant improvements could be made to narrow the gap. There were also key differences surrounding uncertainty in terms of expectations for the future, with most end users believing that uncertainty would decrease within the next 5 to 10 yr; however, providers are well aware that this most likely will not be the case. End users were also of the opinion that uncertainty needs to be reduced to develop effective adaptation strategies, and there were many comments in the free-text sections of the survey relating to the use of uncertainty as an excuse to 'do nothing'. This is a key finding, as some end users in decision-making roles may be waiting for uncertainty in climate information to reduce and are delaying taking action on adaptation and risk planning now; however, this improvement in uncertainty may never eventuate. To help narrow the gap, it is clear that further education of end users is needed with respect to uncertainties in climate science, the limitations of the currently available information, the likely advances in the next 5 to 10 yr and how to best use the available information (taking into account these uncertainties and limitations) to develop effective adaptation plans.

Table 5. List of key issues arising from the workshop ranked according to number of votes. Coloured text: red = communication/translation; green = natural variability/change; blue = tools and methods. CMIP6: Coupled Model Intercomparison Project Phase 6; GCM: general circulation model; RCM: regional climate model

No. of votes	Key issue to arise from workshop
12	The need for **'knowledge broker'** to fill the space between developers of climate science information and application of that information by end users
8	The requirement for **dialogue** between providers and end users to bridge the gap effectively; this is an extremely complex, time-consuming and resource-intensive task which has not been factored into any plans or strategies
7	Greater consideration of **baseline risk** and accounting for **non-stationarity** when developing climate projections
7	Improved **packaging** of climate projections (e.g. climate futures)
6	Improved understanding of **natural variability** drivers and impacts and how that might change in the future
6	More focus on **tools and methods** to integrate between projections and decision making
6	Continue open and frank **dialogue** between scientists and end users in all climate projects
5	Better **communication** of climate science—not just better PowerPoint slides or glossy brochures, but **delivery of practical information** to end users, and feedback to climate scientists regarding end user needs
5	**Better understanding of how decisions are made**
4	Improved **capacity to deal with wide diversity of end users** (each of which need a different approach — the science community does not have the capacity to deliver this)
3	More focus (i.e. funding) on the **attribution of current/recent/historical extremes**
2	Focus on **plausible scenarios** rather than more precise information
2	Black swans... what to do? Ignore and hope for best?
2	Accept that the gap is real and that it is unrealistic to expect it to close... what now?
1	More focus (i.e. funding) on downscaling
1	More focus (i.e. funding) on next round of GCM outputs (e.g. CMIP6)
1	Identification of plausible regional adaptation options
0	More focus (i.e. funding) on GCM/RCM selection/evaluation
0	More focus (i.e. funding) on emission scenarios
0	Insights/quantification of relative importance of different sorts of uncertainties (including non-climatic)

The misuse or misunderstanding of key terminology was another factor that featured in the literature review, survey and workshop. It was clear that end users and scientists used different terms for the same purpose or vice versa; the same terms meant something completely different depending on who was using them and what their background was. For example, 'prediction' (the way things will happen in the future), 'projection' (model-derived estimates of future climate) and 'scenario' (coherent, internally consistent and plausible description of a possible future state of the world) were used interchangeably by end users (and some providers). Fig. 5 and Table 3 also demonstrate that despite uncertainty being a well-defined concept (at least within the scientific community), the end users and scientists who participated in the workshop still came up with an extremely varied set of responses when asked what uncertainty means to them. This lack of consistency on key terminology and interchangeable or uninformed usage causes confusion and is a significant contributor to the gap. A key outcome of the study is the recommendation that a list of key terminology be produced that end users can easily access and interpret. The IPCC has already produced such a list, which could provide the basis for an Australian version of definitions, but education would also be required, particularly within the mainstream media, to ensure that people are aware of and consistently use the correct terminology.

The workshop also emphasised the need for a 'whole of climate approach' to climate-related risk assessment and adaptation (i.e. taking into account climate variability and change, and dealing with extreme events like floods and droughts not as unexpected disasters, but as part of a non-stationary climate system). Embedded in this is how to best incorporate considerations of natural variability with climate change projections (i.e. where is here [~1990], where is there, how do we get there from here, what if variability in the future is different from variability in the instrumental record). Another related issue is defining the baseline for climate change projections and uncertainty surrounding this. Additional research needs to be conducted into natural variability and baseline risk. This information then needs to be translated into a series of recommendations that can be transferred to climate risk/impact studies across a range of disciplines (e.g. flooding, drought planning, infrastructure design). There is also a clear need to further develop tools and methods to integrate between projections and decision making that properly account for uncertainty.

The decision support systems also need to account for non-climatic influences (e.g. social, environmental, political, economic) on what are essentially climate-driven problems that require solutions driven by much more than just the climate. However, the development of decision support tools is secondary to the need for improved education and communication given that the delay in developing such tools may provide an excuse for end users to procrastinate and delay the decision-making process.

Improved communication and packaging of climate information was another key theme highlighted in the survey and workshop. This is not just more glossy brochures and presentations by climate scientists; rather, there is a role for a program or group of people to fill this role. This program was called a 'knowledge broker' during the workshop and was further explored in a follow-up focus group (for more detail, see authors unpubl.). It is clear from the results presented here and in previous studies (e.g. Guston et al. 2000, Cash et al. 2003, Meinke et al. 2006, Ekstrom et al. 2011, Gallant et al. 2012, Lemos et al. 2012, Rickards 2012, Kiem & Austin 2013b) that a 'knowledge broker' (also known as a 'boundary worker' or 'boundary organisation') that provides better synthesis, translation and packaging of climate science could be useful for end users, especially in the water resources and agriculture sectors, and also would increase scientists' awareness of, and ability to work towards addressing, the needs of end users. The role of the 'knowledge broker' would be to package, translate (from both end user to scientist and scientist to end user) and transform climate information, and also to educate decision makers on climate change science and climate change adaptation (e.g. via short courses, seminars, workshops). Importantly, education and communication of uncertainty needs to be improved so that end users are aware of all of the caveats and what can realistically be expected from climate science now and in the near future — and also how to properly use climate science insights and modelling outputs. This 'knowledge broker' should also include strengthening interactions between producers/providers/researchers and end users and addressing weaknesses or gaps by building teams that contain an appropriate mixture of research and communication/outreach skills. There is evidence that end users do appreciate interacting with knowledge-providing experts who understand and address their needs, but they are wary, particularly in the agriculture sector, if that person (or organisation) is seen as something that filters (or possibly modifies) the science (e.g. Hart et al. 2012, Lemos et al. 2012, Moser & Ekstrom 2012, Kiem & Austin 2013a); hence, the 'knowledge broker' needs to be more than just a middleman. These studies also reveal that there is not so much a need for more climate science outputs as a need for improved packaging of information that is consistent, legitimate, credible and useful for end users and decision makers. This is consistent with the results emerging from the survey and workshop conducted in this study (e.g. Fig. 4, Table 4, Table 5).

While this study focused only on Australia, and specifically on climate change adaptation in the water resources and agriculture sectors, the findings are relevant for other sectors as well as internationally. In bridging the gap and developing the 'knowledge broker', useful lessons can be obtained from recent international studies (e.g. Hart et al. 2012, Moser & Ekstrom 2012) that reveal interesting insights into the timing of the demand (and perception of the need by end users or decision makers) for a 'knowledge broker'. Hart et al. (2012) found, also from a survey, that there were surprisingly few people claiming that there was a need for more scientific information (meaning lack of scientific information was not really a barrier to their climate change adaptation processes). Moser & Ekstrom (2012) (an update of Tribbia & Moser [2008]) also found that surprisingly few people in their study on managers of coastal communities (interview- and observation-based) talked about lack of science as a barrier to climate change adaptation. The conclusion reached was that the communities studied (Tribbia & Moser 2008, Hart et al. 2012, Moser & Ekstrom 2012) do not 'need' science information because they are not far enough along in the climate change adaptation process to see the need for more science information or to be able to use it if it were available. Our study also found that there is not so much a need for more climate science outputs, but that those that are farther along in the climate change adaptation process (e.g. agricultural communities and water resource managers in Australia) do need improved packaging of information that is consistent, legitimate, credible and useful for end users and decision makers. Given the limited capacity and capabilities within many existing decision-making organisations, a 'knowledge broker' really could be put to good use (especially in the Australian water resources and agriculture sectors).

Overall, the project identified that there is indeed a gap between end user needs and science capability, particularly with respect to uncertainty, communication and packaging of climate information. This gap has been a barrier to successful climate change adaptation in the past, but based on the recommendations provided in this paper, it may be possible to bridge the gap (or at least improve people's awareness of the gap).

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