Climate prediction: a limit to adaptation?

Suraje Dessai^{1,2}, Mike Hulme^{1,2}, Robert Lempert^{3} and Roger Pielke, Jr.^{4}

1 – Tyndall Centre for Climate Change Research, UK
2 – School of Environmental Sciences, University of East Anglia, Norwich, UK
3 – RAND Corporation, Santa Monica, California, USA
4 - Center for Science and Technology Policy Research, University of Colorado, USA

Chapter in, **Living with climate change: are there limits to adaptation?**
Edited by W. Neil Adger, Irene Lorenzoni and Karen O'Brien
Cambridge University Press, Cambridge

1. Introduction

Projections of future climate and its impacts on society and the environment have been crucial for the emergence of climate change as a global problem for public policy and decision-making. Climate projections are based on a variety of scenarios, models and simulations which contain a number of embedded assumptions. Central to much of the discussion surrounding adaptation to climate change is the claim – explicit or implicit – that decision makers need accurate, and increasingly precise, assessments of future (impacts of) climate change in order to adapt successfully. According to Füssel (2007) "*the effectiveness of pro-active adaptation to climate change often depends on the accuracy of regional climate and impact projections, which are subject to substantial uncertainty*". Similarly, Gagnon-Lebrun and Agrawala (2006) note that the level of certainty associated with climate change and impact projections is often key to determining the extent to which such information can be used to formulate appropriate adaptation responses. If true, these claims place a high premium on accurate and precise climate predictions at a range of geographical and temporal scales. But is effective adaptation tied to the ability of the scientific enterprise to predict future climate with accuracy and precision?

This essay addresses this important question by investigating whether or not climate prediction is a (perceived) limit to adaptation. The chapter examines the arguments implicit in the various claims made about climate prediction and adaptation. It suggests that an approach focused more on robust decision-making is less likely to be constrained by epistemological limits and therefore more likely to succeed than an approach focused on optimal decision-making predicated on the predictive accuracy of climate models. The chapter proceeds in three sections. Section 2 provides evidence of claims that accurate climate prediction on timescales of years to decades at regional and finer spatial scales is necessary for adaptation decision-making. This evidence is drawn from peer-reviewed literature and from published science funding strategies and government policy documents. Section 3 discusses the challenges to accurate climate prediction and why science will consistently be unable to provide reliable and precise predictions of future climate at the regional and local scales that are claimed to be relevant for adaptation. Section 4 explores alternatives to climate prediction with a focus on robust decision-making. The latter captures a variety of approaches that differ from traditional optimum expected utility analysis in that they characterise uncertainty with multiple representations of the future rather than a single set of probability distributions. They use robustness, rather than optimality, as a decision criterion. Section 5 draws together some conclusions and implications for climate and science policy.

2. Climate prediction for adaptation decision-making

Scientific understandings of phenomena are often tested via predictions that are compared against observations. For example, weather forecasters evaluate the skill of their forecasts by comparing predicted weather against actual weather events. Decision makers also make predictions about the relationship of actions and outcomes when they choose one course of action over another. Such predictions involve some expectation of the consequences of action and the desirability of those consequences. Lasswell and Kaplan (1950) explain: "*decision making is forward looking, formulating alternative courses of action extending into the future, and selecting among alternatives by expectations about how things will turn out*."

There is therefore a natural tendency for policy makers to look to scientists to aid decision making by providing insight on how the future will turn out. In many cases, science has provided enormous benefits to decision makers, either by providing an accurate forecast of future events, such as knowledge of an approaching storm, or by enabling technological innovation that helps decision makers consciously steer the future toward desired outcomes, such as with the invention of vaccines that improve public health. But there are other circumstances where an improper reliance on scientific prediction to enable decision making does not have such positive outcomes; policy responses to earthquakes are a notable example (see Sarewitz and Pielke Jr. 1999).

Climate science has proven to be enormously valuable in detecting and attributing recent changes in the climate system. Science has shown that the climate system is undergoing unprecedented changes that cannot be explained solely by natural factors. Unless both natural and anthropogenic forcings are included, climate model simulations cannot mimic the observed continental- and global-scale changes in surface temperature, and other climate-related biogeophysical phenomena, of the last 100 years. Under scenarios of increasing greenhouse gas emissions, climate models estimate that the climate system will continue to change for many more decades and longer.

The ability of climate models to reproduce the time-evolution of observed global mean temperature (within an uncertainty range) has given them much credibility. Advances in scientific understanding and in computational resources have increased the credibility of climate models when projecting into the future using scenarios of greenhouse gas emissions and other climate-forcing agents. Many climate scientists, science funding agencies and decision makers have argued that quantifying the uncertainty and providing more accuracy and precision in assessments of future climate change is crucial to devise adaptation strategies. The quotes in Table 1 exemplify some of these voices. Table 1 includes two quotes from the late 1970s to show that this sort of thinking has been around for at least 30 years.

TABLE 1

If such claims are true, then they place a high premium on accurate and precise climate predictions at a range of geographical and temporal scales as a key element of decision making related to climate adaptation. Under this line of reasoning, such predictions become indispensable, and indeed a prerequisite for, effective adaptation decision-making. According to these views, adaptation would be limited by the uncertainties and imprecision that afflicts climate prediction. The next section briefly assesses the state of climate prediction from an adaptation perspective and asks whether indeed accurate and precise predictions of future climate can (ever) be delivered.

3. Are there limits to climate prediction?

The accuracy of climate predictions is limited by fundamental, irreducible uncertainties. Uncertainty means that more than one outcome is consistent with expectations. For climate prediction, uncertainties can arise from limitations in knowledge (e.g., cloud physics), from randomness (e.g., due to the chaotic nature of the climate system), and also from intentionality, as decisions made by people can have significant effects on future climate and on future vulnerability (e.g., future greenhouse gas emissions, population, economic growth, development, etc.). Some of these uncertainties can be quantified, but many simply cannot, meaning that there is some level of irreducible ignorance in our understandings of future climate (Dessai and Hulme 2004).

A 'cascade' or 'explosion' of uncertainty arises when conducting climate change impact assessments for the purposes of making national and local adaptation decisions (Jones 2000). In climate projections used for the development of long term adaptation strategies, uncertainties from the various levels of the assessment accumulate. For example, there are uncertainties associated with future emissions of greenhouse gases and aerosol precursors, uncertainties about the response of the climate system to these changes (due to structural, parameter and initial conditions uncertainty) and uncertainties about impact modelling and the spatial and temporal distributions of impacts. Wilby (2005) has shown that the uncertainty associated with impact models (in his case a water resources model) arising from the choice of model calibration period, model structure, and non-uniqueness of model parameter sets, can be substantial and comparable in magnitude to the uncertainty in greenhouse gas emissions.

Recent increases in computational power have allowed the partial quantification of model uncertainty in climate projections using techniques such as perturbed-physics ensembles (Stainforth et al. 2005), multi-model ensembles (Tebaldi and Knutti 2007), statistical emulators (Rougier and Sexton 2007) and other techniques. This has partially moved the science from deterministic climate projections to probabilistic climate projections, but the interpretation of the latter are much disputed (Stainforth et al. 2007). Most of this work is done with GCMs of coarse resolution (e.g. 300-500km grids), but ensembles of regional climate model simulations (e.g. 25-100km grids) are also being developed (Murphy et al. 2007, which includes the next set of national UK climate scenarios, UKCIP08). Studies that have propagated these various uncertainties for the purposes of adaptation assessments (sometimes called end-to-end analysis) have found large uncertainty ranges in climate impacts (Whitehead et al. 2006, Wilby and Harris 2006, Dessai and Hulme 2007, New et al. 2007). They have also found that the impacts are highly conditional on assumptions made in the assessment, for example with respect to weightings of GCMs (according to some criteria, such as performance against past observations) or to the combination of GCMs used. Some have cautioned that the use of probabilistic climate information may misrepresent uncertainty and therefore lead to bad adaptation decisions (Hall 2007). Hall (2007) warns that improper consideration of the residual uncertainties of probabilistic climate information (which is always incomplete and conditional) in optimisation exercises, could lead to maladaptation and be far from optimal.

Future prospects for reducing these large uncertainties are limited for several reasons. Only part of the modelled uncertainty space has been explored up to now (due to computational expense) so uncertainty in predictions is bound to increase even as computational power increases. It has proved elusive to find 'objective' constraints with which to reduce the uncertainty in predictions (see Allen and Frame 2007, Roe and Baker 2007 in the context of climate sensitivity). The problem of equifinality (sometimes also called the problem of 'model identifiability' or 'non-uniqueness') – that many different model structures and many different parameter sets of a model can produce similar observed behaviour of the system under study – has rarely been addressed except in some impact sectors such as water resources (see, e.g., Wilby 2005).

It is also important to recognise that when considering adaptation, climate is only one of many processes that influence outcomes, sometimes important in certain decision contexts, other times not (Adger et al. 2007). Many of the other processes (e.g., globalisation, economic priorities, regulation, cultural preferences, etc) are not considered to be amenable to prediction. This raises the question of why climate should be treated differently, or why accuracy in one element of a complex and dynamic system would be of benefit given that other important elements are fundamentally unpredictable. One answer is that we currently live in a society with a strong emphasis on science- and evidence-based policy-making. This has led predictive scientific modelling to be elevated above other evidence base because it can be measured and because of its predictive power (Evans 2008).

The quotes in Table 1 imply that more accurate (i.e., reduced uncertainty) and more precise (i.e., higher resolution) regional climate change predictions will help to solve the challenge of adaptation by providing a more faithful description of the future. However, Bankes (1993) notes that such efforts fall prey to false reductionism: "*The belief that the more details a model contains the more accurate it will be. This reductionism is false in that no amount of detail can provide validation, only the illusion of realism.*" This mindset is visible in the climate science community with many efforts geared towards increasing the spatial resolution of climate models and adding further components to the model structure. Furthermore, there appears to be confusion amongst users about the relationship between accuracy and precision. Higher precision, in the form of higher spatial (e.g., 25 km^2 grids) and temporal (e.g., sub-daily estimates) resolution, is often equated with greater realism (i.e., higher accuracy), but that is not necessarily the case. High precision can have low accuracy and high accuracy can have low precision. For example, the statement that "global mean temperature is projected to increase between 1.4 and 5.8ºC by the end of the century" may prove to have high accuracy but low precision. Correspondingly, the statement that "maximum summer temperature is projected to increase by 5.7 ºC by the end of the century in the London area" may prove to have high precision but low accuracy. According to the Oxford English Dictionary, accurate means 'correct in all details', while precise contains a notion of trying to specify a detail exactly.

We have discussed accuracy and precision in the context of spatial and temporal resolution, but as climate projections move into the probabilistic realm there are interesting trade-offs between accuracy and precision. Figure 1 shows two probability density functions (PDFs), where the dotted PDF is less precise than the full PDF, but the dotted PDF is more accurate than the full PDF. In this case precision can be characterised as the standard deviation of the measurements. The larger the standard deviation the lower the precision. Accuracy relates to the difference between the true value and the PDF in question. The higher the difference the lower the accuracy. Extremely wide PDFs have low precision but may be accurate; they may also make it difficult to make decisions (at least under an optimisation paradigm). On the other hand, narrow PDFs with high precision may lead to inaccurate results and therefore to maladaptation (false negatives and false positives). Given the wide PDFs that climate science will necessarily provide over the next few years (and probably decades) there is likely to be a demand for further precision (i.e., narrower PDFs).

FIGURE 1

There are also fundamental reasons why climate prediction may fail to fulfil the mission expected of it by the advocates quoted in Section 1. For some scholars (see Ravetz 2003), complex models of open systems are best viewed as heuristic tools which help our understanding of what we can observe, measure or estimate, rather than ‘truth machines’ which determine our future. Oreskes et al. (1994) argue that verification and validation of numerical models in the earth sciences is impossible; models can only be evaluated in relative terms, making their predictive value open to question. In the context of complex climate models, Stainforth et al. (2007) have reiterated this point: “*statements about future climate relate to a never before experienced state of the system; thus it is impossible to either calibrate the model for the forecast regime of interest or confirm the usefulness of the forecasting process*”.

Based on ten case studies (from weather to earthquake prediction and many others), Pielke Jr et al. (2000) came up with five conditions that are needed for prediction to be useful for decision-making:

1. Predictive skill is known.

   In other words, decision makers have a basis for calibrating the expected accuracy of the prediction. Government weather forecast agencies issue many millions of forecasts every year, providing a rich basis of experience for evaluating predictive performance. In a situation where the forecast is *sui generis*, an evaluation of expected accuracy is necessarily based on factors other than actual performance.

2. Decision makers have experience with understanding and using predictions.

   When decision makers have experience with using a particular forecast they develop the ability to calibrate its strengths and weaknesses. Research on the use and value of seasonal climate forecasts has indicated that decision makers often fail to understand the forecasts in the context of the decision environment, and because seasonal climate anomalies, such as ENSO, occur only every several years, it is difficult to acquire enough experience for the forecast to become meaningful.

3. The characteristic time of the predicted event is short.

   In order for feedback to take place between a forecast – a decision – and an outcome, the time period of an event being predicted need to be short enough for information on the outcome associated with the decision to be evaluated and factored into the subsequent decision making process. Predictions of events far into the future by definition cannot be verified or learned from on the time scale of decision-making.

4. There are limited alternatives

   In some situations decision makers have alternative approaches to decision making that do not require reliance on predictions. Earthquake policy is an example of such a situation. While some scientists hold out hope for developing predictive skill of particular earthquakes, policy makers have chosen to focus on engineering design of structures such that buildings will withstand shaking regardless when the event occurs. By contrast, for those who live in low lying areas exposed to tsunamis, there is little alternative to a well functioning early warning system to facilitate evacuation from a coming tsunami.

5. The outcomes of various courses of action are understood in terms of well-constrained uncertainties

Decision makers need to understand with some degree of accuracy how various alternative courses of action will relate to particular outcomes. Otherwise, there is no basis for expecting one decision to lead to desired outcomes any more than another decision. A prediction will inform effective decision making only if it is helpful in discriminating among alternative courses of action in terms of their expected outcomes.

Unfortunately, climate prediction at the decadal to centennial scale fails to meet all these conditions. Predictive skill is unknown, and for long-term predictions cannot be known (1). The accuracy at global and continental level is considered to be higher than at the regional level, but at regional to local scales accuracy is largely unknown. There is little (but slowly growing) experience of decision-makers using long-term climate predictions (2) because until the 1980s or 1990s climate was widely assumed to be stationary and long-term climate predictions were non-existent or tentative. The predictions we are considering here are long-term (3), from a decade up to a century. Alternatives to prediction exist (4) and are discussed in the next section. Finally (5), the outcomes of alternative adaptation strategies often depend little on discriminating among various climate predictions.

This section has shown that there are important limitations to our ability to predict future climate conditions for adaptation decision-making. These include widening uncertainties (as we gain more knowledge of how the climate system operates; some uncertainties are irreducible though), lack of objective constraints (with which to reduce the uncertainty of predictions) and the problem of equifinality. Furthermore, there is much evidence that shows that climate is only one of many uncertain processes that influence society and its activities. This suggests that climate prediction should not be the central tool to guide adaptation to climate change. We argue therefore that adaptation efforts should not be limited by the lack of reliable (accurate and precise) foresight about future climate conditions. The next section elaborates on alternatives to prediction.

4. Making decisions despite deep uncertainties

Individuals and organizations commonly take actions without accurate predictions of the future to support them. They manage the uncertainty by making decisions or establishing decision processes that produce satisfactory results in the absence of good predictions. For instance, no one expects to predict the results of scientific research. Organizations nonetheless undertake such activity. For instance, a private firm might fund multiple initial research and development projects that offer potential new products, assess their progress, and continue those few that seem most promising. Such an adaptive policy often proves a successful response to the lack of predictive ability.

In recent years, a number of researchers have begun to use climate models to provide information that can help evaluate alternative responses to climate change, without necessarily relying on accurate predictions as a key step in the assessment process. The basic concept rests on an exploratory modelling approach (Bankes

1993) where analysts use multiple runs of one or more simulation models to systematically explore the implications of a wide range of assumptions and to make policy arguments whose prospects for achieving desired ends is unaffected by the uncertainties.

One fundamental step in such analyses is to use climate models to identify potential vulnerabilities of proposed adaptation strategies. For instance, Dessai (2005) uses information from climate models to identify potential weaknesses in strategies that water management agencies in the UK have put in place to address future climate change. This analysis does not require accurate predictions of future climate change. Rather it only requires a range of plausible representations of future climate that can be used to help the water agencies better understand where their vulnerabilities may lie. This is similar to the argument that effective responses to future earthquakes depends not on knowing when the next earthquake will occur, but simply a general sense of where earthquakes do occur. Even without accurate probabilistic information on the likelihood of identified vulnerabilities, such information can prove very useful to decision-makers.

Dessai (2005) found that the water company's water resource plan remains robust to much of the uncertainty space sampled. However, this was in part due to the fact that the company used among the driest available climate model (HadCM3) and the large supply options considered. The criterion upon which robustness was assessed in Dessai (2005) was security of supply. If the analysis had been done on the basis of financial considerations (i.e., minimising costs and maximising benefits) the water company's plan could not be considered robust as it would be over-investing. A combination of high greenhouse gas emissions in the near future, low aerosol forcing and large precipitation decreases would require further investment by the water company. Using a similar analytic approach in a very different policy area, Dixon et. al. (2007) showed that the current United States government program that offers federal subsidies to encourage private sector provision of insurance against terrorism actually saves the U.S. taxpayer money over a very wide range (over an order of magnitude) of assumptions about the likelihood of future terrorist attacks. This result, based on consideration of thousands of simulation-model-generated scenarios without any claim to predictive skill led to a concise, policy-relevant result invoked by an important senator on the floor of the U.S. Senate (Congressional Record, Nov 16, 2007, Sen Dodd).

Non-predictive information from climate models can also help decision-makers identify and assess actions that may reduce their vulnerabilities to future climate change. Such approaches generally fall under the heading of robust decision-making (Lempert et al. 2006). The IPCC defines robustness as “strength; degree to which a system is not given to influence”. Lempert and Schlesinger (2000) propose that society should seek strategies that are robust against a wide range of plausible climate change futures. For these authors, robust strategies perform well (though not necessarily optimally) compared to the alternatives over a wide range of assumptions about the future. In this sense, robust strategies are “insensitive” to the resolution of the uncertainties. In general, there can be a trade-off between optimality and robustness such that a robust strategy may sacrifice some optimal performance in order to achieve less sensitivity to violated assumptions (Lempert and Collins 2007).

A variety of analytic approaches have been proposed to identify and assess robust strategies. For instance, information-gap decision theory (Ben-Haim 2006) has been applied to climate impact related areas such as flood management (Hine and Hall 2006) and conservation management (Regan et al. 2005). An info-gap is the disparity between what is known and what needs to be known in order to make a well-founded decision. Info-gap decision theory is a non-probabilistic decision theory seeking to optimize robustness to failure, or opportunity of windfall. This differs from classical decision theory, which typically maximizes the expected utility.

The RAND group recently worked with Southern California's Inland Empire Utilities Agency (IEUA) to help identify vulnerabilities due to climate change and other uncertainties in the agencies long-range water management plans and to assess additional actions the agency might take to reduce those vulnerabilities (Groves et al. 2008a). They combined downscaled climate projections for the IEUA region with a simulation of the agency's system and hydrology, used the resulting model to create roughly a thousand scenarios, and identified the key factors that would cause the IEUA to suffer significant shortages. The analysis suggested that under its current investment and management plan IEUA was likely to suffer such shortages only if precipitation declines were large, the agency failed to meet its ambitious recycling goals, and the amount of rainwater percolating into the ground water declined. The analysis shows that all three factors would need to occur simultaneously for future IEUA shortages to become likely. This information, which the agency and its stakeholders found very useful, required a wide range of plausible climate projections but did not require accurate probabilistic estimates of which of these plausible projections were most likely.

The analysis also evaluated a range of adaptation options for IEUA (Groves et al. 2008b). Each option has a particular combination of early actions and actions that can be taken at a later date if groundwater supplies run too low. Testing each option over the thousand scenarios helped IEUA understand the extent to which early action could reduce future climate-related and other vulnerabilities and the extent to which adaptation, that is responding to future observations of impending shortages, could also address these vulnerabilities. Without requiring accurate probabilistic predictions, this analysis helped IEUA understand its most attractive adaptation options.

This section has shown that there are alternatives to basing adaptation decisions on claims of being able to predict future climate (with accuracy and precision). These alternatives may use plausible scenarios derived from climate models, but they do not require accurate and precise predictions of future climate change, and in fact operate under the assumption that such predictive abilities will not be forthcoming. Central to such approaches is the identification of strategies that work well across a wide range of uncertainties. This ethos is particularly appropriate for adaptation to climate change since many of the non-climatic processes that influence effective adaptation (e.g., economic growth, policy regulation, human behaviour) are generally accepted as not being not amenable to prediction.

5. Conclusions

Given the deep uncertainties involved in climate prediction (and even more so in the prediction of climate impacts) and given that climate is usually only one factor in decisions aimed at climate adaptation, we conclude that the 'predict and provide' approach to science in support of climate change adaptation is significantly flawed. Other areas of public policy have come up with similar conclusions (e.g., earthquake risk, national security, public health). We therefore argue that the epistemological limits to climate prediction should not be interpreted as a limit to adaptation, despite the widespread belief that it is. By avoiding an approach that places climate prediction (and consequent risk assessment) at its heart, successful adaptation strategies can be developed in the face of this deep uncertainty. We suggest that decision makers systematically examine the performance of their adaptation strategies/policies/activities over a wide range of plausible futures driven by uncertainty about the future state of climate and many other economic, political and cultural factors. They should choose a strategy that they find sufficiently robust across these alternative futures. Such an approach can identify successful adaptation strategies without accurate and precise predictions of future climate.

These findings have significant implications for science policies as well. At a time when government expects decisions to be based on the best possible science (evidence based policy-making), we have shown that the science of climate prediction is unlikely to fulfil the expectations of decision-makers. Overprecise climate predictions can potentially lead to bad decisions if misinterpreted or used incorrectly. From a science policy perspective it is worth reflecting on where science funding agencies should focus their efforts if one of the goals is to maximise the societal benefit of science in society. The recent World Modelling Summit for Climate Prediction called for a substantial increase in computing power (an increase by a factor of 1000) in order to provide better information at the local level. We believe, however, that society will benefit much more from a greater understanding of the vulnerability of climate-influenced decisions to large irreducible uncertainties than in seeking to increase the accuracy and precision of the next generation of climate models.

Acknowledgements

Dessai was supported by funding from the Tyndall Centre core contract with the NERC, EPSRC and ESRC, by the EPSRC funded project “Simplicity, Complexity and Modelling” (EP/E018173/1) and by an ESRC-SSRC Collaborative Visiting Fellowship. Lempert and Pielke, Jr. were supported by the National Science Foundation (Grant No. 0345925 and 0345604 respectively).

References

Adger, W. N., S. Agrawala, M. Mirza, C. Conde, K. O'Brien, J. Pulhin, R. S. Pulwarty, B. Smit, and K. Takahashi. 2007. Assessment of adaptation practices, options, constraints and capacity. Pages 717-743 *in* IPCC, editor. Climate Change 2007: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge.

Allen, M. R., and D. J. Frame. 2007. Call off the quest. Science **318**:582-583.

Bankes, S. 1993. Exploratory Modeling for Policy Analysis. Operations Research **41**:435-449.

Ben-Haim, Y. 2006. Info-gap decision theory : decisions under severe uncertainty, 2nd edition. Academic, Oxford.

Cooper, C. F. 1978. What Might Man-Induced Climate Change Mean. Foreign Affairs **56**:500-520.

Dessai, S. 2005. Robust adaptation decisions amid climate change uncertainties. PhD. University of East Anglia, Norwich.

Dessai, S., and M. Hulme. 2004. Does climate adaptation policy need probabilities? Climate Policy **4**:107-128.

Dessai, S., and M. Hulme. 2007. Assessing the robustness of adaptation decisions to climate change uncertainties: A case study on water resources management in the East of England. Global Environmental Change **17**:59-72.

Dixon, L., R. J. Lempert, T. LaTourrette, and R. T. Reville. 2007. The federal role in terrorism insurance: evaluating alternatives in an uncertain world. MG-679-CTRMP, RAND.

Evans, S. A. 2008. A new look at the interaction of scientific models and policymaking: workshop report, 13 February 2008. Policy Foresight Programme, James Martin Institute, Oxford University, Oxford.

Gagnon-Lebrun, F., and S. Agrawala. 2006. Progress on adaptation to climate change in developed countries: an analysis of broad trends. ENV/EPOC/GSP(2006)1/FINAL, OECD, Paris.

Groves, D., D. Knopman, R. Lempert, S. Berry, and L. Wainfan. 2008a. Presenting Uncertainty About Climate Change to Water Resource Managers. RAND TR-505-NSF, RAND.

Groves, D., R. Lempert, D. Knopman, and S. Berry. 2008b. Preparing for an Uncertain Climate Future Climate in the Inland Empire - Identifying Robust Water Management Strategies. RAND DB-550-NSF, RAND.

Hall, J. 2007. Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. Hydrological Processes **21**:1127-1129.

Hickox, W. H., and M. D. Nichols. 2003. Climate research. Issues in Science and Technology **19**:6-7.

Hine, D. J., and J. W. Hall. 2006. Convex analysis of flood inundation model uncertainties and info-gap flood management decisions. *in* K. Vrijling and others, editors. Stochastic Hydraulics '05, Proc. 9th Int. Symp. On Stochastic Hydraulics, Nijmegen, The Netherlands.

Jones, R. N. 2000. Managing uncertainty in climate change projections - Issues for impact assessment. Climatic Change **45**:403-419.

Kelly, P. M. 1979. Towards the Prediction of Climate. Endeavour **3**:176-182.

Lasswell, H. D., and A. D. H. Kaplan. 1950. Power and society: a framework for political inquiry. Yale University Press, New Haven.

Lempert, R. J., and M. T. Collins. 2007. Managing the Risk of Uncertain Threshold Response: Comparison of Robust, Optimum, and Precautionary Approaches. Risk Analysis **27**:1009-1026.

Lempert, R. J., D. G. Groves, S. W. Popper, and S. C. Bankes. 2006. A general, analytic method for generating robust strategies and narrative scenarios. Management Science **52**:514-528.

Lempert, R. J., and M. E. Schlesinger. 2000. Robust strategies for abating climate change. Climatic Change **45**:387-401.

MOHC. 2007. Climate research at the Met Office Hadley Centre: Informing Government policy into the future. *in*. Met Office Hadley Centre, Exeter.

Murphy, J. M., B. B. B. Booth, M. Collins, G. R. Harris, D. M. H. Sexton, and M. J. Webb. 2007. A methodology for probabilistic predictions of regional climate change from perturbed physics ensembles. Phil. Trans. R. Soc. A **365**:1993-2028.

Murphy, J. M., D. M. H. Sexton, D. N. Barnett, G. S. Jones, M. J. Webb, M. Collins, and D. A. Stainforth. 2004. Quantifying uncertainties in climate change from a large ensemble of general circulation model predictions. Nature **430**:768-772.

NERC. 2007. Next Generation Science for Planet Earth: NERC Strategy 2007-2012. Natural Environment Research Council, Swindon.

New, M., A. Lopez, S. Dessai, and R. Wilby. 2007. Challenges in using probabilistic climate change information for impact assessments: an example from the water sector. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences **365**:2117-2131.

Oreskes, N., K. Shraderfrechette, and K. Belitz. 1994. Verification, Validation, and Confirmation of Numerical-Models in the Earth-Sciences. Science **263**:641-646.

Patrinos, A., and A. Bamzai. 2005. Policy needs robust climate science. Nature **438**:285.

Pielke Jr., R. A., D. Sarewitz, and R. Byerly Jr. 2000. Decision making and the future of nature: understanding and using predictions. Pages 361-387 *in* D.

Sarewitz, R. A. Pielke Jr., and R. Byerly Jr., editors. Prediction: science, decision making and the future of nature. Island Press, Washington, D.C.

Ravetz, J. R. 2003. Models as metaphors. Pages 62-78 *in* B. Kasemir, J. Jager, C. C. Jaeger, and M. T. Gardner, editors. Public participation in sustainability science. Cambridge University Press, Cambridge.

Regan, H. M., Y. Ben-Haim, B. Langford, W. G. Wilson, P. Lundberg, S. J. Andelman, and M. A. Burgman. 2005. Robust decision-making under severe uncertainty for conservation management. Ecological Applications **15**:1471-1477.

Roe, G. H., and M. B. Baker. 2007. Why is climate sensitivity so unpredictable? Science **318**:629-632.

Rougier, J., and D. M. H. Sexton. 2007. Inference in ensemble experiments. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences **365**:2133-2143.

Sarewitz, D., and R. A. Pielke Jr. 1999. Prediction in science and policy. Technology in Society **21**:121-133.

Stainforth, D. A., T. Aina, C. Christensen, M. Collins, N. Faull, D. J. Frame, J. A. Kettleborough, S. Knight, A. Martin, J. M. Murphy, C. Piani, D. Sexton, L. A. Smith, R. A. Spicer, A. J. Thorpe, and M. R. Allen. 2005. Uncertainty in predictions of the climate response to rising levels of greenhouse gases. Nature **433**:403-406.

Stainforth, D. A., M. R. Allen, E. R. Tredger, and L. A. Smith. 2007. Confidence, uncertainty and decision-support relevance in climate predictions. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences **365**:2145-2161.

Tebaldi, C., and R. Knutti. 2007. The use of the multi-model ensemble in probabilistic climate projections. Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences **365**:2053-2075.

Whitehead, P. G., R. L. Wilby, D. Butterfield, and A. J. Wade. 2006. Impacts of climate change on in-stream nitrogen in a lowland chalk stream: An appraisal of adaptation strategies. Science of the Total Environment **365**:260-273.

Wilby, R. L. 2005. Uncertainty in water resource model parameters used for climate change impact assessment. Hydrological Processes **19**:3201-3219.

Wilby, R. L., and I. Harris. 2006. A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. Water Resources Research **42**:W02419, doi:02410.01029/02005WR004065.

WMO. 2008. Future Climate Change Research and Observations: GCOS, WCRP and IGBP Learning from the IPCC Fourth Assessment Report. GCOS-117, WCRP-127, IGBP Report no. 58, WMO/TD No. 1418, World Meteorological Organization.

Table 1. Statements about climate prediction and adaptation from the peer-reviewed and grey literature (bold emphasis our own).

Table 1

“*We must be able to **predict more accurately** the climatic effect of increased levels of atmospheric carbon dioxide. This is now the major uncertainty in assessing environmental impact ... We must learn to anticipate the … consequences of climatic change.*” (Cooper 1978) – scientist perspective
“*In planning the rational use and distribution of ... resources, **reliable predictions of the climatic future are ... absolutely essential**.*” (Kelly 1979) – scientist perspective
“*It is … essential that GCM* [global climate model] *predictions are accompanied by quantitative estimates of the associated uncertainty in order to render them **usable** in planning mitigation and adaptation strategies.*” (Murphy et al. 2004) – scientist perspective
“*It is … vital that **more detailed** regional climate change predictions are made available both in the UK and internationally so that **cost-effective adaptation** and appropriate mitigation action can be planned*” Met Office Hadley Centre (MOHC 2007) – scientist perspective
“*NERC-funded science must play a leading role in the development of risk-based predictions of the future state of the climate – on regional and local scales, spanning days to decades. Advances in climate science … are **necessary** to develop the high-resolution regional predictions **needed** by decision makers. New scientific knowledge will enable policy-makers to develop adaptation and mitigation strategies*.” NERC Strategy 2007-2012 (NERC 2007) – science funding agency perspective
“*Policy needs robust climate science. Societies need robust infrastructures to deal with extreme weather conditions. Such measures will rely on scientific understanding and **accurate predictions** of regional climate change …*” (Patrinos and Bamzai 2005) – decision maker perspective
“*plans will only be effective to the extent that climate science can provide … agencies with climate scenarios that describe a range of possible future climates that California may experience, at a scale **useful** for regional planning. **Reducing uncertainty** in projections of future climates is critical to progress …*” (Hickox and Nichols 2003) – decision maker perspective
“*Increased acceptance that some degree of climate change is inevitable is now coupled with **increasing demand** from communities, industry and government for **reliable** climate information at **high resolution** and with **accurate extremes**. There must, therefore, be development in regionalizing climate information, principally through downscaling.*” World Meteorological Organization (WMO 2008)
“*The climate models will, as in the past, play an important, and perhaps **central, role in guiding the trillion dollar decisions** that the peoples, governments and industries of the world will be making to cope with the consequences of changing climate. … adaptation strategies **require more accurate and reliable predictions** of regional weather and climate extreme events than are possible with the current generation of climate models*.” World Modelling Summit for Climate Prediction, ECMWF - Reading (UK), May 6-9, 2008.
“*Predicting the effects of climate change on hydrological and ecological processes is **crucial** to avoid future conflicts over water and to conserve biodiversity. …**downscaling climate predictions** and assessing their impact on mountain environments is an exciting scientific challenge that may allow us to protect the livelihoods of millions of people.*” NERC PhD studentship at the University of Bristol http://www.ggy.bris.ac.uk/PGadmissions/projects/buytaert-phd2.pdf

Figure 1. Accuracy and precision for two probability density functions