






CLIMATE SCENARIOS AND PROJECTIONS:

THE KNOWN, UNKNOWN, AND THE UNKNOWABLE AS APPLIED TO CALIFORNIA

PREPARED BY: SUSANNE C. MOSER

ASPEN GLOBAL CHANGE INSTITUTE

CLIMATE SCENARIOS AND PROJECTIONS:

THE KNOWN, THE UNKNOWN, AND THE UNKNOWABLE AS APPLIED TO CALIFORNIA

11-14 March 2004 Aspen, Colorado

CO-CHAIRS:

Richard H. Moss and Stephen H. Schneider

CO-SPONSORED BY

The Alfred P. Sloan Foundation and the California Energy Commission's Public Interest Energy Research Program

This publication is part of the Aspen Global Change Institute's *Elements of Change* series.

Series Editor: John Katzenberger

Prepared for the Aspen Global Change Institute by Susanne C. Moser

ASPEN GLOBAL CHANGE INSTITUTE

OUR MISSION

The Aspen Global Change Institute (AGCI) is an independent, 501 (c)3 non-profit organization. Its mission is to further the understanding of Earth systems and global environmental change through interdisciplinary meetings, publications, and educational programs.

AGCI

100 East Francis Street
Aspen CO 81611
http://www.agci.org
970 925 7376
agcimail@agci.org

ACKNOWLEDGEMENTS

AGCI gratefully acknowledges the assistance of Sue Bookhout and Michelle Masone in preparing the report, and the workshop participants for their contributions and edits.

More information about the workshop, including individual presentations, and background papers, and DVDs of talks are available at http://www.agci.org.

Design and production by: max_ink [www.max-ink.net]

ISBN 0-9741467-2-2

TABLE OF CONTENTS

EXECUTIVE SUMMARY

On 11-14 March 2004, the Aspen Global Change Institute convened a workshop on "Climate Scenarios and Projections: The Known, the Unknown, and the Unknowable as Applied to California," jointly chaired by Richard Moss and Stephen H. Schneider. The workshop, co-sponsored by the Alfred P. Sloan Foundation and the California Energy Commission's Public Interest Energy Research Program, brought together nearly 30 experts and California decision-makers to focus on one of the most hotly contested scientific questions of the last 25 years: What can we know about the future climate of Earth? Equally important, the workshop also asked how what is known, unknown, and unknowable can be communicated most effectively to decision-makers.

Policy-makers concerned with mitigating climate change need to know what constitutes "dangerous interference with the climate system" (Article 2 of the UN Framework Convention on Climate Change), while decision-makers and resource managers at regional and local levels require information to make appropriate long-term decisions in light of climate change. The workshop explored the state of the art and prospects for improvements in (1) the development of emissions scenarios and the understanding of the underlying societal drivers, (2) progress in global climate change projections using general circulation models, (3) advances in downscaling methods, (4) approaches and skill in assessing the impacts of climate change, and (5) best practices in communicating uncertain science to policy-makers, resource managers, and the larger public.

California served as an excellent test case due to the state's relatively complex topography and meteorology, its sensitivity to climate variability and change, the state's ambitious research program on climate change, and its bellwether position in the nation on climate-related policy and management efforts. The topics discussed at this workshop are also intended, however, to be useful to other regions (transferable lessons summarized in Chapter 6) and to the Lead Authors participating in the forthcoming IPCC Fourth Assessment Report.

Introduction to the known, unknown and unknowable from scientific and practitioner perspectives (Chapter 1)
Experts from different disciplines and practitioners do not necessarily share a common vocabulary or philosophy of how to approach, assess, and deal with the known, unknown and unknowable. Chapter 1 lays out some of these differences, thus providing a foundation for the remainder of the report. There, California decision-makers also confirm that in many decision situations, probabilistic climate information, more information about the reasons for existing uncertainty, and timely communication of scientific information would be welcome and could improve management of climate-sensitive resources.

Improvements in GCMs and emission scenarios to enhance their utility for regional modeling and impacts assessment efforts (Chapter 2)
Uncertainties in the projections of future climate change result from our incomplete understanding and ability to predict the drivers of change as well as from the interactions among them, and on the uncertainties resulting from methodological and structural differences in general circulation models (GCMs). How much warming will result from a given increase in emissions (climate sensitivity) is considered by many as one of the most essential questions to reduce uncertainty in climate projections. Key research tasks are summarized on p.16.

Barriers and opportunities for improved statistical downscaling and regional climate models (Chapter 3)
In order to appropriately and adequately prepare for climate change impacts where they occur (i.e., locally), decision-makers need regionally specific climate change information. The development of such high-resolution projections of climate change is far from trivial. While significant progress has already been made in recent years in downscaling global model outputs to regional scales, there is significant uncertainty involved in both dynamical and statistical downscaling.

Regional climate models tend to be better documented and more mature than other dynamical downscaling approaches. Major challenges include model validation and underlying uncertainties in the data, scale-dependent parameterization, and the uncertainties introduced by the driving GCM. Statistical downscaling uses statistical transfer functions to connect a fine-scale predictand with a set of coarse-scale predictors. Establishing high-quality statistical relationships is dependent on the availability of reliable data sets, validation, and the quality of the driving GCM scenarios. Key research tasks are summarized on p.22.

Improvements in the assessment of vulnerability, adaptive capacity and impacts of climate change (Chapter 4)

It is the threat of tangible impacts or the realization of changes on the ground that makes climate change real, and helps mobilize different actors to develop and implement mitigation and/or adaptation policies.

The economic costs of climate change are difficult to assess because they depend on assessors' choices of the impacted entity, the conceptualization and measurement, and the aggregation of different costs and benefits. Most existing economic impacts models characterize the state of an economy when in equilibrium and are used to compare alternative equilibria. The major economic effects of climate change, however, may well be associated with out-of-equilibrium phenomena, depending on how long it takes for technologies, institutions, societal values, and individual behaviors to reach equilibrium in response to changes in climate. To produce more realistic assessments, economic impact modelers must address numerous data and model-related uncertainties, but most importantly better understand change in technology and human preferences.

Countless ecological impact assessments have examined the potential impacts of climate change on species, ecosystems, and the relationships between species and their environment. Significant theoretical advances have been made in understanding species-temperature relationships. Fairly recent observations of changes in spatial and temporal species behavior linked to climatic change are also accumulating, but pre-historic and historic information remains sparse, thus limiting trend analyses. Modeling approaches to project ecological impacts are still very simple at this stage, using climate envelopes of single climate drivers (typically temperature), while neglecting other interactive factors, and focusing on individual species rather than species assemblages. At the same time, the scientific consensus on temperature-species relationships is strong.

Examining the exposure, sensitivity, and ability to cope and adapt of individuals, communities, economic sectors, and ecosystems to potential changes provides essential insights into the determinants of vulnerability, and into the expected severity of impacts from climate disruption. Socio-economic, institutional, entitlement, and environmental factors have been examined in great contextual detail, yet the larger challenges of integrating and comparing these studies, developing generalizations, and feeding emergent findings into the urgent development of adaptation strategies remain.

Integrated assessment models attempt to functionally link the various components of atmospheric chemistry, climate, terrestrial ecosystems, and human activity, reflecting both driving forces of change and responses to climate change. Like other impact assessment tools, it is used to explore various policy strategies. The complexity and challenge of this endeavor echo the data, modeling, and fundamental knowledge challenges faced by expert communities focused on any of its components.

Another policy-relevant tool is robust adaptive planning – an iterative, analytic process used to identify robust strategies, which are relatively insensitive to most uncertainties. The approach also helps characterize the small number of uncertainties to which selected strategies remain sensitive.

Finally, significant interest exists at present in defining "dangerous interference with the climate system." Ultimately a value judgment, scientific progress is nonetheless being made in exploring probabilistically under what policy scenarios dangerous climate change might occur. Key research tasks are summarized on p.36.

Communication of irreducible ignorance and uncertainty to potential users of scientific information (Chapter 5)
Identifying the specific goal of the communication and the relevant constituencies that need to be reached is essential for developing the appropriate message, determining what about climate change uncertainties needs to be told, and how this information should best be delivered. There is no one-size-fits-all set of rules or approaches for this sort of communication. The ethical and professional imperative for scientists and other communicators, however, is to ensure that a clear message emerges about wat is well known, what is partially known, and what remains speculative at this time.

Understanding communication as a two-way process aimed at mutual learning and trust-building will create a discursive environment, in which climate change knowns, unknowns, and unknowables can be told and heard. Simple and consistent terminology should be accompanied by transparent explanations about the nature, degree, and sources of uncertainty. If the aim of such communication is to supply the scientific underpinnings for sound decision-making, then scientists would be well advised to lead with certainty, speak through familiar metaphors, connect with the common experiences, language, and decision problems at hand, and provide those decision-makers willing to take political risks with the necessary backing so that they are equipped to take action when windows of opportunity arise.

The transferability of methods and lessons learned from California to other regional impacts modeling (Chapter 6)
California as a case study for the exploration of the known, unknown and unknowable in climate change is harder (geographically) than some and easier (politically) than other regions, thus requiring great care in transferring lessons to other regional efforts. The enormous complexity of climate projections and impacts assessments impose significant limits on science's ability to model them with credibility and confidence. Generally speaking, the complexity of such models should be inversely related to the decision time horizon (more complex for the near-term, less complex for longer-term projections), and may be easier to increase for testable physical models than for social models. Once global projections are available, the choice of downscaling method should be guided principally by the ability of the approach to replicate influences on regional climate.

Scientists can do far more to make their knowledge more useful to decision-makers. Foremost, impacts assessments should be linked to the specific needs of decision-makers in terms of timing, format, and relevant decision variables. More effective communication of uncertainty in such information can be achieved through appropriate training of scientists and other communicators, and through mutual education and interaction between scientists and practitioners. Better communication – while much needed – is not a sufficient condition, however, for better decision-making under uncertainty. While the public and decision-makers are hungry for frank information about the state of the planet and our knowledge about it, probablistic information is useful, but not always needed. Resolution of uncertainty is neither a hindrance to public discourse, nor to decision-making, and decisions related to climate change will have to be made under great uncertainty for years to come.

LIST OF ACRONYMS

AEEI	Autonomous energy efficiency improvement
AGCI	Aspen Global Change Institute
AGCM	Atmosphere General Circulation Model
AOGCM	(Global coupled) Atmosphere-Ocean General Circulation Model
AR4	(IPCC) Fourth Assessment Report
CALSIM	California Simulation Model
cdf	Cumulative density function
CEC	California Energy Commission
CMIP	Coupled Model Intercomparison Project
DSM2	Delta Simulation Model 2
ENSO	El Niño/Southern Oscillation
GCMs	General circulation models
GDP	Gross Domestic Product
GHG	Greenhouse gases
IA/IAM	Integrated assessment/Integrated assessment model
IGSM2	Integrated Groundwater and Surface Water Model 2
IPCC	Intergovernmental Panel on Climate Change
MER	Market Exchange Rate
NAST	(U.S.) National Assessment Synthesis Team
NGOs	Nongovernmental organizations
pdf	Probability density function
PDO	Pacific Decadal Oscillation
PDSI	Palmer Drought Severity Index
PIER	(California) Public Interest Energy Research (Program)
PNA	Pacific-North America
PPP	Purchasing Power Parity
RCM	Regional climate model
RDM	Robust decision-making
SRES	(IPCC) Special Report on Emission Scenarios
TAR	(IPCC) Third Assessment Report
UNDP	United Nations Development Program
UNFCCC	United Nations Framework Convention on Climate Change

PREFACE

The Challenge

What can we know about the future climate of Earth? This is perhaps one of the most hotly contested scientific questions of the last 25 years, made even more challenging by scaling the query down to a single region such as the state of California. Besides posing vexing scientific challenges, the question of future climate change is also an urgent international policy problem as the United Nations Framework Convention on Climate Change (UNFCCC 1992) requires of its 190+ signatories stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system (Article 2).

What is dangerous interference in the climate system?

Unfortunately, the UNFCCC never actually defined what it meant by dangerous. What we do know is that dangerous climate change is a concept that cannot simply (or objectively) be inferred from a set of observations or calculated by a model. It is a concept that is closely tied to questions about the distribution of the impacts of climate change across different regions and population groups. Different regions, sectors, and populations will be impacted to different degrees by climate change due to the magnitude and pace of climatic change. Moreover, people and regions differ in their sensitivity to these climatic changes as well as in their ability to cope with the challenges they will face. These differences in vulnerability are compounded by differential degrees of responsibility for contributing to the problem. Thus it can be argued that any climate change that impacts more upon those who contributed the least to the problem is less just and thus arguably more dangerous and could have repercussions that extend beyond environmental damages (to security, health, and economy, for example).

Defining dangerous is ultimately a political question because it depends on value judgments about the relative salience of various impacts and the ability to face climate change-related risks as well as norms for defining acceptable risk. However, once thresholds have been defined that parties to the Convention have agreed should be avoided, then quantitative goals such as allowable emissions can be described.

The role of scientists

Although scientists are not solely responsible for interpreting what is dangerous interference with the climate system, they must help policy-makers evaluate what it entails by laying out the elements of risk, which is classically defined as probability x consequence. They should also help decision-makers by identifying thresholds and possible (imaginable) surprises, as well as estimates of how long it might take to resolve many of the remaining uncertainties that plague climate assessments.

At finer scales of decision-making, the question of future climate is already of great importance to resource managers today, especially to those who make investment, infrastructure, or planning decisions with long time horizons. What can scientists offer to resource managers who must operate in a local or regional jurisdiction facing a global problem over which they have little or no control? At what geographical and temporal scales, and with what levels of confidence, can projections of temperature, precipitation, and other attributes of climate be developed and provided to decision-makers to assist with resource management? A great deal of information can already be provided (for example on the frequency, magnitude, and duration of floods and droughts resulting from changes in seasonal temperatures and distribution of precipitation), but this information has uncertainties associated with it; scientists must communicate clearly and effectively not only the basic information, but their level of confidence in the information they provide.

Drivers of climate change
To estimate future climate changes, it is first necessary to make projections of demographic changes, economic activities, and the technologies and organizations that will provide the estimated productivity levels and resultant energy and material flows in the biosphere. Until these societal processes actually happen they are unknowable in principle, hence there is no frequentist data possible for the future. On the other hand, there is already considerable understanding of how physical, biological, and social systems function. Combining such information into integrated assessment models allows us to generate a range of alternative, plausible scenarios for the future.

Methodologically, we already know how to do this, but uncertainties are inherent in every step. Moreover, categorizing the uncertainties and trying to assess subjective probabilities for various elements of the scenario-generation exercise is a frontier in climate assessment (e.g., Moss and Schneider 1997, 2000; Giles 2002). Determining which of the major uncertainties can be narrowed (i.e., which are ultimately knowable) through normal scientific investigation (e.g., Schneider, Turner, and Morehouse-Garriga 1998; Schneider and Turner 1995) versus which uncertainties cannot be reduced through science is an ongoing task of integrated assessors (e.g., Morgan and Dowlatabadi 1996; Rothman and Robinson 1997; Schneider 1997).

Workshop Foci
This report summarizes the discussions at a workshop convened at the Aspen Global Change Institute in March 2004 to take stock of science's current ability to create plausible scenarios of the future, build and evaluate global climate models, downscale from global climate projections to regional scales, complete comprehensive impacts and vulnerability analyses, and effectively connect the scientific findings to regional decision-makers. The major challenges placed before the workshop participants on each of these issues are laid out below.

Scenarios
To estimate a range of future greenhouse gas emissions, the Intergovernmental Panel on Climate Change (IPCC) commissioned a Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2001). The very innovative IPCC SRES storylines outlined in that report, while encompassing a broad range of emissions estimates, did not attempt to assess the likelihood of any of the storylines. Without such probabilistic information about future climate scenarios, it is very difficult for policy-makers to perform risk-management exercises. Furthermore, without probabilities (and their attendant subjective confidences), it is left up to decision-makers to guess the likelihood of the scenario. Clearly, that is a poorer basis for risk management – whether at federal, regional, or private levels – than an honest assessment of the likelihood of various projections from the expert assessment community. However, estimating such probabilities raises many methodological and philosophical challenges. How far can researchers responsibly go in assigning probabilities to groups of scenarios, to individual scenarios, and to subjectively defined ranges and probability distributions of potential future emissions?

Climate sensitivity
In addition to estimates of the subjective probabilities of emissions and land use scenarios, analysts must also estimate subjective probabilities of climate sensitivity. This, too, was not attempted by the IPCC in its Third Assessment Report (TAR). Thus, this workshop looked at the possibility of developing joint probability functions for emissions and climate sensitivity. The result would be a probabilistic estimate of climate changes in, say, 2050 or 2100, from which risk-management

decisions could be considered. Fortunately, there have been a number of such joint probabilistic analyses in the literature recently (e.g., Andronova and Schlesinger 2001; Forest et al. 2002; Wigley and Raper 2001, Schneider 2002; Webster et al. 2003). However, a broader analysis of the underlying uncertainties will be a feature of the next IPCC assessment (expected in 2007). This workshop was designed to take stock of what is known about climate sensitivity and offer suggestions for further analysis potentially useful for additional climate sensitivity assessments.

Climate models: Global to local

The workshop went one step beyond global analysis by considering a specific case study region: California. Focusing on a particular region entails downscaling of the climate projections (e.g., Easterling et al. 2001), as well as other methods to do cross-scale analyses and impacts assessments (e.g., Harvey 2000; Harvey 1998; Root and Schneider 2003), again, with uncertainties embedded in each step.

We know with a high degree of confidence that existing global circulation models (GCMs) estimate temperatures in California to continue to rise over the century as concentrations of greenhouse gases in the atmosphere increase. Less confidence is associated with projections of precipitation change. Some of these models suggest that precipitation levels will increase well above historical levels, while others estimate a small but significant decrease in precipitation (e.g., Dettinger 2004). This poses a challenge for scientists and policy-makers because it is difficult to design robust (e.g., Lempert and Schlesinger 2000) adaptation measures that would work under these widely divergent scenarios. At the same time, little attention has been paid to the estimation of the performance of the global circulation models regarding the large-scale oceanic and atmospheric features that determine California's climate. Models that perform adequately for California in terms of temperature projections may or may not show less divergence with respect to precipitation levels for that region.

It would also be of interest for California to develop climate projections based on the outputs of global models that properly model the California region at larger scales, while at the same time, trying to assess probabilities to these regional climatic projections. At the moment most GCMs have a typical resolution of about 300 km. They therefore require downscaling models with resolutions of 50 km or less. However, new high-speed computing efforts such as those lead by Philip Duffy at Lawrence Livermore National Laboratory have recently been demonstrated at resolutions as fine as 50 km. These high resolution global simulations have been used to drive a nested regional model at very fine spatial resolution (9 km), but it is not yet known the extent to which they are useful to regional impacts analysis. Sorting through the capabilities of various modeling approaches was an important task at this workshop.

Vulnerabilities and impacts

Impacts (and vulnerability and adaptive capacity) assessments are complementary bottom-up approaches to the top-down scenario-driven analyses of the consequences of climate change. These assessments, too, are fraught with uncertainties stemming from hard-to-measure and project complex socio-economic, institutional, and environmental factors. While numerous local (place-based) vulnerability assessments have been conducted, a broader synthesis is not yet available. Such a synthesis could provide a better understanding of general, causal relationships, and hence enhance our predictive policy-making capacity. The workshop discussed advances in this direction and future research needs.

Linking science and decision-making: The case of California
A main purpose of this expert meeting was to build momentum for a discussion on how the global scenarios, and their associated subjective estimates of likelihood, should be linked with regional climate projections and ultimately regional decision-making needs. California is an excellent test case due to the relatively complex topography and meteorology, and the influence of the Pacific Ocean on its climate. Moreover, California has embarked on an ambitious research program, which is one of the first state-funded climate change research programs in the nation. Moreover, the state leads the nation in numerous climate-related policy and management efforts. Thus, there already are and continue to be great opportunities in California for implementing the findings from this workshop in the immediate future. California's program is designed to complement national and international efforts to produce policy-relevant research that the state can use in the design of mitigation and adaptation strategies. This can then serve as a model for other regions to perform assessments that fit their needs. The topics discussed at this workshop are also intended to be useful to Lead Authors participating in the IPCC Fourth Assessment Report (AR4).

To increase the likelihood of fit between scientific analysis and assessment and the ultimate use of this information in policy- and decision-making, the workshop included both explicit discussion of decision-making contexts and needs, as well as several California decision-makers. With this applied focus, the meeting was designed to address four closely linked problems.

Guiding questions
Workshop discussions of the five workshop foci detailed above were guided by four principal questions:

1. How likely are the SRES scenarios? How can subjective probabilities be assigned, and at what levels of confidence? What methods are most promising in such estimation? And how vexing is the lack of subjective probabilities for regional analyses for the California case study?

2. How successful are GCMs at producing meteorological variables at regional scales? Which of the various strategies to improve GCMs provide the greatest direct aid in improving knowledge of, and confidence in, the California regional modeling efforts and assessment strategies?

3. Utilizing California as a regional case study, how can the assessment and eventual reduction of uncertainties, combined with improved downscaling models, better inform regional decision-making and resource management? What are the stakes?

4. What elements of integrated analyses are essentially unknowable? Can robust strategies be developed in spite of those unknowns in the analysis?

The findings on each of these challenging questions are summarized in the six chapters of this report.

A Map to this Report and Additional Workshop Outcomes
The workshop aimed to be of great interest and relevance to the work of the California Energy Commission's Climate Change Program and to a broader research and practitioner community. In

advance of the meeting, and particularly to aid in the development of concepts relevant to California as a case study, several discussion papers were prepared with the support of the California Energy Commission and distributed prior to the meeting. These, along with workshop presentations and post-workshop contributions, are available at the AGCI website (http://www.agci.org). Chapter 1 summarizes some of these basic concepts, and offers perspectives on uncertainty from both the analytical and the practitioner side.

The outcomes of the workshop discussions are then summarized along five major questions:

1. How can GCMs and emission scenarios be improved in a way that enhances their utility for regional modeling efforts? (Chapter 2)
2. What are the key barriers and opportunities for improving downscaling and regional climate models? (Chapter 3)
3. How can improvements in global and regional models be applied in such a way that they reduce California's vulnerability to climate change? (Chapter 4)
4. How can we best communicate irreducible ignorance and uncertainty to potential users of uncertain information? (Chapter 5)
5. To what extent and in what ways can the methods and lessons from the California case be transferred to regional impacts modeling elsewhere? (Chapter 6)

The Workshop Participants

Thirty-two experts participated in the three-day workshop, representing a wide spectrum of academic and practitioner expertise, including climate modelers and climate data analysts, oceanographers, ecologists, technologists, economists, policy analysts, geographers, resource managers, policy-makers, hydrologists, risk analysts, and communication experts. These participants included members of the U.S. and international climate modeling centers covering global and regional modeling expertise, as well as representatives of the SRES community, and government labs and university centers. Members of the California Energy Commission's Climate Change Program and its partners played a pivotal role in informing the meeting of California's unique issues, work accomplished to date, and plans to utilize new information generated by this workshop. They also provided their insights on how decision-makers receive probabilistic information and cope with large uncertainties.

The workshop leaders and convener thank all sponsors and participants for a highly stimulating meeting.

Stephen H. Schneider and Richard H. Moss
August 2005

1. INTRODUCTION

Chapter 1 summarizes workshop presentations by Morgan, Pulwarty, Franco, Janetos, Chung, Rosenfeld, and Boyd.

Scientists and decision-makers view the challenge of uncertainty from rather different perspectives. While scientists aim to examine the sources of uncertainty, characterize it, and – if possible – reduce or eliminate certain types of uncertainty, decision-makers need to know how uncertainty affects their policy choices. To frame subsequent discussions in this context, the basic concepts, approaches, and challenges are laid out below.

1.1 A SHORT PRIMER ON UNCERTAINTY AND IGNORANCE

Uncertainty Paradigms

Probability is considered the basic scientific language of uncertainty. The two major paradigms for looking at probability are the frequentist and the subjectivist or Bayesian approaches. In the former view, probability is the objective frequency of a particular outcome occurring in a known universe of possible outcomes. In other words, the uncertainty associated with a specific outcome is a function of the known number of possible outcomes. In the Bayesian view, on the other hand, probability is a statement of the degree of belief an analyst has that a specified event will occur, given all the relevant information currently known by that person. Subjective probability of an outcome thus is a function of a person's state of information about all imaginable outcomes, made with clear understanding that many factors influencing the outcome are not or cannot be precisely known.

Even in the subjectivist view of probability, the outcome or quantity of interest has to be well specified for a probability, or a probability distribution, to be meaningful. Moreover, such probabilities must conform to the axioms of probability and, not surprisingly, be consistent with available empirical data since they are often derived from them.

In the context of climate change, where much about the future is not known, the subjectivist method is often the only available approach. Although subjective probabilities often look like frequency distributions – e.g., a Monte Carlo simulation of future temperatures from model simulations – they are in fact only approximations of the frequency with which results might occur "in the real world" because they are only as accurate as the assumptions made and processes included in the models used to develop them. Their subjective component lies in the assessment of the extent to which the assumptions underlying the construction of the model will hold in the future obviously something for which no frequency data is possible in principle as the future has not yet occurred, and no measurements of the future are possible. However, objective frequency data can be – and usually is – used to construct the models applied to project future risks. In cases where the person's state of information approaches ignorance, scientists speak of deep uncertainty (Figure 1).

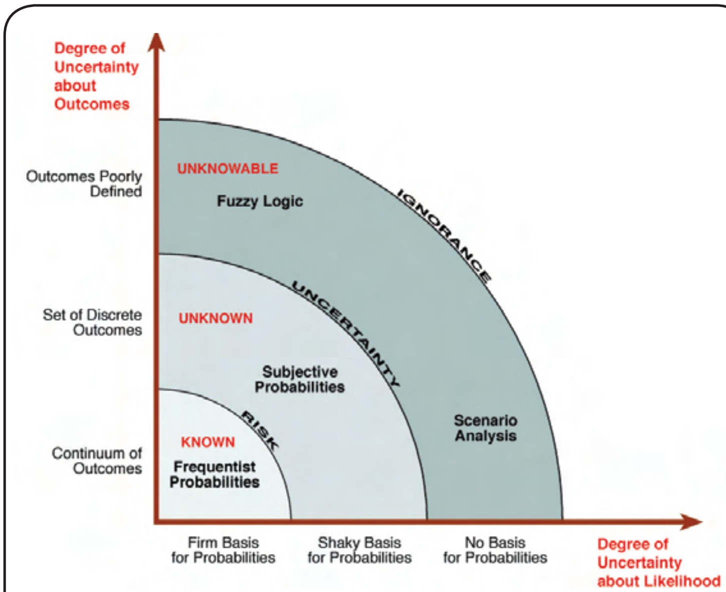


FIGURE 1: **Approaches to Uncertainty as a Function of the Degree of Uncertainty about Probabilities and Outcomes.** Building on a graphic conceptualization first developed by Funtowicz and Ravetz (1990), this graphic depicts the realms of the known, unknown, and unknowable – and examples of the analytical tools available to tackle them – distinguished by the degree of scientific uncertainty about probability and consequences. (Source: Modified from Dessai and Hulme 2003; reprinted with permission)

Quantitative versus Qualitative Characterization of Uncertainty

If probability is taken to be not primarily dependent on the objective state of the world, but defined as a function of subjective knowledge, then why not move away entirely from a quantitative approach and use qualitative descriptors for the unknown, such as likely and unlikely instead? Most experts in decision analysis would view such qualitative characterization as inadequate because the same words can mean very different things to different people. The same words can even mean different things to the same person in different contexts. Such concepts also hide important differences in experts' judgments about the underlying mechanisms (functional relationships) and how well key coefficients are known. These differences contribute to uncertainty.

An illustrative study in which qualitative descriptors were mapped to quantitative probabilities was conducted by Wallsten and colleagues in 1986 (Figure 2). The figure shows the range of probabilities that people assign to certain words, absent any specific context.

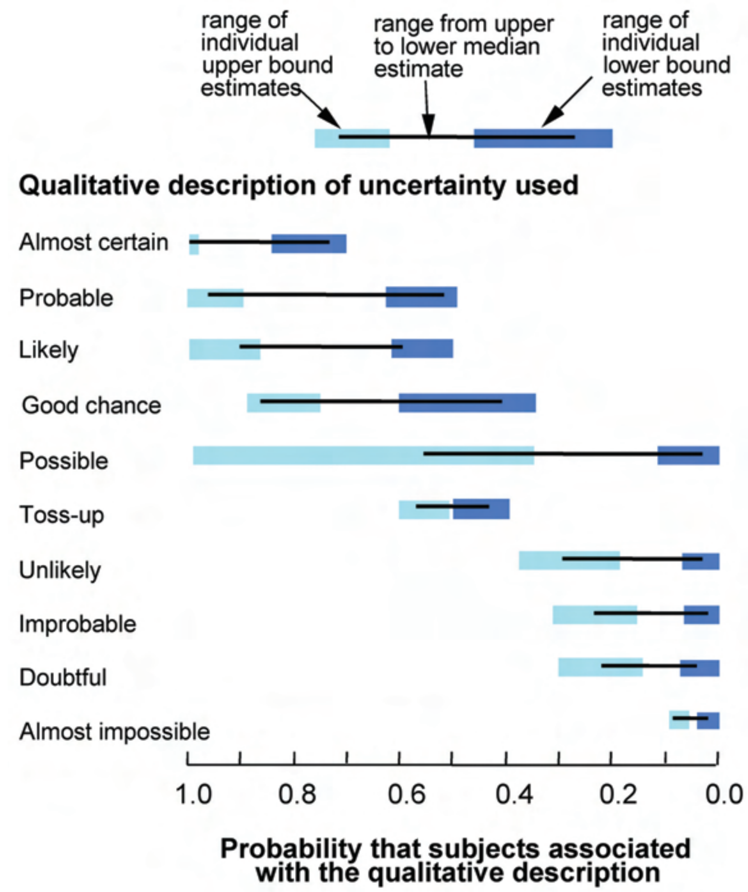


FIGURE 2: **Mapping Words to Probabilities.** (Source: Adapted from Wallsten et al. 1986; reprinted with permission)

Clearly, qualitative descriptors mask the fact that terms are applied to a wide span of quantitative probabilities, that these ranges overlap, and that different people have vastly different understandings of the causes and meanings of uncertainty. It is for these reasons that experts such as Morgan (in the case of the U.S. National Assessment), Moss and Schneider (in the case of the IPCC), and others have urged the move to clear quantitative calibration of uncertainty terms (Figure 3).

How Can Different Uncertainties Be Described and Analyzed?

Scientists typically distinguish three types of uncertainty:

- *Uncertainty in data* – a situation where the inputs that describe variables are incomplete, variable, inaccurate, or otherwise uncertain; thus parameters xbuilt on such data are uncertain (e.g., annual precipitation distribution).[1]
- *Uncertainty in processes* – a situation where the relevant variables are known, but their functional relationships (i.e., underlying processes) are unknown (e.g., climate sensitivity).
- *Uncertainty in model structure* – a situation where not all variables or their functional relationships are known or included (e.g., the relationship between current energy prices and future technical innovation).

Uncertain values are commonly graphically depicted in the form of probability density functions (pdfs) or cumulative density functions (cdfs) (Figure 4). To develop such probability distributions, high quality data and/or good physical and statistical theory are needed. When either is inadequate, subjective expert judgment about model parameters or structure must be elicited to develop a subjective assessment of probability.

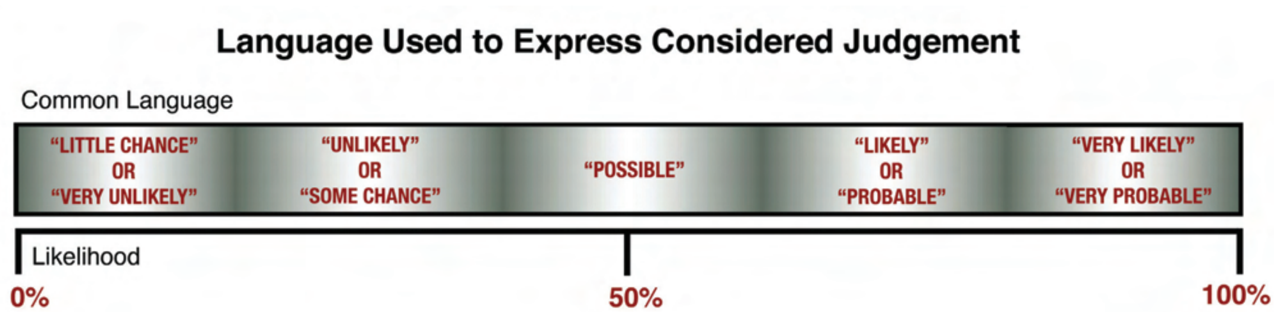


FIGURE 3: **Expert Judgment of Uncertainty as Standardized in the First U.S. National Assessment** (Source: NAST 2001)

[1] Some scientists draw a sharp distinction between variability and uncertainty. Variability involves random change over time or space (e.g., the midday temperature in Beijing in May is variable), and can be viewed as one source of uncertainty. One reason to distinguish variability from uncertainty is that the former can often be measured objectively, while other forms of uncertainty require subjective judgment.

Eliciting subjective expert judgment is of increasing importance in the context of global change where many relationships between variables are incompletely understood or barely known. Thus, analysts should take great care in eliciting subjective probabilistic judgments from experts participating in the process. Developing and testing an appropriate interview protocol typically takes several months. Each expert interview may require several hours. As Granger Morgan concluded at the workshop, "When addressing complex, scientifically subtle questions of the sorts involved with most problems in climate change, there are no satisfactory short cuts. Attempts to simplify and speed up the process almost always lead to shoddy results."

Subjective assessments of risk and uncertainty – no matter whether elicited from lay people or from experts – are always affected by cognitive heuristics, i.e., simple rules of thumb that people use to arrive at judgments. In many day-to-day circumstances, these simple rules help decision-makers to arrive at judgments efficiently and quickly. In some instances, however, they can lead to biases (e.g., overconfidence) and oversimplifications that then lead to misjudgments of values, risks, or problems. Among the most common cognitive heuristics include the availability, anchoring and adjustment, and representativeness heuristics.

The availability heuristic suggests that one's probability judgment is driven by the ease with which one can either remember previous occurrences of similar events or imagine such occurrences. The anchoring and adjustment heuristic causes probability judgments to be driven by a reference or starting point which serves an anchor. For example, if an expert were asked to give a subjective probability estimate of a particular climate change outcome of interest in comparison to the probability of an unrelated event, the latter would serve as an anchor and influence the probability the expert might place on the climate change outcome. Finally, the representativeness heuristic suggests that people tend to judge the likelihood that an object belongs to a particular class in terms of how much it resembles their perception of that class. These kinds of cognitive biases need to be carefully assessed and minimized in expert elicitations, i.e., interviewers must be aware of them and probe experts in numerous ways to minimize the influence of such heuristics on expert judgment (Box 1)

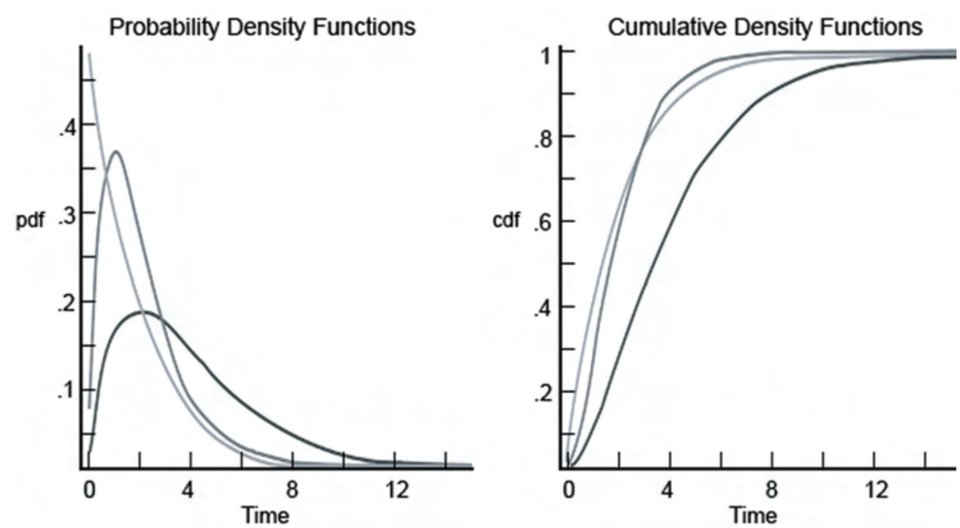


FIGURE 4: **Examples of Probability Density Functions** (pdf, left) and Cumulative Density Functions (cdf, right). Three different probability distributions of an abstract variable over time are shown in these graphs. When depicted as a pdf, one – the darkest curve – shows a relatively low probability near the origin with only slowly diminishing probability over time. The same data transformed into a cdf, this distribution translates into an S-curve with a relatively flat slope. By contrast, pdf's with high probabilities near the origin and rapidly decreasing probabilities thereafter translate into steeply rising, then rapidly flattening cdf curves.

Often uncertainty about model form or structure is as important, or even more important, than uncertainty about values of coefficients. Recently, some good progress has been made in addressing and exploring model uncertainty (see, e.g., Dowlatabadi and Morgan 1993; Evans et al. 1994a, 1994b; Budnitz et al. 1995; Morgan and Dowlatabadi 1996; Bankes 1993; and Lempert et al. 2003). Integrated climate assessment models ideally can deal with both uncertain coefficients and uncertain model functional form. They do the former by assigning pdfs to uncertain coefficients, and then simulating how this coefficient uncertainty propagates through the model. Uncertainty about model functional form, on the other hand, is assessed by exploring the results of multiple plausible model assumptions. Typically such different model assumptions lead to dramatically different model outputs. Thus, rather than trying to project plausible future worlds or optimal climate policies, model uncertainty explorations may better lend themselves to explore the relative robustness of policy approaches that different countries or blocks of countries may choose to adopt. The development and assessment of robust policies also needs to account for the fact that climate change will occur in the context of other environmental and societal changes (see Chapter 4).

Scenarios best describe such interlinked sets of simultaneously occurring and/or changing climatic, societal, and ecological conditions. They can serve as useful devices to think about the future, especially about path-dependencies, or the internal cohesiveness of multiple changes occurring in the same space and time. Scenario analysis, however, is also fraught with challenges. For example, scenarios relying on expert judgment encounter the same problems with cognitive heuristics

Box 1: A Model Protocol for Expert Elicitation

Expert elicitations should be carefully prepared, tested, and informed by an understanding of how cognitive heuristics can bias expert judgments. A well-crafted elicitation process is not a test of the experts' knowledge, but allows experts to provide their carefully considered judgment, supported by all the resources they deem relevant to consult. The elicitation process should include the following elements:

- Interviewers prepare a background review of the relevant literature.
- Questions are carefully crafted in collaboration with selected experts.
- Pilot studies are conducted with younger (e.g., post-doc) experts to distill and refine the questions.
- Interviews are conducted in the experts' office, which allows full resources to be at hand.
- The process should give ample opportunity to the expert for subsequent review and revision of the judgments provided.

Combination of divergent expert judgments can be challenging and is sometimes ill-advised. Often it is preferable to explore the implications of each expert's views, so that decision-makers have a clear understanding of whether and how much the differences matter in the context of the overall decision.

Several excellent examples of expert elicitations are provided in (Morgan et al. 1978a, 1978b, 1984, 1985; Nordhaus 1994; Budnitz et al. 1995; Morgan and Keith 1995; Hanks 1997; Casman et al. 1999; Morgan 2001; Morgan et al. 2001; Rao et al. 2003; Ha-Duong et al. in press).

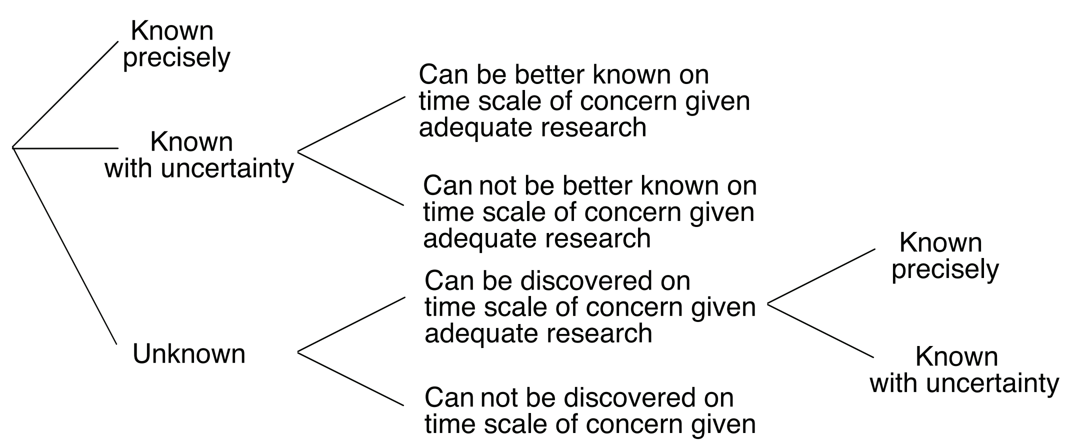


FIGURE 5: **Distinction of the Known, the Unknown, and the Unknowable** The distinctions between the known, unknown, and unknowable are made from the perspective of a decision-maker, i.e., with regard to the state of knowledge at the time a decision has to be made. Whatever improvement of the knowledge base may occur outside the decision timeframe – while in principle possible – is irrelevant to the decision-maker. Therefore further distinctions (on the right of the figure) were omitted to avoid confusion. (Source: Morgan; reprinted with permission)

described above; scenarios that are too detailed can make a useful analysis unnecessarily difficult and produce "uncertainty cascades" (chains of events with increasing uncertainty) that render results meaningless. Thus, simpler parametric models may sometimes suffice to examine the impacts of plausible alternative scenarios on outcomes, and hence to place plausibility boundaries around future worlds.

The only effective way to deal with those cases that are either unknowable on policy-relevant timescales or in principle is to devise robust and adaptive strategies.

Extreme or Deep Uncertainty: The Unknowable

Dealing with uncertain data is not quite as challenging as dealing with uncertain coefficients, and that in turn is less difficult thav n dealing with uncertain model functions. A common strategy is to switch to successively simpler models as one moves into less well understood regions of the problem, until finally, one is confronted with complete ignorance. That which is currently unknown, may – in principle – be knowable, while other unknowns cannot (Figure 5).

The only effective way to deal with those cases that are either unknowable on policy-relevant timescales or unknowable in principle is to devise robust and adaptive strategies – relatively flexible ways to adjust to future conditions as they unfold. To analytically identify such strategies, scientists employ integrated assessment and a range of policy analysis tools (see Chapter 4). How decision-makers deal with the associated uncertainties is summarized in the following section.

1.2 UNCERTAINTY AND IGNORANCE FROM THE PERSPECTIVE OF DECISION-MAKERS

The fact that not everything is known does not constitute a new or unusual situation for decision-makers, but it puts them in the pivotal role of managing – at times substantial – risks and opportunities. Obtaining desired or required outcomes, or avoiding undesirable outcomes, can thus be viewed as a balancing act between trade-offs when numerous decision variables are uncertain. In fact, decision-makers never have perfect knowledge of all the different factors that affect their decisions. They are habituated to the generic condition or experience (perception) of having imperfect knowledge of the scientific and non-scientific aspects of a decision problem. As such, a policy-maker's understanding of the word uncertainty is far broader and less specific than a scientist's definition of that term.

Against this backdrop, there are normal and novel aspects of uncertainty for decision-makers in the context of climatic change. Potential risks are enormous in light of California's sensitivity to changes in temperature and especially precipitation. In addition, the risk of practically irreversible environmental change grows with the rate and magnitude of climate warming. At the same time, California managers are used to using weather and climate information in their resource management decisions. They confirmed during the workshop that in cases where climate change can be factored into existing decision processes, i.e., when climate change does not fundamentally change what decision-makers already do, then information is more likely to be perceived as useful. This is especially true if the information is presented in forms that easily fit existing information formats. In situations where climate change demands a significant change to existing decision processes, scientists are more likely to encounter resistance to climate information from resource managers, particularly when very large uncertainties are involved.

What's Useful, What's Needed:
Climate-Sensitive Decision Challenges for California Resource Managers

California is sensitive to climate variability and change in numerous ways. The sectors highlighted below pose some of the greatest challenges to resource managers, both at present and over the near- and long-term futures.

Water Resources

The key impacts expected from climate change on California's water resources will result from a combination of increases in air temperature, changes in precipitation quantity and timing, changes in runoff quantity and timing, and sea-level rise. Scientists and water managers expect:

- Changes in the frequency, magnitude, and duration of floods and droughts, with more floods in winter; reduced runoff in spring; and less water available during the hot, dry summer season (Figure 6a and 6b).
- Changes in water supply, which would impact the amount of water available to meet urban-residential, industrial, agricultural, and ecological water needs; the amount and timing of inflows into reservoirs; and consequently water system operations, requiring difficult balancing decisions between flood control and reliability of water supplies throughout the year.

FIGURE 6: (A) The 1987-1991 drought affecting Oroville Reservoir (left); (B) Flooding near Sacramento in 1997 (right). (Source: CA Dept. of Water Resources; reprinted with permission)

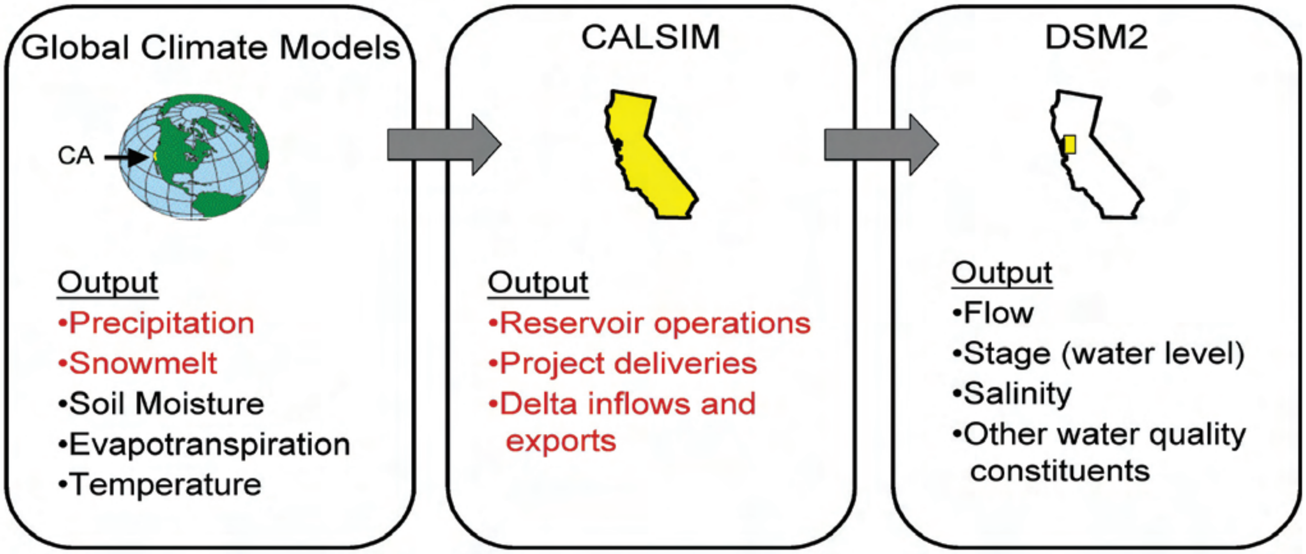


FIGURE 7: **From Global Climate Model to Regional Water Resource Planning Tools** CALSIM = California Simulation Model; DSM2 = Delta Simulation Model 2. Note: Outputs in red provide input to the next model. (Source: Chung; reprinted with permission)

- Changes in water quality, both for drinking and environmental needs (e.g., through higher river and lake temperatures, changes to in-stream flows). Impacts on the San Francisco Bay-San Joaquin Delta system through sea-level rise and saltwater intrusion, impacting the estuarine ecology. As a result, levee stability in the face of more flooding and sea-level rise might be challenged. Sea-level rise could also potentially disrupt the conveyor system that brings fresh water from northern to southern California.

To understand the true magnitude of the challenge water resource managers face, it is necessary to put these potential changes into their natural and institutional context. California confronts both a seasonal and geographic mismatch between supply and demand. Seasonally, runoff is greatest in the winter and spring, while demand is greatest in the summer. Geographically, most of the state's water supply comes from the north (Sierra Nevada Range), while the greatest demand is in the agricultural production areas of the Central Valley and, secondarily, the population centers of central and southern California. The north-south transfer of water is critically dependent on the hydrology of the Bay/Delta region, hence the importance of sea-level rise impacts on that region. Finally, water resource management in California is a multi-jurisdictional effort, with local, state, inter-state, federal, and even international (e.g., Mexican) water projects, institutions and agreements involved.

To coordinate multi- and cross-jurisdictional water management, California has developed several water management tools:

- CALSIM – or CALifornia SIMulation model, a statewide water operations optimization model;
- DSM2 – Delta Simulation Model 2, a one-dimensional hydrodynamics and water quality model linking all water channel networks; and
- IGSM2 – Integrated Groundwater and Surface Water Model 2, a quasi three-dimensional groundwater and one-dimensional surface water model.

If climate change information is to inform water resource management in California, it needs to fit into these existing state and regional water management tools (Figure 7).

In 2003, California's Department of Water Resources together with the U.S. Bureau of Reclamation, formed an ad hoc Climate Change Team to provide qualitative and quantitative estimates of the effects of climate change on California's water resources, and to ensure that this information is relevant to water resources decision-makers. The team, in collaboration with universities, state, and federal agencies and laboratories, uses outputs from climate models to assess potential impacts of various climate change scenarios on California's water resources (statewide and local). The team also works very closely with the California Energy Commission's Public Interest Energy Research (PIER) Program, providing data and technical assistance to ensure the usefulness of PIER research projects to state water planning efforts.

In the absence of probabilistic forecasts of climate futures, the team deals with the associated uncertainty through two basic approaches. The first of these is what it calls the bookend approach – a bracketing of potential impacts by using two commonly advanced yet rather different climate projections (hot and dry versus warm and wet). The projections are used to conduct sensitivity analyses for key management-relevant variables under these different climate conditions (e.g., snowmelt timing, April 1 snow pack, end-of-year reservoir storage). In this sensitivity analysis, both ends of the projected range are assumed to be equally likely. The goal is to identify robust management strategies under each or both climate scenarios, and – to the extent possible – develop contingency plans for future conditions that exceed the range of currently projected climate futures. The second approach is to focus on the impacts on water resources from those climate variables that are least uncertain – increases in air temperature and sea-level rise – and then to identify risk management strategies that minimize those impacts.

An as-yet-unexplored third approach might be to identify those climatic conditions that could cause significant breakdowns in the managed system (e.g., where management goals can no longer be achieved). In a variation on this approach, one could conduct analyses of those institutional, managerial, or infrastructural elements in the water management system that are most sensitive to climate shifts, and then identify climatic thresholds beyond which those critical system elements are no longer able to perform adequately.

Many no-regrets options exist that would provide benefits under greater or lesser climate variability.

California water managers suggested that quantitative uncertainty analysis would be of critical support in their long-range planning and management because diametrically opposed precipitation scenarios are difficult, if not impossible, to prepare for. State water managers identified the following information needs:

- Comparative assessments of water resource sensitivity to air temperature, precipitation, and natural runoff (using monthly aggregate data)
- Water resource projections at the watershed scale
- Water resource projections at various decision-relevant timescales (e.g., 25 and 50 years out)
- Quantitative uncertainty information for various climate projections (multiple CO_2 increase scenarios; comparison of multiple GCMs using different CO_2 scenarios)

Once such probabilistic information associated with potential impacts of incremental climate change is available, managers could use it to develop management plans, determine priorities in resource allocation, and develop adaptation measures.

Climatic Hazards

Current global climate models offer no conclusive evidence for either increases or decreases in regional climate variability, although the projected intensification of the hydrological cycle is expected to increase some extreme events. Some models also project increases in El Niño events. If these projections materialized, they would be of great importance to water resource managers, farmers, and hazards managers in California.

Decision-makers need to know whether recent changes in climate variability are part of natural climatic oscillations or indicators of large-scale, lasting change, as there is a danger of maladaptation in some cases where climate variability is confused with long-term climate change. Many no-regrets options exist, however, that would provide benefits under greater or lesser climate variability.

Ecological Resource and Biodiversity

California, with its wide variety of climates and variable topography from the coastal ocean to alpine regions, is a hotspot for biodiversity. It is, sadly, also a hotspot for endangered species. Climate change is expected to increase pressures on individual species and natural ecosystems. Some ecosystems may not survive, while others may do so only in selected, isolated places (e.g., coastal sage scrub). On the other hand, managed ecosystems are expected to fare better as human intervention may assist in adapting to changing climatic conditions.

Probabilistic climate projections can help California resource managers to identify high-risk species and ecosystems, design migration corridors, and find appropriate adaptation strategies that take climate and other societal pressures on the natural environment into account.

Air Quality

The higher temperatures expected with climate change will increase ozone formation and concentration. As workshop participants reported, some air districts are already reporting a trend toward more days conducive to ozone production. Air quality managers view ozone as a growing problem as climate warms, since they will face greater and greater challenges in the future meeting state and federal ambient air quality standards.

Air quality managers are not only concerned with temperature trends and their effects on ozone, however. They also need to control particulate matter, concentrations of which are influenced both by temperature and precipitation. For example, ammonium nitrate dominates wintertime particulate matter levels in California. Those concentrations decrease with more precipitation and higher ambient air temperatures. Thus, while many decisions in the air quality sector have shorter time horizons, decision-makers also require temperature and (less certain) precipitation information. A further challenge managers face is understanding and tracking global circulation patterns that transport aerosols from outside California such as recent dust storms, wildfires, and fossil combustion products with origins across the Pacific ocean.

Energy Supply and Demand

Energy demand in California is expected to grow under warmer

Box 2: Delaying Global Climate Change via Energy Efficiency?

The IPCCs former base case emissions scenario, IS 92a, assumed an autonomous energy efficiency improvement (AEEI) of 1% annually. As a thought experiment, if this rate were doubled, the trend line for world energy demand/need would nearly level out. If such a 2% rate were assumed for all western developed countries, the world energy demand in 2100 would be lower than it is at present.

These figures illustrate the enormous importance increases in energy efficiency could play in determining future energy consumption and, hence, greenhouse gas emissions. They also point to additional energy/climate policy opportunities beyond those focused on changing the energy supply mix (e.g., move away from GHG-intensive fossil fuels toward renewable energy sources) or sequestering CO2: improvements in the energy efficiency standards in the appliav nce, building, and transportation sectors.

Experience in California over the past 30 years with setting and gradually tightening energy efficiency standards for appliances (e.g., refrigerators and air conditioners) and buildings illustrates that such demand-side management efforts are highly cost-effective, reduce GHG emissions and local air pollution, and in no way inhibit economic growth or quality of life.

To put the value of energy efficiency measures into perspective, it is illustrative to focus on just one example: energy efficiency in refrigerators and freezers. To run 150 million such appliances at 1974 efficiency standards would require roughly 280 billion kWh per year. At 2001 efficiency standards, 2/3 of that energy would be saved. This saved energy (or avoided energy consumption) is more than twice the energy produced by all currently existing renewables in the U.S.

This example indicates the vast energy savings that could be achieved through efficiency measures, and thus of their potential contribution to reducing heat-trapping gas emissions, especially in rapidly developing countries such as India and China.

Source: Rosenfeld (data based on IPCC IS92a scenario)

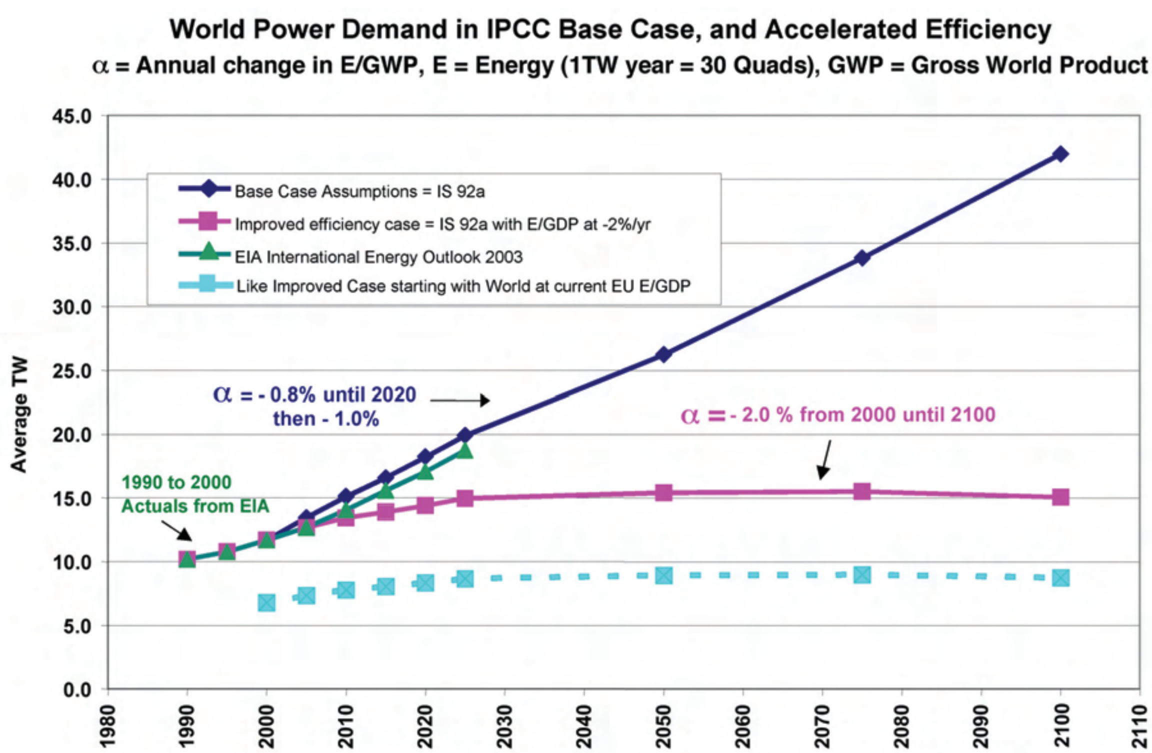


FIGURE 8: **World Power Demand under Varying Energy Efficiency Improvement Assumptions** Using the IPCC IS92a scenario as the base case, this figure compares this case with three alternative trajectories of the world's primary energy consumption. The IS92a case (dark blue) assumes e/gdp improving at -0.8% per year through 2020 and -1.0% per year thereafter through 2100. The second trajectory (green) is taken from EIA's Annual Energy Outlook 2003. The third (pink) is a case where e/gdp is assumed to improve at -2.0% annually through 2100. In assuming this e/gdp improvement, gdp is held at the same level as in the IS92a case and e is reduced so that e/gdp improves by -2.0% per year. The final case (turquoise) is similar to the third case, except that is assumes the starting point to be the current e/gdp for the European Union applied to the entire world. (Source: Rosenfeld; reprinted with permission)

climate conditions to meet growing cooling needs. Most studies assessing climate change impacts on energy demand have used average temperatures or cooling/heating degree days in their model approaches. However, the asymmetric changes in diurnal temperature profiles (more heating at night, Tmin increasing faster than Tmax) make that approach problematic and are likely to overestimate the potential impact. At the same time, new evidence suggest that existing global climate scenarios may be underestimating the likelihood of more dramatic global warming (Stainforth et al. 2005) but these projections have not yet been downscaled to the California region. Potential increases in heat extremes (frequency and intensity) may also not be captured well by approaches that use average temperature increases.

Scenarios can serve as useful devices to think about the future, especially about path-dependencies, or the internal cohesiveness of multiple changes occurring in the same space and time.

Decision-makers in the energy sector thus require better energy demand projections to manage short-term demand-and-supply fluctuations, make long-term investment decisions, and devise cost-effective and reliable energy management strategies (see also Box 2).

Summary

In each of the sectors discussed above, a range of non-climatic factors complicate the so-called baseline projections. As mentioned above, the management of climate change impacts in California is confounded, for example, by the influx of air pollutants from Asia, which affect pollution levels and may also affect rainfall patterns. Urbanization and land use changes directly affect local ecosystems and modify temperature and rainfall patterns. The growing population increases the demands on natural resources such that even without pressures from climate change California would face difficult problems over the coming decades to meet them. These stresses would be added to pressures created by human-induced and natural climate change surprises.

1.3 RECONCILING DECISION-MAKER NEEDS WITH MAINTAINING SCIENTIFIC CREDIBILITY

Scientists interested in providing policy-relevant climate information frequently assume that probabilistic scientific information is essential to decision-makers. While maybe too sweeping an assumption, California decision-makers confirmed that in many specific decision situations, probabilistic climate information, as well as more information about the reasons for existing uncertainty, would be welcome in the management of climate-sensitive resources (Figure 9).

To build a better bridge between climate science and decision-making, workshop participants specifically suggested pursuing work guided by the following principles:

- ***Timeliness and Matching Time Horizons:*** Scientific data must be offered at the right time in the decision/planning process (e.g., annual decision calendars, semi-regular updates to long-term plans). If possible, scientific data should extend over the time horizon relevant to the decision being made (e.g., 20-30 year planning horizons).

- ***Relevance:*** What decision-makers most need is scientific research focused on the impacts variables which concern them, or over which they have management control (e.g., spring snow pack, runoff timing and amounts, and diurnal temperature changes). In general, the highest priority for many resource management problems in California is improved precipitation projections. Second, higher spatial and temporal resolution on all climate variables and extremes would help with specific local management challenges.
- ***Causality and Robustness:*** If probabilistic information

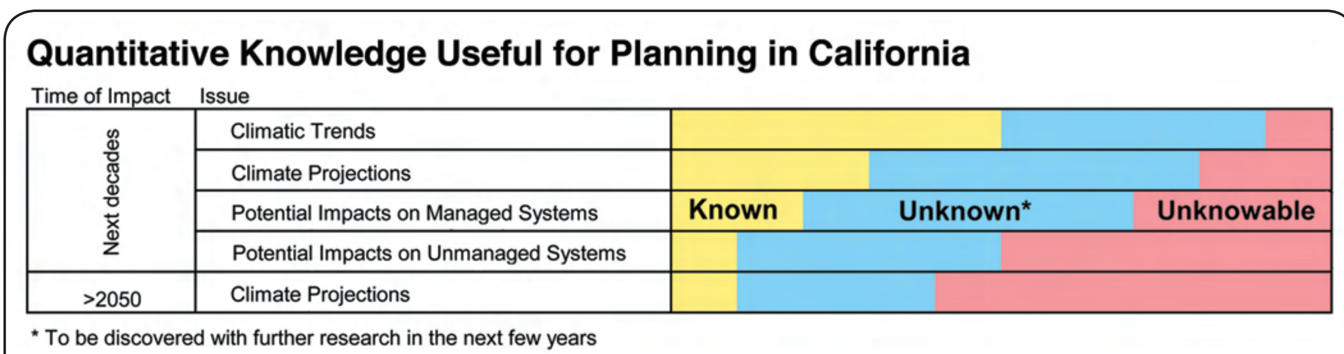


FIGURE 9: **Quantitative Knowledge Useful for Planning in California** (Source: Franco; reprinted with permission)

cannot be provided at this time, even drawing tighter bounds around projections would be helpful to assist in the identification of adaptive strategies and robust policies. Moreover, scientists can assist managers in identifying no-regrets strategies in the face of uncertainty, and conduct retrospective studies to better understand the climate/impact relationship.

- ***Criticality:*** While awaiting improved climate information, analyses that identify critical institutional thresholds or the most climate-sensitive elements in a managed system would help narrow the most important information needs.
- ***Post-Mortem Evaluations:*** Evaluations of the decision-making process and of the science-management interaction – while typically neglected – would provide valuable information on the needs and constraints of scientists and decision-makers, and the potential to improve the process for climate-sensitive decisions.

Receptivity of decision-makers to probabilistic information should not be taken for granted, however. Many resource managers are less familiar with probabilistic, numerical information. In those cases it will be more important to carefully and consistently relate uncertain climate information in ways and with terms that connect with decision-makers' frame/understanding of the problem.

At the same time, scientists and decision-makers acknowledged the inevitability and persistence of varying degrees of uncertainty, and even complete ignorance. Resolving these unknowns is not a prerequisite for action from either a policy standpoint or a scientific perspective. Nor is improved communication from scientists to decision-makers the solution to all decision problems under uncertainty. Identifying feasible solutions despite high degrees of uncertainty remains a tall challenge for both scientists and decision-makers. In fact, science is making important progress in identifying robust strategies under uncertainty (see below), and decision-makers already make difficult decisions under conditions of deep uncertainty in many sectors of society, from farming to industry.

As decision stakes, the risk of irreversibility, and the degree of uncertainty grow, so does the need for robust, adaptive management strategies. Much past experience shows, however, that adaptive management – which is based on awareness of uncertainty and updating decisions as new information becomes available – has frequently failed in practice. Thus, to realize the promise of the adaptive approach in resource management, attention has to be paid to the barriers, constraints, and human perceptions (e.g., of uncertainty) that impede incorporation of updated information in decision-making. At the same time, managing uncertainty through adaptive strategies offers science a prominent role. Scientific input and analysis is needed during the problem identification and analysis phases as well as during the identification of management options, and subsequently in the implementation, monitoring, assessment, and evaluation phases. Close involvement of scientists in this way will allow decision-makers to continually learn, update, and adjust their management options.

To realize the promise of adaptive resource management, attention has to be paid to the barriers, constraints, and human perceptions that impede incorporation of updated information in decision-making.

Clearly, in such close collaborations, decision-makers, with their need for greater specificity (geographical and temporal resolution), greater certainty, and higher confidence, will push climate change science to the edges of what it can produce with credibility. There is no one-size-fits-all resolution of this difficult, yet unavoidable tension. Instead, the right balance has to be found on a case-by-case basis in the context of the constraints imposed by present knowledge about risks and by the decision environment.

Great progress could be made, however, workshop participants concluded, in bridging the science-policy gap if both researchers and decision-makers made greater efforts at understanding their different cultures and starting points. History, economic factors, the political climate, identity politics, institutional stove-piping, and professional requirements can limit the science-policy interaction and the decision space. At the same time, serendipitous opportunities will arise from focusing events, fortuitous timing, strong leaders willing to take risks, and shifting political circumstances. A strong dual commitment to credibility and relevance in an ongoing process of communication between information producers and users emerged as the strongest guidance for improved science-decision-maker interaction (see also Chapter 5).

2. PROSPECTS FOR IMPROVING EMISSIONS SCENARIOS AND GENERAL CIRCULATION MODELS

Chapter 2 summarizes workshop presentations by Nakicenovic, Richels, Sanstad, Rosenfeld, Pitcher, Schlesinger and Andronova, Dettinger, Wigley, Cayan, and Duffy.

Uncertainties in the projections of future climate change result from a number of key sources. This chapter focuses on those deep uncertainties rooted in our ability to understand and predict the drivers of change as well as from the interactions among them, and on the uncertainties resulting from methodological and structural differences in general circulation models (GCMs). The key question guiding this chapter (and the underlying workshop presentations and discussion) is how GCMs and emission scenarios can be improved in a way that enhances their utility for regional modeling efforts.

2.1 THE KNOWN, UNKNOWN, AND UNKNOWABLE ABOUT EMISSIONS SCENARIOS AND UNDERLYING SOCIETAL DRIVERS OF CHANGE

Future greenhouse gas (GHG) emissions are the result of very complex dynamic systems, determined by driving forces such as demographic dynamics, socio-economic development, and technological change. Their future evolution is highly uncertain (Nakicenovic et al. 2000). To explore the implications of economic convergence of developed and developing countries, the IPCC developed four "storylines" or families of scenarios. In spite of their assumption of convergence, these storylines differ fundamentally in their trajectories of societal evolution and result in widely differing levels of emissions over the 21st century and beyond. The IPCC did not assign probabilities to these scenarios. The scenarios are non-interventionist in the sense that they do not include explicit climate policies, although one – A1T – assumes technology developments that are similar to those that might occur with climate policies, especially when compared to the fossil-intensive scenario A1FI, which continues to rely on fossil fuel intensive energy technologies that have higher impact on climate (e.g., Schneider and Lane 2005b).

Critique has arisen in the literature over the past few years about the process of developing these scenarios, the scenarios themselves, and the lack of alternative scenarios (see, e.g., Castles and Henderson 2003a, 2003b; Holtsmark and Alfsen 2004; McKibbin, Pearce, and Stegman 2004; Nakicenovic et al. 2003). The major strands of critique focus on (a) methodological issues, (b) questions regarding the range of scenarios, and (c) the lack of probablistic assessment of different scenarios. Regarding the first point, critics have questioned the comparability across countries when GDP is calculated on the basis of Market Exchange Rates (MER) rather than Purchasing Power Parity (PPP). The extent to which the difference in calculation affects the outcome is considered debatable, but may not be too large. The SRES range of scenarios is limited to a particular kind of growth scenarios. For example, the current set of SRES scenarios does not include major regional economic collapses or even a collapse of the world economy resulting from pandemics, hostilities, or other factors undermining neo-liberal economic growth (globalization of trade) which would lead to significant economic stagnation or decline and smaller CO_2 emission increases than current SRES scenarios consider. The current set of scenarios does not include more extreme emission increases either. Those might come about if one imagines oil prices of $65 or above per barrel that could trigger the massive extraction of non-conventional oil from tar sands or oil shales, which in turn would produce GHG emissions that make A1FI a middle scenario. Thus, while the scenarios group did not consider disaster scenarios, any serious analyst could not set subjective probabilities for these more extreme cases much below ten percent. Finally, the scenarios group did not assign probabilities to *any* of the basic scenarios. Instead, it called each scenario "equally sound," i.e., it assumed a uniform probability distribution. While this may have provided a compromise to appease the IPCC-SRES community, equal likelihood of each of these scenarios may not necessarily represent the best thinking about the relative likelihood of, say, the A1FI high carbon emissions scenario versus the more egalitarian B1 scenario.

The workshop did not focus on these critiques per se, but instead on the level of understanding of each of the driving forces and their interrelationships. The main societal drivers of future emissions include:

- Demographic evolution (population growth rates, migration, age structure, etc.)
- Economic development (growth, structure, inter- and intraregional integration and disparities)
- Social change (values, lifestyles, policies)
- Technological change (rates of innovation, market penetration, improvement, technology mix)

The uncertainties associated with these four key drivers stem from the level of understanding of each of the drivers, the relationships and interdependencies between them, and the resulting emissions (the most direct, immediate outcome). They can be considered conditional uncertainties, as future changes in these drivers emerge from and depend on prior developments (path-dependencies).

In addition, future atmospheric GHG concentrations will not only be driven by emissions but by terrestrial and ocean uptake of carbon and other environmental feedbacks, which are of uncertain directionality and magnitude. At a meta-level, storylines about socio-economic and technological changes are subjective interpretations of trends in delivery and valuation of resources, goods, services, and the other factors driving societal development and emissions. These assumptions (subjective uncertainties) are expressed through experts' choice of metrics, discount rates, and inclusion of non-market damages and benefits (e.g., Schneider and Lane 2005b).

Most attention at the workshop focused on demographic and technological change, and to a lesser extent on economic development, while social change, environmental feedbacks, and questions of subjective expert judgment about valuation were treated in the context of the discussion of each of the main drivers of change.

Demographic Change

The SRES scenarios differ markedly in the population element:

- ***A1 family*** – Global population peaks in mid-century and declines thereafter, convergence, high degree of social interaction
- ***A2 family*** – Continuously increasing population, fertility patterns vary regionally and converge only slowly, global heterogeneity
- ***B1 family*** – Global population peaks in mid-century and declines thereafter, convergence, global solutions, high degree of equity
- ***B2 family*** – Continuously growing global population, albeit at slower rate than A2, diversity, social equity, regional and local solutions

Subjective choices by the modeler have the overriding influence on the projections of future economic development.

The envelope of potential world populations and resulting emissions widens considerably over the course of the 21st century with global population in 2100 ranging from about 4 to 14 billion, and cumulative emissions from 1,000 to over 3,400 GtC. While global population projections have come down overall in recent years, uncertainty remains considerable. As with projections of other drivers, total population projections vary relatively little in the near future, but diverge sharply after 2050. Underlying uncertainties apply not only to the specification of key demographic variables such as total completed fertility, mortality, or life expectancy. At a deeper level the greatest uncertainties concern our causal understanding of the fundamental functional relationships that determine population shifts and whether these causal relationships hold over time. For example, is it reasonable or defensible to expect a leveling off of life expectancy, and if so, at what age? What will be the key determinants of future mortality: diseases of aging, injuries, infectious diseases, the sophistication and availability of health care, and so on? How does migration – currently neglected in SRES scenarios – affect population change? How should we deal with demographic nonlinearities that are likely to result from biotechnology, human cloning, overuse of antibiotics, and so on? What would be the impact of value shifts in affluent societies back toward bigger families, and how sure are we that this will not happen?

Workshop participants called for both detailed empirical examination of these questions in case studies of the past and present, as well as for sensitivity analyses in which assumptions about future demographic changes are tested carefully.

Socio-Economic Change

As with demographic change, the economic futures depicted in the SRES storylines vary in the degree of inter-regional integration, disparities, and the pace of economic development. What is common to all scenarios is the overall thrust toward convergence, greater prosperity, and an overall expanding world economy.[2]

A probablistic analysis of future global CO_2 emissions conducted by Rich Richels used subjective expert opinions to assess the relative importance of critical factors such as economic growth, energy use, and emissions per unit of energy. The study showed that – ceteris paribus – future economic growth rate (as measured by Gross Domestic Product, GDP) tends to dominate emissions growth. While few doubt the overriding importance of the economic growth term in the development of future scenarios, an all-else-remaining-equal world is, of course, an unrealistic assumption. Instead, the key question – and a significant uncertainty – is how tightly the GDP growth rate is linked to energy use, and, in turn, how closely energy use is tied to GHG emissions. Sensitivity analyses show that assumptions about the elasticity of price-induced energy conservation or substitution or about the rate of autonomous energy efficiency improvements (AEEI) often have little impact on the overall emissions by 2100. However, this observation may depend on the discount rate and the assumption that markets function perfectly. Some studies in fact have shown that induced technological change can significantly affect emissions pathways (e.g., Goulder and Schneider 1999; Azar and Schneider 2002).

[2] While SRES scenarios do not include a storyline in which global or regional collapse occurs, an older study (Mesarovic and Pestel 1974) used the Club of Rome model which did produce regional collapses in a globally growing world.

What a survey of the economic literature reveals instead is that subjective and policy choices by the modeler have the overriding influence on the projections of future economic development. For example, assumptions about future carbon pricing, the type and cost of different climate and energy policies (mix of supply- and demand-side management) (see Box 2 above), or the choice of discount rate exert significant influence on the projections of societal economic futures (see e.g., Mastrandrea and Schneider 2004). The differentiating impacts of such subjective assumptions become increasingly apparent the further into the future the projections reach. In addition, few models exist projecting (even just regional) economic collapse. Workshop participants suggested that a close and systematic evaluation of economic model assumptions and inter-comparison of economic models with each other and with empirical data where appropriate should be undertaken, affording these models a comparable level of scrutiny as climate models. In addition, specifically examining past economic development (say, over the past 50 years) for the constraints that caused actual economic development to turn out lower than projected could yield important insights into realistic bounds on economic projections into the future. Particularly important would be a search for (and then avoidance of) those decisions or constraints that caused lock-in (i.e., a long-term commitment to a particular technology or course of action).

A significant challenge for a meaningful comparison is the conceptual difficulty of formulating a pure business-as-usual or climate policy-free reference case. Even before the Kyoto Protocol went into effect, or – geographically more confined – in the absence of a U.S. national climate change policy, decision-makers frequently begin responding to the possibility of such a policy before it actually comes into force. For example, some investment banking evaluations of CO_2 emitting industries already consider carbon emissions a debit on their future balance sheets based on a reasonable probability that there will be a shadow price on carbon before too long, and certainly well before the economic lifetime of such carbon-emitting projects is expired. As Steve Schneider stated at the workshop, "It's not about policy; it's about the expectation about the existence of policy." This action-in-anticipation effect in point of fact eliminates the no-policy case against which other policy-scenarios could be compared adequately. Maybe more important would be to explore different policy mixes, describe the costs at various levels of policy, or the sensitivity of economies to different levels of carbon constraints, rather than a no-policy case. Moreover, decision-makers' reflexivity about future policy regimes, future climate, and other decision-makers' actions, causes an irreducible degree of uncertainty in projecting future societal development.

Technological Change

Technology – being the principal intermediary between population, consumption, and environmental impact – is viewed by many as the key variable determining future emissions. In a technology-dominated world, in fact, many count on technological solutions to the climate problem (which technology helped create). Consequently, differences in energy technology (with higher or lower GHG emissions), and varying degrees of global and inter-regional coordination and market penetration of technologies play a prominent role in the IPCC's SRES scenarios. Because technological change is insufficiently understood and impossible to predict with much confidence beyond ~30 years out, many see it as a major wildcard in scenario development (see also Gritsevskyi and Nakicenovic 2000).

A prevailing opinion, for example, is that the climate problem is so big that no single technological solution will hold the silver bullet answer. Instead, an all-encompassing portfolio of solutions including efficiency improvements, fuel switching, renewable energy sources, carbon sequestration, and nuclear energy is commonly assumed. Gap analysis can illustrate any one technology's potential under varying assumptions about investments, prices and so on. The key uncertainty here is which policy signals will be set, at what level, to realize maximum feasible capacity or maximum feasible contribution of a technology. Of course, the rate and amount of technology investment (i.e., the strength of the policy signals) will also be affected by the perceived risk and the reduction of unknowns associated with defining dangerous climate change.

An even cursory review of past technological changes, however, shows that "doing everything" is inconsistent with historical experience; typically, one dominant technology emerges, while others survive in smaller niches. Identifying which technology is likely to be the dominant energy technology of the future is speculative, however, and this limits modelers' ability to produce realistic forecasts. Instead, developing (and assuming in model projections) the broad portfolio of technologies is appropriate at this time, even if we can be certain that one technology will eventually become dominant. Such sharp transitions from one technology to another – resulting from a combination of policy signals, network externalities, and the pressures of building economies of scale – have been commonly observed in the past. Historically, transitions in primary energy systems, however, have shown to occur more slowly than technological innovations on the demand side due to the large capital investments required and design lifecycles of installed capacity. Experience also shows that enormous socio-economic and political forces form coalitions to try to preserve existing systems or block threatening innovations, thus reinforcing technology- or investment-given system lags.

Systematic sensitivity analyses of how different policies and energy costs may affect the pace and direction of change as well as the mix of technologies may be more useful to policy-makers than speculating about the long-term technological future. In other words, careful comparative policy analysis can explore how certain policy measures may help stimulate technological innovations. This would provide more policy-relevant information than scenarios of different technology futures. Similarly, developing comparative cost estimates for reducing emissions via different technologies or at different points in the future (likely involving some measure of subjective expert elicitations) would yield important policy-relevant information. Decision-relevant timescales would be those associated with R&D and investment decisions (typically, a few decades). By contrast, attempts to resolve uncertainties about future energy or technology investment costs will keep confidence in such projections low due to the above-mentioned human reflexivity and social learning, as well as unpredictable market uptake rates of innovations, human behavior changes, and conditional uncertainties resulting from path-dependencies.

Another branch of decision-relevant research may focus on the impacts of different mixes of technology-related policies. For example, how can policies supporting R&D be best harmonized with demand-side incentives (e.g., tax breaks for development and purchase of high-efficiency appliances or vehicles)? The two are intimately connected in that policy-makers cannot impose standards until there are several competing producers; on the other hand, standards can cause spurts in innovation and investment in technologies and their markets, hence inducing a commitment to developing better technology. Again, retrospective studies of policies that can explain the relative success or failure of particular technologies would yield important insights and may be able to constrain projections of near- to medium-term technology futures. This type of research could also inform decision-makers on the types of incentives needed to move toward desirable energy futures, understanding that the mix of incentives will differ by technology.

It's not about policy; it's about the expectation about the existence of policy.

Workshop participants suggested that projections of technological change and technology assessments could be vastly improved if practicing technology experts and independent technology consultants interested in developing climate solutions would be involved.

Interactions Among Drivers

The above discussion of demographic, socio-economic, and technological drivers of change is artificially separated. Changes in any one of these affect, and are affected by, changes in the others, and each in turn reflects and influences underlying social values, priorities, and policies.

Past research has shown that any combination of drivers can produce high, medium, or low emissions – and hence warming. Similarly, when explicit energy- or climate-policy intervention is included in the analysis, almost any combination of drivers can meet a specified emissions reduction goal. The policy context (be it specifically for climate or not) affects the directions, interactive dynamics, and pace of societal change. It also affects the costs incurred and benefits enjoyed by different sectors, and the efficiency and effectiveness of policy implementation. For example, non-harmonized policies can impede the efficient introduction of new forms of energy and technology, or of social and economic innovation.

Interactions between societal drivers of change can promote, impede, or (sometimes) not affect changes in other drivers or aspects of society. Better understanding of the ways in which certain drivers condition the evolution of others could help constrain the projections of possible societal pathways. Serious investigation of lock-in events, bifurcations, social tipping phenomena, and the implications of such events on other societal drivers is especially needed. Similarly, SRES scenarios do not consider surprises, and while they cannot be predicted, they are likely to occur over the span of a century. Exploring the implications of surprises that can either promote stringent climate policies – or completely relegate climate change to the back burner – could yield valuable insights into the dynamics of interacting drivers of societal change. Workshop participants singled out the careful and systematic evaluation of the interactions and interdependencies between different drivers as a high priority for future research.

2.2 THE KNOWN, UNKNOWN, AND UNKNOWABLE ABOUT GENERAL CIRCULATION MODELS

Emissions scenarios constitute the prime anthropogenic forcing used to drive general circulation models (GCMs), although land use change forcings are becoming more widely studied recently (Pielke Sr. et al. 2002). Natural forcings – such as solar variability, emissions from volcanic activity, etc. – also drive GCMs, but their relative importance has been increasingly dominated by anthropogenic forcing in GCM runs for the past several decades (IPCC 2001a, Root et al. 2005). Natural forcing is expected to become relatively less of a factor in climatic trends in the foreseeable future given the increasing dominance of human influences on climate.

This section focuses on how different climate models are built mathematically, and how they translate emissions scenarios into climate projections. Recent studies suggest that the uncertainty involved in future emissions trajectories is roughly equal to that due to inter-model differences. The two main reasons for model uncertainty are, first, our still-limited understanding of the climate system and in particular its sensitivity to forcing, and second, the limited ability to translate our best understanding of the climate system into algorithms that account for processes occurring on smaller scales than we can resolve (e.g., clouds, storms). The latter challenge is compounded by computer-hardware constraints on computational speed and storage space.

The Question of Climate Sensitivity

Climate sensitivity is the responsiveness of the climate system to a particular amount of forcing (commonly estimated as the temperature change for a doubling of CO_2 above pre-industrial atmospheric concentrations). How much warming will result from a given increase in emissions is considered by many as one of the most essential questions to reduce climate projection uncertainties. It is also one of the key terms distinguishing different climate models (see below). Should climate sensitivity turn out to be relatively low, i.e., if the climate response to anthropogenic forcing is small, then the problem of human-induced climate change may be less pressing than if the climate turned out to be highly sensitive to such forcing.

The key factors that make determining climate sensitivity so difficult include:

- Estimation of net (instantaneous or adjusted) radiative flux (including inter-hemispheric differences; and the influence and feedback of clouds
- Estimation of radiative forcing from the sun and/or anthropogenic and natural aerosols
- Estimation of the rate and amount of heat uptake by the oceans
- Detection of the climate change signal against the constant background noise of natural climate variability

Published estimates of climate sensitivity vary by nearly two orders of magnitude, depending on the underlying methods (e.g., paleoclimatological, instrumental, and varying modeling approaches) (Andronova and Schlesinger 2000, 2001, and Andronova et al. forthcoming) (Figure 10). Workshop participants suggested that reducing the uncertainty in climate sensitivity estimates requires reducing the uncertainty in the radiative forcing, not only by aerosols, but also by the sun and volcanoes. The uncertainty in climate sensitivity

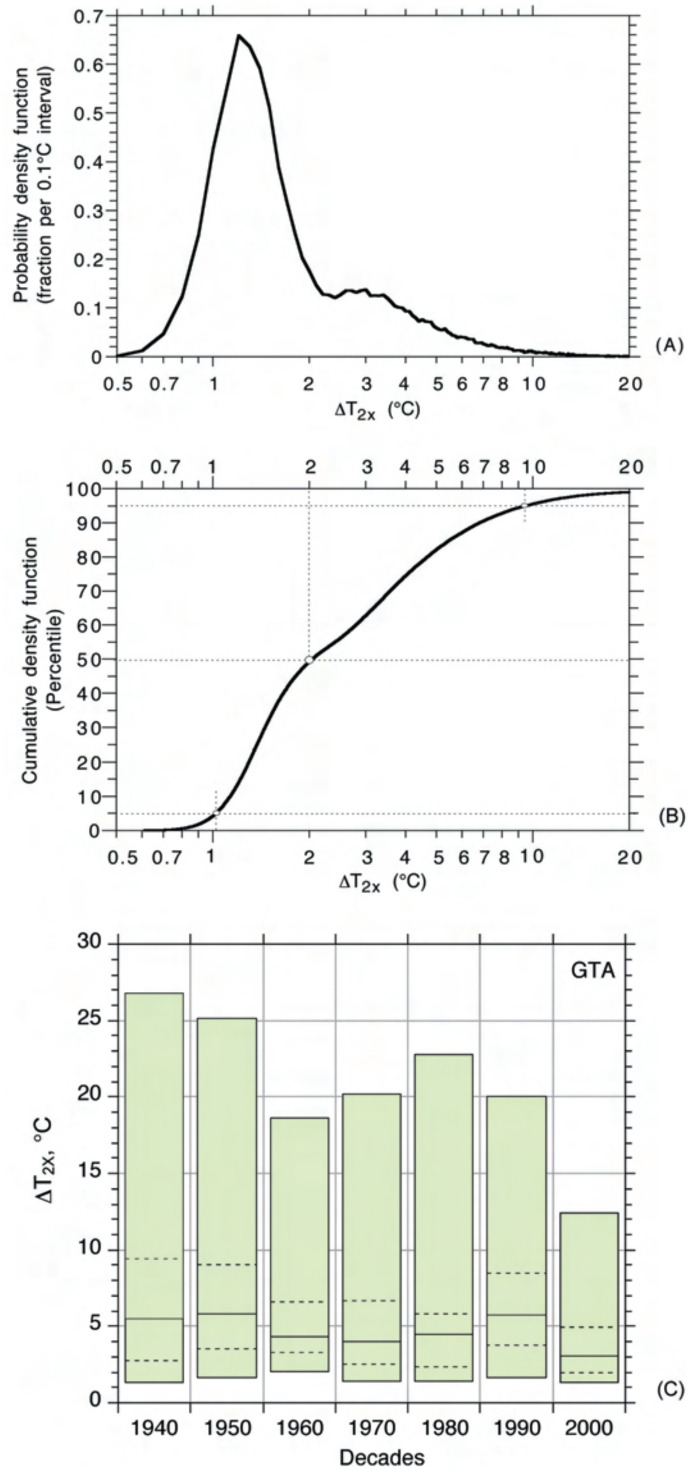


FIGURE 10: **Climate Sensitivity: (A) pdf, (B) cdf, (C) Historic Estimates**

Global climate sensitivity (temperature change per doubling of atmospheric CO_2 concentration) is shown here as (A) a probability density function and (B) a cumulative density function. The curves suggest that climate sensitivity is quite unlikely to be as small as 0.5-0.7°C, highly likely to be in the range between 1-2°C or even as big as 3-4°C, but again rather unlikely to lie in the realm of >6°C. (C) Box plots of climate sensitivity over time (1940-present). (A, B Source: Andronova and Schlesinger 2001; reprinted with permission.C Source: Schlesinger and Andronova 2005, in press) due to climate noise can slowly be reduced by statistical averaging over time, i.e., by using longer and more accurate observational records from the past and – as they become available – extended into the future, to scale climate responses to various forcings. Workshop participants estimated that a significant reduction in this key climate uncertainty will take a decade or more to achieve.

Modeling Pluralism and Methodological Uncertainty: Living with the Differences

Model uncertainty expresses itself in the differences between model outputs when different models are driven by the same inputs, e.g., when GCMs are forced with the same anthropogenic emissions scenarios and natural forcings, or when different impact assessment models are driven by the same climate projections.

> Better understanding of the ways in which certain drivers condition the evolution of others could help constrain the projections of possible societal pathways.

In the case of GCMs, modelers place varying emphases on different aspects of atmospheric chemistry and physics, reflecting their subjective expert understanding and judgment about the relative importance of these components in a coupled land-ocean-atmosphere model. As a result of these differences in internal mathematical representation of the interactions between global systems, GCMs display different strength and weaknesses (e.g., some are better than others in representing certain regional climate patterns, teleconnections, or patterns of inter-annual climate variability). One common measure of evaluating GCMs against the backdrop of these differences in internal structure and in output is their ability to approximate global historical climatic trends and patterns without artificial adjustments. Enormous efforts among all climate modeling groups at improving GCMs have led to the current situation where modern models perform reasonably well in replicating the major patterns of past global climate, while still differing significantly in internal structure and (geographic and temporal) skill to replicate observations at finer time and spatial scales.

Given the impossibility (and foolishness) of agreeing on the use of just one GCM, the multi-model approach is one method to hedge against the uncertainties in future climate. This model pluralism, however, makes assigning probabilities to climate projections challenging. Workshop participants agreed that moving toward probabilistic climate forecasts requires some comparative evaluation of models and the subjective choices made to construct them. Building on previous inter-model comparison projects (e.g., the Coupled Model Intercomparison Project, CMIP), they agreed on the need for dedicated time and resources for such a comparative assessment, and to narrow the scope of such evaluations to produce meaningful insights into the factors that can explain output differences. This would require developing evaluation protocols that hold certain parameters and assumptions constant; systematically testing models against historical periods; methodically examining the parameterizations, measurement, and calibration of one key driver of a model; and using both qualitative and quantitative meta-analyses of model outputs (as previously conducted, e.g., by Repetto and Austin 1997; Weyant and Hill 1999; Fischer and Morgenstern 2003; Hawellek et al. 2004).

Workshop participants also reiterated specific areas of research that are expected to significantly reduce uncertainty in the parameterization of climate processes in GCMs. Among the top priorities are the representation and functioning of clouds and water vapor, the link between atmospheric chemistry and physics (e.g., carbon cycle feedbacks as climate changes), and an improved scientific understanding of the relative forcing of the less well-known contributors (e.g., aerosols or land use changes). Workshop participants reported on important progress in several of these aspects (e.g., super-parameterization of cloud processes at sub-grid scales; ensemble runs of individual models to examine the impact of different initial conditions), but urged further research as well as improved and continuing empirical observation of uncertain parameters as recent results seem to promise significant reductions of model uncertainty, if sustained research efforts are systematically carried out over at least a decade or two.

Finally, instead of simply attempting to better predict what may happen in the future, innovative analyses of multi-model projections – e.g., for joint behaviors of climate variables such as temperature and precipitation – could be used to identify future climate changes that are extremely unlikely to unfold (Dettinger 2004). In California, where precipitation projections vary widely among models, such an approach may help policy-makers rule out certain climate futures, and in turn, narrow the range of potential futures for which they should prepare.

2.3 KEY RESEARCH TASKS: A SUMMARY

Workshop participants expected significant progress over the coming years in improving our understanding of societal drivers of change, resulting emissions, and in global climate modeling. Important improvements are also viable in uncertainty estimates of varying components of global climate projections. Probabilistic estimates of long-term societal changes seem impossible, i.e., unknowable beyond very low confidence, given the unpredictability of human drivers over time horizons of multiple decades to a century.

However, workshop participants saw important potential for improving scientific understanding of the conditional interdependencies between driving forces, and for developing policy-relevant information.

Among the high-priority research tasks identified were:

• ***Improvement of our understanding of individual driving forces of change:***
We should improve our understanding of causal links between reproductive choices and social values through detailed empirical examinations of demographic case studies of the past and present. Sensitivity analyses should be undertaken to carefully test assumptions about future demographic change. In addition, backcasting could be used to evaluate quantitatively how well economic forecasting models do and to better understand the constraints that made actual economic development less than projected. Backcasting and retrospective studies could also be used to illuminate the limits to the technological improvements of existing technologies. Finally, a fuller exploration of the potential of demand-side management should be conducted and included in future storylines (which currently only consider supply-side approaches to energy technology change).

How much warming will result from a given increase in emissions is considered by many as one of the most essential questions to reduce climate projection uncertainties.

• ***Improvement of our understanding of the interactions among driving forces:***
Empirical studies and modeling exercises should be conducted to better understand the interactions between, e.g., policy and technology, economic development and demographic change. The aim would be to highlight the levers that can be moved to effect change. Studies of past technological changes could yield a better understanding of the mix, timing, and staging of incentives that helped bring them about, and thus improve the analysis of technology choices and relevant policy tools. The projections of possible societal pathways could be further constrained through studies that explore the ways in which certain drivers of change condition the evolution of others. And finally, a serious investigation of lock-in events (e.g., establishment of policies that clearly favor, develop, and subsidize a particular technology and related infrastructure such as nuclear energy), bifurcations (e.g., emergence of different political blocks of countries pursuing distinctly different policies and goals), social tipping phenomena (e.g., emergence and widespread adoption of values, practices, and policies that favor sustainable development), and the implications of such events on other societal drivers is especially needed, including the potential surprise of economic and/or environmental collapse.

• ***Improvements in scenarios:***
Workshop participants suggested that building tools that take path-dependencies seriously would be an important step toward improving scenarios, e.g., by conducting alternate modeling runs in which one technology becomes dominant over other possible contenders ("winner takes most" scenarios). In addition, the impacts of surprises on scenario/pathway evolutions should be investigated to produce important insights into the critical levers and dynamics of societal change.

• ***Systematic inter-comparison of economic models:***
Close examination and comparison of economic models of mitigation costs and impacts through a systematic evaluation of model assumptions and comparison to empirical observations would begin to subject economic models to the same level of scrutiny as climate models. Building on previous climate model inter-comparisons, the scope of the economic model comparison should be narrowed to produce conclusive insights into the factors that create model differences.

• ***Improvement of climate sensitivity estimates:***
Reducing uncertainty in climate sensitivity estimates will require focused attention on the radiative forcing of aerosols (anthropogenic and natural) and the sun. One possible venue is to explore a CO_2 baseline scenario and vary other types of emissions as a way to get at climate sensitivity to these other forcings. Uncertainty in climate sensitivity due to climate noise can only slowly be reduced by use of longer observational records in future estimations, as well as an ensemble approach to modeling.

• ***Investigation of parameter uncertainties in individual GCMs:***
Identifying key model parameters and their plausible ranges of uncertainty, and then performing an ensemble of present-climate simulations with different combinations of parameter values may help to estimate this kind of uncertainty, and eventually reduce it. Progress could also be made by identifying different combinations of parameter values that result in simulations that reproduce key observations within observational errors. With each of these combinations of parameter values, future-climate simulations could be performed. This exercise would likely require thousands of multi-year simulations, and thus would be extremely demanding computationally. Yet it would yield crucial information on the importance of uncertainty with respect to parameter values relative to other components of uncertainty. Recent attempts at this – using cooperative members of the public to lend their

home computers to this task – has begun in the UK (Allen 1999; Murphy et al. 2004; Stainforth et al. 2005; see also http://climateprediction.net/index.php).

• Assessment of the importance of neglected feedbacks:
Feedbacks between climate and chemistry, and between climate and the carbon cycle, are seen as potentially important feedbacks; however, they are still commonly omitted from virtually all of today's GCMs. A limited number of simulations with more comprehensive models that include these feedbacks may be able to assess the importance of these feedbacks. Another area of essential basic research is the further development and testing of better representations of clouds, aerosols, and water vapor in GCMs.

> Given the impossibility (and foolishness) of agreeing on the use of just one GCM, the multi-model approach is one method to hedge against the uncertainties in future climate.

• Innovative analysis of joint behavior of climate variables:
Through innovative analyses of joint behavior of climate variables, researchers could determine more quickly which climate futures are highly unlikely, thus helping to redirect decision-makers' attention to possible climate futures with high policy relevance.

• Institutional support for improving global climate modeling efforts:
Finally, because accurately estimating uncertainties requires dramatically more computational and human effort than making a single model projection, cross-institutional cooperation is essential in the immediate future. This may involve agreements to use the same input data (climate change scenarios, boundary conditions, etc.) for the models developed in different institutions; active encouragement to align institutional priorities and schedules; and financial support for data storage and management. Cooperation between modeling groups would offer the greatest value if results of all simulations were made readily available to other analysts, presented in common file formats, and placed on a common server for downloading with accompanying meta-data information. [3]

The following chapter examines the challenges involved in downscaling results from global climate models to regional scales.

[3] The historical evolution of GCMs (see e.g., IPCC 2001a, Technical Summary, Box 3, pp. 48-49), suggests a growing complexification of these models, requiring ever-growing computational capacity.

3. BARRIERS AND OPPORTUNITIES FOR IMPROVING DOWNSCALING METHODS AND REGIONAL CLIMATE MODELS

Chapter 3 summarizes workshop contributions by Wigley, Duffy, and Dettinger.

Even if the uncertainties with emissions trajectories and global climate models could be resolved beyond any reasonable doubt, the resulting global climate projections would not suffice to meet all policy- and decision-makers' needs for scientific information. This is most clear for the case of adaptation decisions. In order to appropriately and adequately prepare for climate change impacts where they occur (i.e., locally), decision-makers need regionally specific climate change information. The same case can also be made for mitigation decisions, as policy-makers frequently can only be motivated to mitigate climate change if negative impacts (potentially) affecting their constituents can be described and expected with considerable confidence. The greater the specificity in climate change information, the greater the motivation to act and the likelihood that such information is used in decision-making.

Of course, the development of such high-resolution projections of climate change is far from trivial. In a paper prepared for this workshop, Tom Wigley (2004) provided the following overview of the challenge involved in moving from global to regional scales in climate projections:

Global coupled Atmosphere-Ocean General Circulation Models (AOGCMs) currently used for projecting future climate have a grid box size of 100-200 km. Many of these models are able to simulate present-day climate well on spatial scales of 1000 km upwards, and the best models provide reasonable representations of the climate on somewhat smaller scales. Their grid-box resolution, however, cannot capture the details of orography nor resolve important cyclonic disturbances or similar-sized circulation features. This precludes an accurate representation of the climate on scales of individual grid boxes. For many impacts models, however, information is required on sub-grid scales of 10 to 100 km (referred to here as the local to regional scale). (See Wigley at http://www.agci.org)

While significant progress has already been made in recent years in downscaling global model outputs to regional scales, there is significant uncertainty involved in doing so. The guiding question of this chapter thus is what the key barriers and opportunities are at present for improving downscaling approaches and regional climate modeling.

3.1 CHALLENGES AND PROSPECTS

The primary goal of downscaling is to produce local- to regional-scale climate information, generally from coarse-resolution, global-scale climate models, and secondarily to improve the reliability of short timescale climate information. Generally, two downscaling methods are distinguished: dynamical and statistical downscaling. Each is discussed below with its respective challenges, limitations, and prospects.

Dynamical Downscaling

Dynamical downscaling uses physically based models with finer spatial resolution than the original global model. Four different approaches fall under this rubric (Table 1).

TABLE 1: **Overview of Dynamical Downscaling Approaches**

Method	Drivers
Nested Regional Climate Model (RCM)	Lateral and surface boundary conditions (state and fluxes) from global Atmosphere-Ocean-General Circulation Models (AOGCM)
Stretched-Grid Atmosphere-GCM (AGCM)	Surface boundary conditions from AOGCM
High-resolution AGCM	Surface boundary conditions from AOGCM
Hybrid method	AOGCM feeding into a high-resolution AGCM feeding into an RCM

(Source: Wigley)

Uncertainties in dynamically downscaled climate information – as Table 1 suggests – arise from (a) the downscaling method and (b) from the climate data that are used to drive the regional models. The choice of downscaling method should be guided principally by how well the approach is able to replicate the influences of a variety of processes on the regional climate (Box 3).

Reviews and inter-comparison projects of regional climate models (RCMs) in the U.S. and in Europe show that they tend to be better documented and more mature than other dynamical downscaling approaches (see assessment of these studies in Wigley 2004).

With the increasing capacity for high-speed computing efforts such as those at Lawrence Livermore National Laboratory, researchers have recently been able to complete global climate simulations at resolutions as fine as 50 km. These high-resolution global simulations have been used to drive a nested regional model for the western United States, including California at very fine

Box 3: Synoptic Climatology of California

The climate of the western United States, including California, is determined by the large-scale influences of the Aleutian Low and the North Pacific Subtropical High, which control the prevailing winds and storm tracks, along with their seasonal changes. These aspects are modified significantly by the complex geography and orography of the region. The main north-south oriented mountain ranges increase precipitation on the western sides of the coastal ranges, the Cascades, and the Sierra Nevada, and produce a pronounced rain shadow on the eastern (lee) sides. Thus, California experiences strong precipitation gradients over distances of less than 100 km, gradients that cannot be captured in current low-resolution global AOGCMs.

For precipitation, seasonal variability is controlled by the sources of moisture. On western slopes, the main moisture source is from the Pacific and brings precipitation primarily during the winter months. Northward movement of the Aleutian Low causes a fairly abrupt reduction in precipitation as the seasons shift from winter to spring to summer. On eastern slopes, the main moisture sources come from the Gulf of Mexico (upper-level influx) and from the lower latitudes of the eastern Pacific and the Gulf of California associated with the development of the North American monsoon in June and July (lower-level influx). Inter-annual variability is strongly influence by the El Niño/Southern Oscillation (ENSO). The influence of ENSO manifests itself through changes in the intensity of the Aleutian Low and the subtropical high, and through a pattern of changes known as the Pacific-North America (PNA) pattern. Longer timescale changes appear to be associated with the Pacific Decadal Oscillation (PDO) (Figure 11).

Numerous regional climate models exist for the western United States, which have made considerable progress in producing many of the region-specific climate features (Figure 12).

Source: Text adapted from Wigley (2004)

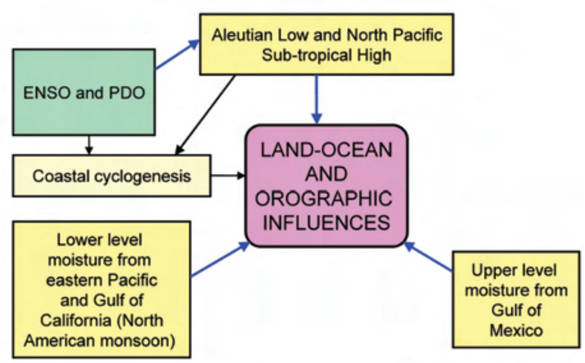


FIGURE 11: **Synoptic View of Influences on California's Climate** (Source: Wigley; reprinted with permission)

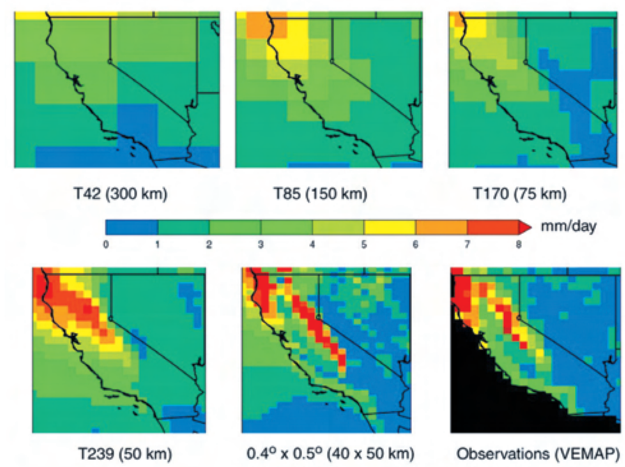


FIGURE 12: **Annual Mean Precipitation in California** The lower right panel shows observed precipitation on a 0.5 deg. latitude-longitude grid. The other panels show results of a series of global climate model simulations performed by P. Duffy et al. at Lawrence Livermore National Laboratory. As the model resolution is increased (top row and lower left), the simulated precipitation pattern becomes more realistic. The lower center panel shows results obtained using a new approach to solving for the atmospheric circulation. This allows more accurate representation of topography, which results in a superior simulation of precipitation. (Compare to the lower left panel, which uses essentially the same spatial resolution but a different dynamical core.) (Source: Duffy; reprinted with permission)

spatial resolution (9 km). This combination of high resolution in the nested model, which allows realistic representation of topography, and high resolution in the driving global model, which provides relatively unbiased boundary condition data, can result in very realistic simulation results (Figure 13).

The second major source of uncertainty in dynamical downscaling is the data that are used to drive and validate these models. Generally, global climate model outputs feed into dynamical models. The availability of suitable GCM runs, the quality of the GCMs (validated through observational or reanalysis data), the availability of runs with adequate temporal resolution, and parametrization biases, however, must be considered in choosing adequate drivers of the regional models. The concerns with each of these are discussed in more detail below.

RCMs need to be forced with suitable GCM runs which means, (a) present-day runs for validation and baseline purposes, and (b) future runs of adequate length. For model validation, adequate historical data are required. Reanalysis data are preferable to original observational data, and more recent reanalyses are demonstrably better than previous ones. The key question to ask in validation is how closely the AOGCM/RCM combination replicates present-day or historical climate. What the most appropriate validation metrics and foci are, however, does not have a simple or generalizable answer. For example, instead of a global

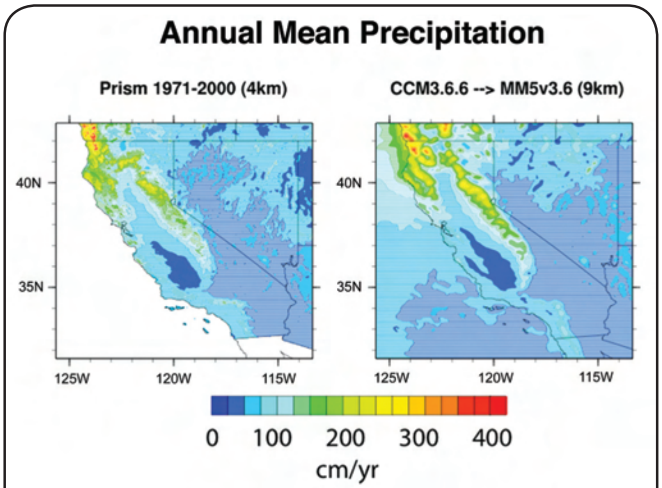


FIGURE 13: **Annual Mean Precipitation in California/Nevada** The panel on the right shows annual mean precipitation as simulated at Lawrence Livermore National Laboratory using the MM5 regional climate model at 9 km resolution nested within the NCAR CCM3 global climate model at ~100 km resolution (T170 truncation). The panel on the left shows an observation-based estimate of annual mean precipitation based on station and radar data. (Source: Duffy; reprinted with permission)

performance validation, perhaps a restricted-area validation – ideally over a larger region than the area of interest – may be preferable. Likewise, model performance differs by statistical performance measures, suggesting that a variety of performance metrics may be required. Models also differ in how well they produce certain climate variables (compared to present-day conditions) or patterns. Many are better for some variables (e.g., temperature) than for others (e.g., precipitation). Comparative studies have shown that more recent model versions are not necessarily better than earlier versions in this respect. Thus, there are model-internal inconsistencies in terms of performance, only some of which may be resolved by increasing model resolution. Finally, model performance evaluation should consider both spatial and temporal climate variability (replication of temporal climate variability patterns). In particular, performing evaluation exercises that use specified perturbations (e.g., seasonal cycle) to simulate responses, and then comparing those with the observed record, should yield important new insights.

Another major challenge is that drivers for AOGCMs either do not account for or only crudely treat land use/cover changes and aerosols, both of which can be of great importance to climate regionally. How to account for these components is an area of considerable ongoing and future scientific study. For example, because many AOGCMs currently do not include the regionally important impact of aerosols, corrective measures have to be inserted into the RCMs to account for aerosols (e.g., interactive atmospheric chemistry models, three-dimensional aerosol masks). The radiative properties of some aerosols are better understood than others; thus, uncertainty concerning radiative forcing varies by aerosol.

As discussed above (Chapter 2), climatic processes are parameterized differently in different GCMs. These parameterizations are scale-dependent. Thus, in the process of downscaling, physical processes must be represented differently, and frequently, how precisely to do so, and how to link the different physical representations across scale, is not well understood. Such cross-scale parameterization is made more difficult in places where global models have systematic biases. For example, many AOGCMs currently do not accurately replicate the observed diurnal cycles of key climate variables; others do not adequately replicate the observed seasonal distribution of precipitation. Unless such systematic biases are removed, AOGCM biases simply translate into similar biases in RCMs. Workshop participants agreed that research to improve sub-grid physics is a promising and much needed way forward, albeit one requiring substantial time and computational resources, as well as appropriate data for validation and testing. A promising example highlighted at the workshop was a high-resolution AOGCM, developed in Japan, whose grid resolution is sufficient to represent, for example, the orographic features of a state like California.

Statistical Downscaling

Statistical downscaling – the second major and more mature approach to downscaling – uses statistical relationships (or transfer functions, usually some form of regression equation) to connect a fine-scale predictand with a set of coarse-scale predictors. Statistical downscaling is predicated on the assumptions that the fine-scale variable is reliable, and that the predictand–predictor relationship is stable over time. While necessary assumptions for the construction of a mathematical relationship, both are questionable and create sources of uncertainty. Which set of predictors is best for any given predictand in any given location cannot be generalized and has to be established on a case-by-case basis. Thus establishing high-quality statistical relationships is dependent on the availability of reliable data sets (empirically observed or reanalysis data). In some instances, the best predictors may also be spatially removed (in remote grid boxes) from the site of interest that is to be predicted.

Statistical downscaling techniques – like dynamical downscaling methods – require model validation. This validation frequently involves challenges resulting from spatial collinearity of variables, and from temporal autocorrelation between predictors and predictands. Also similar to dynamical downscaling is the problem of distinguishing signal from noise, which requires many case studies and adequate sampling strategies to assure statistical significance of conclusions.

Once the transfer function is established, statistical methods are similarly dependent on the credibility of the driving AOGCM as in the case of dynamical downscaling. For example, if there is a major north-south mountain chain like the Cascades, and the AOGCM has an incorrect representation in its control climate of the frequency of westerly winds, then this error would be translated by any downscaling method into erroneous higher resolution fields. Thus, it is imperative for any type of downscaling to be sure that the major variables that drive local climates are adequately represented in the large-scale models as they provide the boundary conditions for downscaling methods. Of course, confidence in the downscaled results would be greater if the AOGCMs adequately represent these key large-scale drivers of local/regional climates (e.g., the frequency of westerly winds in the example of the Cascades). Thus, validation, testing and assigning of confidence to downscaled results involves assessment of both the large scale model performance and the downscaling technique, separately and as a system.

3.2 KEY RESEARCH TASKS: A SUMMARY

Numerous studies comparing the performance and results of the two main downscaling approaches have concluded that there is no clear difference in skill in replicating present-day climatic conditions. At the same time, results show that even equally well performing methods for present conditions can produce considerably different regional climate futures. It appears as if systematic biases in dynamical downscaling may cause such differences, and that additional research is needed to remove those and fully explain the differences in results (see Wigley 2004). Where possible, performing both types of analyses can yield not only complementary results, but possibly insights that will improve the performance of each.

Workshop participants reiterated the general consensus in the scientific literature that, when driving factors depart substantially from present conditions, dynamical downscaling holds greater promise for future progress than statistical downscaling, yet such improvements may take many years and consume considerable computational resources to achieve. Recent advances in producing high-resolution GCMs appear to produce superior results (both in terms of detail and accuracy) to those of nested RCMs. This might be expected since high-resolution models allow two-way communication between the modeled large- and small-scale processes, whereas RCMs embedded in GCMs can only perform a one way transformation from the large-scale fields of the global models to regional variables without any feedback from the regional processes back to the higher scale. Thus, using such high-resolution models, either by themselves, or where very high resolution results are called for, as drivers of RCMs (the hybrid approach) offers great promise.

Specific research tasks discussed by workshop participants include:

In dynamical downscaling:

• ***Improvements in model validation:*** Future research must address questions such as: how wide a grid space is needed around the region of interest to reproduce the historical record? For which climate variables or patterns should the model perform well? Which performance metrics are most appropriate? How well do models replicate not only spatial but also temporal climate variability at both large and regional scales?

• ***Integration of regionally important land use/cover changes and aerosols in RCMs:*** Dynamical downscaling must increasingly account for regionally important drivers of regional climate such as land use/cover change and aerosol sources. This would require adequate data and projections of their respective changes in the future.

• ***Improvements in sub-grid processes (physical, biological and chemical):*** Such improvements are required to improve scale-dependent parameterization uncertainties.

• ***Removal of systematic biases (e.g., diurnal and seasonal cycles):*** A special focus on removing systematic bias in global – and hence regional – climate models is required to better fit historically observed data.

In statistical downscaling:

• ***Improvements in model validation:*** Future research will have to address the problems arising from collinearity, and temporal and spatial autocorrelation of predictor and predictand variables.

• ***A closer examination of the predictand–predictor relationship:*** The understanding of this relationship is at the heart of statistical downscaling. Future research should assess the assumption of stability of driving factors or underlying processes over time to improve confidence in future projections.

Given that considerable uncertainty persists when moving from global to finer scales in projecting certain climate variables such as precipitation, the approach discussed in Chapter 2 of assessing the joint behavior of variables or that of climatic indices that integrate several variables (e.g., Palmer Drought Severity Index (PDSI) which reflects both temperature and precipitation) may be promising in the context of downscaling as well.

While global climate projections have been used for regional impacts analyses, workshop participants expected considerable progress from using downscaled climate information to drive regional impacts models. Until both downscaled climate variables and impact assessment models enjoy higher confidence in their results, uncertainty may not necessarily be reduced. The greater specificity alone, however, would help decision-makers better appreciate the potential threats in their region from climate change. A better understanding of the local vulnerabilities and potential impacts of climate change is a necessary complement to higher-resolution climate information. These are discussed in the next chapter.

4. REDUCING UNCERTAINTY IN VULNERABILITY AND IMPACTS ANALYSES: COMPLEMENTARY APPROACHES

Chapter 4 summarizes workshop contributions from Hanemann, Root, Moss, Webster, Weyant, Lempert, and Schneider.

It could be argued that decision-makers and ultimately the public are most interested not in climatic changes per se, but how these atmospheric changes might affect their lives, livelihoods, and the near and far environments which they manage or care about. Frequently, it is the threat of tangible impacts or the realization of changes on the ground that make climate change real, and mobilize different actors to develop and implement mitigation and/or adaptation policies.

While policy goals may be directed at preventing negative impacts (or, more specifically, dangerous anthropogenic interference in the climate system), the scientific goal is to understand and project potential impacts with enough accuracy to support the development of preventive, mitigating, or adaptive strategies. Top-down impact assessments – driven by available emissions scenarios, which in turn are fed into global and regional climate models – have to deal with a cascade of uncertainties that multiply as ecological and socio-economic factors come into play. A complementary approach to impact assessments begins from the bottom-up and seeks to understand the multiple environmental and societal factors that make particular sectors, communities, or social and ecological systems vulnerable or resilient to climatic changes. It, too, is fraught with uncertainties, albeit different ones (Figure 14).

> It is the threat of tangible impacts or the realization of changes on the ground that make climate change real, and mobilize different actors to develop and implement mitigation and/or adaptation policies.

The question is not which approach is generally preferable. Different research traditions have contributed different and vital insights, coming to the topic of impacts and vulnerability from different sides. Each highlights different knowns and unknowns, and thus is appropriate for solving different problems. Instead, the question is how improved global and regional models can be applied in such a way to reduce vulnerability to climate change, and – in parallel – what insights the bottom-up approach can offer to better support the analysis of differential vulnerability and adaptation needs. The ultimate goal common to both approaches is the search for more accurate scientific understanding of the impacts question. The insights gleaned from these approaches can help minimize negative impacts from climate change on the environment and people, and – where possible – to support the development of a long-term sustainability strategy for society and its life-support system.

Given the overall focus here on uncertainties, the first section below discusses important research needs in economic and ecological impacts assessment, as well as in vulnerability assessments. Subsequent sections examine recent progress in integrated assessments (IA) and other policy analysis approaches, as well as in the question of probabilistic assessments of dangerous anthropogenic interference in the climate system.

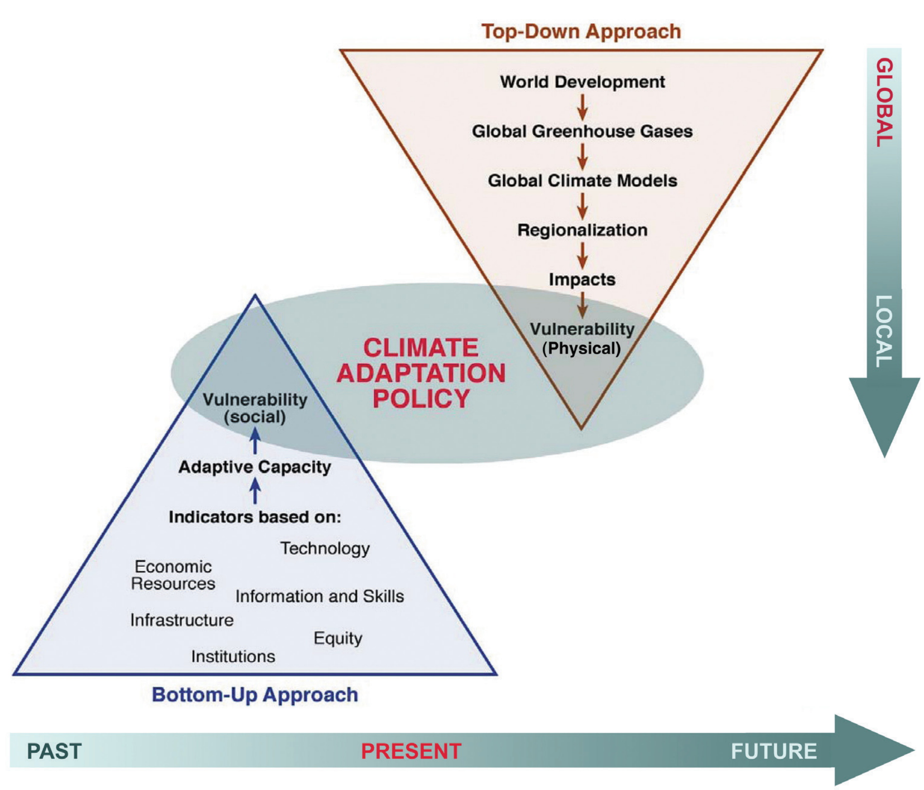


FIGURE 14: **Two Complementary Approaches to Impact and Vulnerability Assessments** (Source: Dessai and Hulme 2003; reprinted with permission)

4.1 THE STATE-OF-THE-ART IN VULNERABILITY AND IMPACTS ASSESSMENTS

Economic Impact Assessments

The economic costs of climate change are difficult to assess for a number of reasons. First, the question of economic impacts depends on who is affected by climate change. For example, firms' losses differ from consumers' or workers' losses, which in turn may be very different from taxpayers' losses. Moreover, these different losses do not easily add up to a cumulative total. Someone's loss may be another's benefit, or a loss in one metric might be paired with a gain in another metric. Aggregation in such cases is difficult and often controversial.

Second, the economic impacts of climate change differ depending on how these are conceptualized: the costs of emission reductions – most commonly assessed to date – are very different from the costs (and benefits) of climate change impacts and associated adaptation measures. How each of these economic impacts is measured may also differ and can render direct comparisons difficult. For example, the cost of emission reduction can be expressed as a loss of profit, a loss of income or wages, a loss of jobs, or higher prices. The costs (or benefits) of climate change impacts can be measured by similar indicators, or as changes in input quantities and qualities, disruption of production processes, loss of utility or well-being, increased uncertainty (e.g., through less tangible impacts on consumption and production), loss of options and flexibility (i.e., a reshaping of the choice set), or the cost of non-routine adaptation measures. Some of these measures are fairly easy to track and capture in existing models; others are not. It remains a challenge to economists to measure these indicators, monetize them, or assess their relative importance, and integrate them into economic models.

Most current economic impact models are general equilibrium models but the major economic effects of climate change may well be associated with out-of-equilibrium phenomena.

The nature of existing models presents an even deeper challenge to the assessment of economic impacts from climate change. Most current economic impact models are general equilibrium models; they characterize the state of an economy *when in equilibrium*, and they are used to compare alternative equilibria. However, the major economic effects of climate change may well be associated with out-of-equilibrium phenomena, depending on how long it takes for technologies, institutions, societal values, and individual behaviors to reach equilibrium in response to changes in external stimuli. Such non-equilibrium calculations have received negligible attention so far in climatic impact assessments.

The non-equilibrium phenomenon that is expected to have the greatest economic significance and impact is that of adaptation, especially the rate (speed) and degree of efficiency and effectiveness of adapting to new conditions. The better people can anticipate the need for change and the greater their ability to implement adaptation measures, the faster they will move through the costly non-equilibrium phase. Thus, to produce more realistic assessments, economic impact modelers must better understand the determinants of change in technology and human preferences. Some of these changes – such as in human values – are currently assumed to remain constant, when in reality they do not. Not knowing how and toward what they will change, of course, produces big problems for long-term projections. Such cases may be better handled by switching to simpler rather than more complex models, and using the more transparent tools for bounding analyses rather than for explicit calculations of distributions of costs and benefits.

Workshop participants agreed that economic models suffer from uncertainties at least as much as climate models: in model specification, model estimation or calibration, and in model forecasting. The types of uncertainty affecting economic modeling are also similar to those in climate modeling. Economic uncertainties stem from:

- Inaccuracies or inadequacies of data
- Estimation errors
- Different model specifications
- Heterogeneity in human behavior (which cannot be captured adequately through deterministic, linear models, but at best through probabilistic stochastic models; qualitatively different human behaviors are difficult to aggregate)
- Forecasting of exogenous variables
- Temporal heterogeneity (i.e., the unpredictable short-term variation in determinants of human behavior)
- Structural changes over long time periods (i.e., shifts in technology, cultural preferences, policy, etc.)

It is therefore appropriate, just as with climate models, to subject economic models to more stringent testing against empirical events and inter-comparisons across different models driven by similar forcings.

Model Specification

While analysts widely acknowledge the types of uncertainties listed above, they typically do not estimate or integrate them into climate impacts analyses. Instead, both climate change scenarios and assessments of their economic impacts are usually deterministic rather than probabilistic. This is not because modelers have a high level of confidence in the accuracy of their model projections; rather they assume uncertainty to be so pervasive that it is impractical to attempt to quantify the uncertainties of all the underlying model components.

Often bracketing assumptions are given as a surrogate for full probabilistic analysis, or sensitivity analysis. This is a good first step to portraying uncertainties in analytic tools, but still a big step away from full capability to manage the full range of different types of uncertainty.

What is it then that makes more explicit treatment of uncertainties in economic modeling and forecasts so difficult? The long timeframe alone is not the only reason. There can be substantial economic uncertainty about economic predictions even over short timeframes (e.g., five years). The deeper reason lies in the nature of what economic models try to predict, namely human behavior and preferences. There are no known laws of human behavior similar to the laws of physics. At best there are social mechanisms that describe tendencies contingent on certain circumstances or conditions. [4]

In addition, the type of economic modeling that is most relevant for most micro-economic policy, including in the context of climate change, involves forecasting of the demand and supply of what might be called *disaggregated* commodities, i.e., specific items, with specific characteristics, desired or applied by specific groups of individuals in specific locations and decision-contexts. By contrast, conventional economic theory is conceptualized in terms of broad commodity aggregates. The difference is that between, say, predicting the demand of young adults in Pittsburgh buying lemon-flavored diet coke in plastic 20-ounce bottles versus predicting the aggregate U.S. demand for beverages. Clearly, predictions of aggregate behavior are easier to make and more often correct than predictions of the specific. The demand for disaggregated commodities is likely to be strongly influenced by specific attributes of these commodities – and by consumer's subjective perceptions of these attributes. These are difficult to model without very specific, field-based information. Modelers still do not understand very well what drives preferences among different individuals or groups, and how these preferences change over time. Thus, they inevitably start out with considerable ignorance about the relevant attributes, how these are perceived, what the choice set is, and the degree of heterogeneity among decision-makers, and within specific sectors. Furthermore, most existing economic models do not allow explicitly for variation in institutions over time (i.e., in the norms and rules that govern economic exchanges such as water markets or property rights), nor do they encompass other factors that affect economic decision-making such as the timing of decision-making, perceptions of uncertainty, or the degree of risk aversion among decision-makers.

In climate impacts modeling, a higher degree of specificity is needed to fully understand and appreciate economic consequences, but the current capacity of integrated assessment models for disaggregating both spatially and sectorally is still limited. Of course, there is a role for both aggregate (i.e., not detailed) and more disaggregated economic impact assessments for particular sectors and locales. But there is also a trade-off between the breadth of coverage of all sectors of the economy and specificity in detail. To date many economic impact models are still highly aggregated both spatially and in terms of the affected commodity. Some models – e.g., hedonic (partial-equilibrium) models – are able to provide spatially disaggregated economic assessments, however, their underlying assumptions about the validity of time and space substitution have been deeply questioned (e.g., Schneider, Easterling and Mearns 2000; Schlenker and Hanemann 2005, forthcoming).

Model Calibration or Estimation

General equilibrium models are frequently calibrated using some form of expert judgment for individual coefficients combined with some manipulation to ensure that the model overall reproduces a given baseline. Partial equilibrium models are often estimated using statistical analysis applied to some observational data. Both can be problematic in that calibration may lack validity, and econometric validation is plagued by missing variables as well as by problems inherent in observational data and uncertain functional relationships among variables.

> It is appropriate, just as with climate models, to subject economic models to more stringent testing against empirical events and inter-comparisons across different models.

The problem of model misspecification is thus a considerable one (potentially bigger than parameter uncertainty) – from both a scientific and policy and adaptive management perspective. Improvements in this area may be achieved through a mixture of model estimation and Bayesian model averaging. General guidance as to the correct form of economic models, however, cannot be given, as model form is dependent on the specific modeling purpose.

Model Forecasting

As discussed previously, because of the considerable uncertainties involved, economic impacts models should be scrutinized in similar depth and detail as climate models. A more serious attempt at model validation, for example, could significantly contribute to both model and forecast improvement. Promising approaches include backcasting, or starting models in the past and forecasting the (already realized) future. Another approach is to test the models' predictions after

[4] In physics, by contrast, the laws are derived for solid bodies and particles. Of course, a complex system consisting of interlinked solid bodies or particles may have, similarly to many social systems, unique behavior not easily derived from any universal laws. However, natural/physical system models do not have to deal with one factor that plagues social system models: changing attitudes of the agents over time and with the evolving state of the system – in short, with altering preferences and values. Particles simply do not change their minds as they witness the system evolve.

some known shocks like the OPEC price fixing in the 1970s or a similar major interference in the market. This would be analogous to testing of climate models by geophysical shocks like volcanic eruptions or major El Niño events.

In short, improvement in economic models is critical and achievable, e.g., in their parameters, underlying data and functional relationships, the ability to reproduce past economic dynamics, and their ability to forecast the future. Beyond these, two important questions remain: first, even if we could improve economic forecasts, what should be the normative response to uncertain economic forecasts? And second, how can we seriously address the many uncertainties in economic modeling, express them quantitatively in the models, and communicate them effectively?

The normative questions as to whether and how the presence of uncertainty should influence present-day decisions remain unanswered by analysis, though different perceptions of precaution and efficiency could illuminate possible answers. At issue here is the problem of irreversibility: in cases where irreversible binary decisions must be made, the presence of uncertainty suggests to risk-averse decision-makers that the more cautious decision choice – the one that is more likely to leave future options open and allow learning – would be the preferable one. Where decision choices are not made just once in time, but rather arise repeatedly over time, uncertainty may not have such an irreversibility effect. However, the exact conditions under which it has that effect are still debated in the economic literature.

The question of how uncertainty should best be incorporated in economic models is just beginning to be discussed in the macroeconomic literature. Among the considered approaches are: (a) the model-error modeling approach, in which a reference model is estimated and model residuals are regressed against a general set of variables; (b) an information-based complexity modeling approach using robust stochastic dynamic programming; (c) a random coefficient modeling approach; or (d) mixture model estimations. Ultimately, how to conceptually and mathematically represent uncertainty in economic models depends on the distinction of soft from hard uncertainty and the latter from complete ignorance:

- ***Soft uncertainty*** – Decision-makers' beliefs may be represented by a unique, fully reliable, additive probability distribution.
- ***Hard uncertainty*** – When decision-makers' beliefs may only be represented in terms of incompletely reliable non-additive probability distributions or multiple probability distributions, modelers can rely on:
  - Choquet capacities as non-additive measures of uncertainty
  - Dempster-Shafer belief function models
  - Zadeh's fuzzy set theory
  - Robust decision-making
- ***Complete ignorance*** – When no conceivable probability distribution is reliable enough to be plausible, modelers can draw on:
  - Arrow and Hurwicz's maxim theory
  - Gilboa and Schmeidler's case-based decision-theory

In addition, these different types of uncertainty and their impacts on economic assessments need to be described and communicated clearly to interested lay people and decision-makers. In summary, economic uncertainties have been recognized, but frequently not openly acknowledged and only recently begun to be seriously scrutinized and addressed formally in impacts models. Significant progress is possible in describing – and in some instances quantifying – them, and in others reducing them. However, the nature of what economic models try to project into the future – human behavior around discrete commodities – defies high degrees of certainty, and in many instances even probabilistic description.

Ecological Impact Assessments

The potential impacts of climate change on species, ecosystems, and the relationships between species and their environment have been examined in countless studies. A review of this vast body of literature reveals the enormous complexity involved in the dynamic interconnectivity between species, and their biotic and abiotic context across space and time. Theory, observations and modeling results, and the degree of scientific consensus about the emerging findings about these complex interactions are all used to determine what is known, unknown, and unknowable (Figure 15).

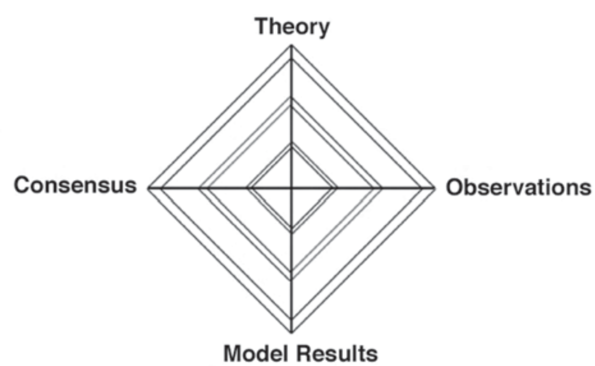


FIGURE 15: **Four Factors Affecting Levels of Scientific Confidence**. The graphic – used here in the context of ecological knowledge –represents different factors that affect the levels of confidence for any of the areas discussed in this report. While it is not a graphic for representing the known, unknown, and unknowable, it does depict different factors that contribute to the subjective assessment of levels of confidence. (Source: Moss and Schneider 2000; reprinted with permission)

Ecological theory has made significant progress over the past several decades in understanding so-called first principles of ecological dynamics, i.e., the general relationships among biotic factors, such as predator–prey relationships, competitive and symbiotic interactions between species, and abiotic factors, including the impact of average climate, climate extremes, and day-lengths on species behavior, which together determine species' spatial distribution and movement in response to climate. For example, Terry Root established a linear relationship between songbird species metabolic rate and their body weight – known as *Root's 2.5 Rule*. It suggests that in the winter the northern range limits of such species are set by their ability to sustain throughout the night a metabolism of 2.5 times their basal metabolic rate. Typically, the birds stay south of an isotherm (line connecting equal temperature values) where they are able to maintain that nightly metabolic rate. This empirically confirmed temperature-range relationship has been used in many studies to assess the impacts of climate warming on bird ranges.

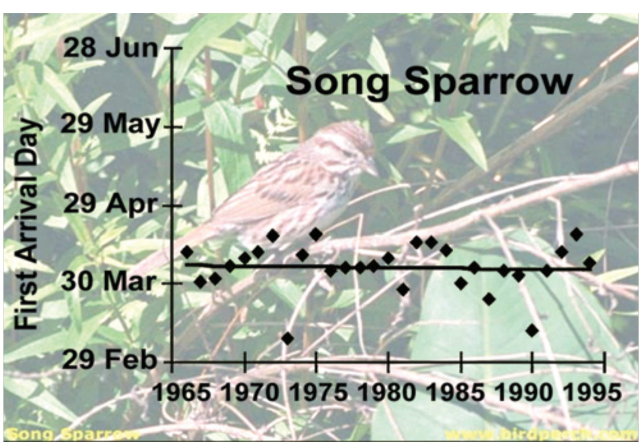
Similarly, first principles have been sought in understanding how biotic factors (as above) and abiotic factors (such as day length or heating degree days) determine species temporal behavior. For example, studies comparing spring arrival dates of certain migratory bird species have found that some – such as the song sparrow – are not noticeably affected in their migratory behavior by temperature change, but instead strongly influenced by the (constant) factor of day-length (i.e., the time available for foraging). By contrast, other species (such as the Sandhill Crane) are also apparently responding to temperature change, perhaps even more so than to day-length (Figure 16). In summary, ecological theory underlying species-temperature relationships may be judged to be fairly well understood at this time.

Observations of changes in spatial and temporal behavior linked to climatic change, on the other hand, provide needed information about how species change. Prehistoric data, which would extend available time series and allow for deeper analysis, are spotty and historic data are infrequent. Much empirical data come from non-traditional sources (e.g., collected by amateurs) and were frequently not collected in a systematic or scientifically controlled manner. How to integrate and make optimal use of such information remains a challenge in ecological research, particularly for trend analyses.

Modeling approaches to project ecological impacts are still very simple at this stage. Typically, such studies have used climate envelopes (driven by very different emissions scenarios or representing very different climate futures), focused on single climate drivers (e.g., only temperature change), and neglected other interactive factors. For example, modeling studies to date still leave numerous questions unresolved: How easy or hard is it for species dislocated poleward or upward to invade new habitats? Are analogue habitats even available? Are there viable migratory pathways between the current and the future range? Do land uses in the destination region permit species establishment? Such questions expose an unrealistic optimism in the notion of species "marching poleward," and call for more realistic studies that examine the likely adaptation challenges that species will face under climate change and movement through highly disturbed habitats.

Most modeling studies also only focus on individual species, obscuring the network of biotic relationships in which each species is embedded. Each species will respond differentially to climate change, leading to a breakdown of biotic interactions and a reassembly in the new abiotic and biotic context. Current scientific understanding does not allow reliable predictions as to where or in which cases this breakdown and reassembly will be ecologically catastrophic or successful.

Finally, the question of scientific consensus was recently examined in a global meta-analysis of ecological impact studies (Root et al. 2003; Parmesan and Yohe 2003). Root and colleagues included only those studies that had focused on the impacts of temperature change and covered a minimum period of 10 years of temperature records. Studies that included highly variable precipitation changes did not yield a clear-enough signal to be included in the analysis. The more than 2,500 studies included in Root et al.'s meta-analysis were categorized into two tiers.;



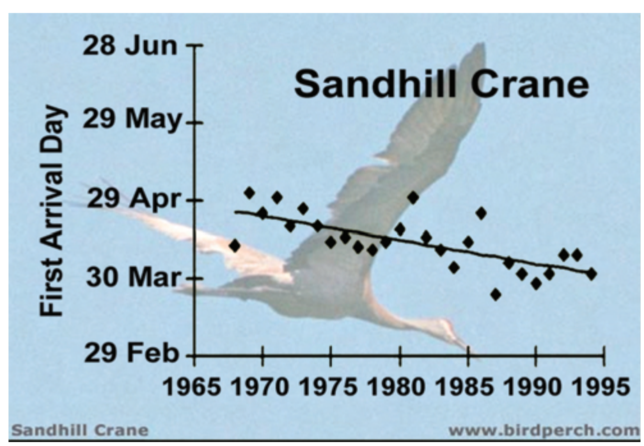


FIGURE 16: **Arrival Dates Over 30 Years of the Song Sparrow (left) and the Sandhill Crane (right)** (Source: Root et al. 2005; reprinted with permission. Image of the Song Sparrow and Sandhill Crane courtesy of www.birdperch.com, © copyright Maria Bajema)

• ***Tier 1 studies*** (most of which had been included in previous IPCC assessments) were all those that showed some trait in the species to exhibit a statistically significant trend over time; this trait had to be associated with temperature. In addition, temperature also had to show a statistically significant trend over the study period.
• ***Tier 2 studies*** – less stringent in requirements by removing some of the statistical significance stipulations – were all those that showed some trait in the species to exhibit a statistically significant trend over time; this trait tended to be associated with temperature. Temperature trends may have been reported in these studies, or could be derived from other studies for the same region.

Of the more than 2,500 studies, 78 met Tier 1 criteria, 56 met Tier 2 criteria. The total of 134 studies offered a broad global coverage (albeit over-representing North America and Europe since few long-term studies exist outside of these continents), and examined the behavior of a total of 1,859 species. All but the hard-to-observe taxa were represented in this sample. About 20% (386) of these species showed no change, with the remaining 80% (1,473 species) exhibiting a variety of changes, e.g., range shifts, shifts in abundance, phenological, and/or morphological changes. Interestingly, for the group of species that showed change, about 20% (277) of the species changed opposite to the expected change due to temperature increase, but an overwhelming 80% (1,196) changed in the direction expected. This simple meta-analytic approach of combining all observed changes and counting "votes" for how many of the observed changes were in the expected direction for warming yields a strong scientific consensus about the temperature–species change connection. Using the Moss/Schneider visualization tool for uncertainty (see Figure 15 above), Root and co-authors estimate that the degree of uncertainty in climate-ecological impacts studies can be graphically depicted as in Figure 17.

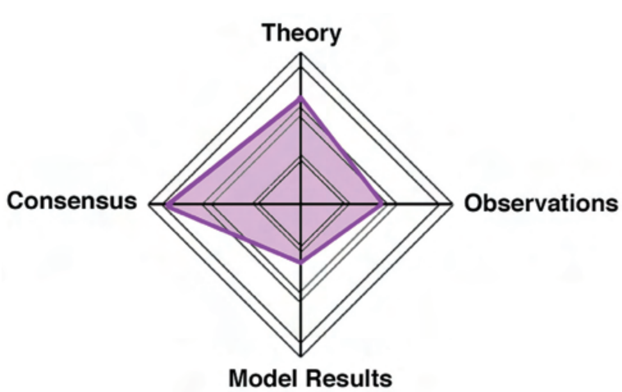


FIGURE 17: **Current State of Knowledge in Ecological Impacts Studies**
(Source: Adopted from Root et al. 2005, reprinted with permission)

Among the important challenges ahead in climate-ecological impact studies are:

• ***Examinations and projections of the*** synergistic impacts of climate change, land use change, biological invasion, and chemical pollution
• ***Examinations and projections of the*** synergistic impacts of climate change mitigation actions (e.g., forest protection) and climate change
• ***Analysis of the*** breakdown and reassembly of ecosystems (rather than single-species climate impacts assessments)
• ***Examination of the*** impacts of climate change on migration patterns (drawing on data and insights from people studying biodiversity hotspots and other observation networks)
• ***Better integration of data collected from non-traditional sources*** (e.g., native knowledge, lay observers)

Vulnerability and Adaptive Capacity Assessments
Even in the absence of reliable climate change information, much can be learned about potential climate change impacts by honing in on the vulnerability of individuals, communities, economic sectors, and ecosystems. Examining their exposure and sensitivity to climate, as well as their ability to cope and adapt to potential changes, provides essential insights into the determinants of vulnerability, and into the expected severity of impacts from climate disruption.

Despite differences in definition, underlying theory, and analytic approaches, scholars generally recognize a complexity of interacting factors that affect vulnerability to climate hazards, including:
• ***Socio-economic factors*** such as the composition of the economy, dependence on climate-sensitive resources, the level of education, the accessibility and efficacy of the health care system, the availability of technology
• ***Institutions***, both formal and informal, such as markets, kinship ties, land tenure
• ***Distribution of entitlements*** that allow access to resources of particular demographic or social groups and geographic regions
• ***Environmental factors*** such as the degree of land fragmentation, prior exposure to air and water pollution.

In any number of case studies, these factors have been examined in great contextual detail to determine and represent the unique causes of vulnerability of specific population groups, sectors, or environments at all scales (from neighborhoods to countries). Currently, the larger research challenges at hand are (a) how to integrate and compare the findings, exploring for generalizable relationships among the myriad of studies, and (b) how to feed the emergent findings into the urgent development of adaptation strategies. The latter requires several essential steps (drawing on Berkhout 2002):

• Identification of key users of adaptation assessments
• Characterization of the sensitivities of priority sectors/ domains/regions to climate change

• Development of a coherent, and yet sufficiently flexible conceptual framework of adaptive capacity
• Identification of proxy variables of vulnerability and adaptive capacity (which would enable a comparative assessment informed by underlying causal factors)
• Mapping and measuring current adaptive capacity (baseline measurements)
• Development of tools for generating future scenarios

Numerous studies currently underway are making progress on several of these elements: multiple case studies and comparative international projects; attempts to downscale SRES scenarios to the country level to examine the implications of the storylines for adaptation in the U.K. (UK Climate Impacts Programme 2001); studies developing vulnerability indicators (e.g., Moss, Brenkert and Malone 2001) (see below); and UNDP-funded efforts to develop guidelines for socio-economic scenarios to be used in national communications (Moss, Lim, Malone, and Brenkert 2002). Workshop participants were not aware of probabilistic studies of these issues to date.

Efforts to quantify vulnerability and resilience to climate change depend on the development of sensitivity indicators for climate-sensitive sectors and – in parallel – the development of coping and adaptive capacity indicators. Many of the variables determining sensitivity and coping/adaptive capacity cannot directly be measured (or can theoretically be measured, but past/baseline data do not currently exist and would be too time-consuming to obtain). Instead, researchers attempt to identify potential proxy variables for the factors contributing to vulnerability. One study, for example, uses the following variables and proxies to measure them (see Moss, Brenkert and Malone 2001):

• ***Economic capacity*** (e.g., GDP/capita; Gini Index) – proxy for the distribution of access to technology, markets, other resources useful for adaptation
• ***Human and civic resources*** (e.g., dependency ratio, literacy) – proxy for social and economic resources available for adaptation after meeting other present needs, human capital and adaptability of the labor force
• ***Environmental capacity*** (e.g., population density, SO_2/area, percent of land unmanaged) – proxy for population pressures and stresses on ecosystems, air quality and other stresses on ecosystems, landscape fragmentation and ease of species migration

By establishing functional relationships among these variables, national baseline estimates and projections of sectoral indicators can be developed and compiled into sensitivity and coping/adaptive capacity indicators (e.g., Adger and Vincent 2005; Haddad 2005; Yohe and Tol 2002; Brooks et al. 2005). Those two indicators in turn are then combined into a single vulnerability or resilience indicator (Figure 18).

In principle, such indicators suffer from a similar set of basic uncertainties as climate or impact models: inaccurate or incomplete data; the use of proxies in the face of our inability to measure certain variables directly; incompletely understood functional relationships among variables; uncertainty or even

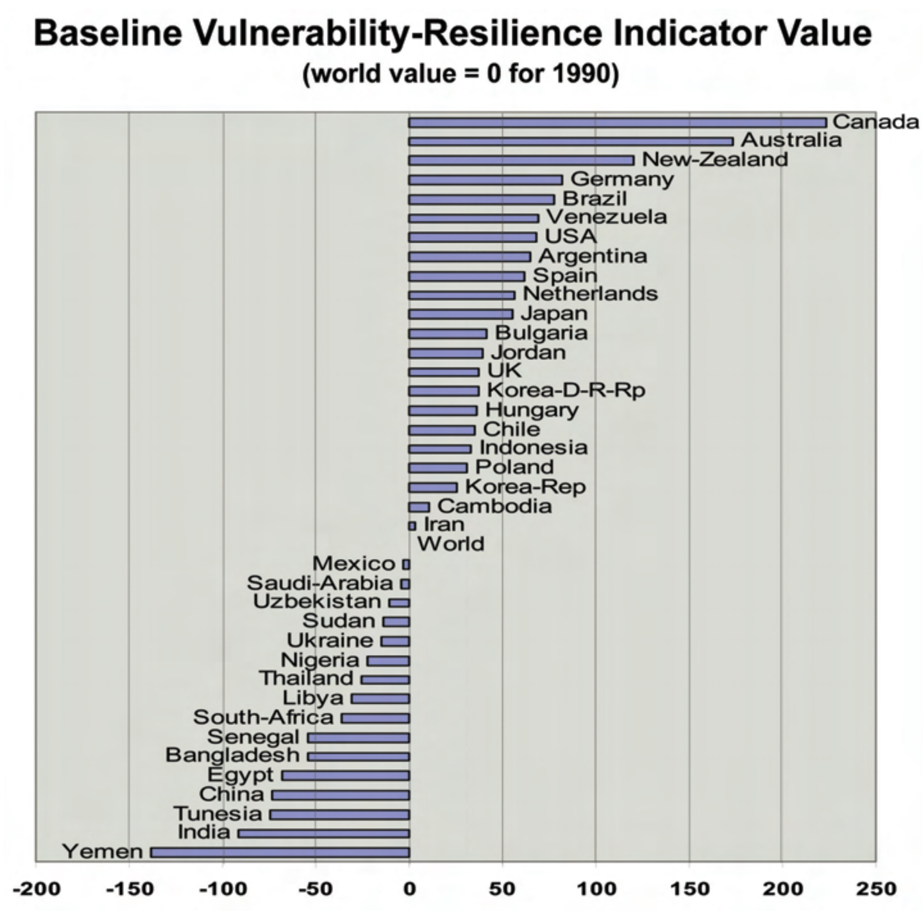


FIGURE 18: **Baseline Vulnerability-Resilience Indicators for a Range of Countries** The vulnerability index developed by Moss and colleagues uses theory-derived relationships between economic capacity, human and social capital, and environmental capacity to assess the present-day degree of sensitivity to climate change and nations' ability to cope with it. While the overall pattern may not be surprising, some developing countries turn out to be surprisingly resilient, while some developed countries rank unexpectedly low. These findings point to the necessity for in-depth studies of individual countries to fully understand the nature of their resilience or vulnerability. (Source: Moss, Brenkert and Malone 2001; reprinted with permission)

ignorance hidden in high levels of aggregation; and – once used to project into the future – all the uncertainties associated with forecasting human choices and relationships. Both probabilistic and scenario approaches may yield interesting and complementary results and both should be pursued.

Despite these uncertainties, indicator studies yield valuable and novel insights, and raise new research questions. For example, the indicator prototype summarized in Figure 18 yields unique vulnerability pathways for countries and reveals some unexpected results. Maybe surprising to some, it illustrates that some developing countries are less vulnerable than some developed countries. These unexpected results seem logical or plausible only when examined in detail. In particular, wealth is neither a necessary nor a sufficient determinant of vulnerability and resilience. Although country vulnerability–resilience indicators tend to correlate with GDP per capita, more than 20% of the countries studied show no significant correlation. Thus, the lack of knowledge about inequality in societies and potential inequality in the future hampers our ability to assess who in a society is vulnerable, to what degree, and to which stressors.

Clearly, future research on vulnerability and adaptation will have to focus specifically on the question of inequality, and the specific mechanisms creating different degrees of vulnerability. Moreover, research has to address not just how to reduce vulnerability or increase adaptive capacity, but whether any single response to climate change would actually be effective, and at what cost. It would also have to address very specifically questions regarding peoples' capacity to use such research results. Similar to the critical issues raised around synergisms in ecological impact studies (see section above), vulnerability and adaptation studies must also tackle the critical synergisms arising from multiple stressors (e.g., globalization or war and climate change).

Such challenging and sensitive questions make clear why adaptation and vulnerability research can be so controversial. An example of this is recent research that focused on equity in mitigation regimes. Vulnerability and adaptation research frequently traces the causal chains of forces and international and societal relations that give rise to vulnerability. In addition, it often leads to the identification of policy options that redress the underlying causes of vulnerability, rather than just its symptoms. For example, farming marginal lands is both an expression of and creates deeper vulnerability. Several options are available to address such a situation: (a) identify and promote better dry-land farming methods; (b) develop and sustain a social safety net to smooth out societal consequences of climate variability; or (c) address the forces that drive such unsustainable use of marginal lands (O'Brien and Liverman 1991; Glantz 1996). Thus, it is entirely possible that even as scientific uncertainty about vulnerability and adaptive capacity is reduced in the future, policy options may be constrained by ignore-ance (Glantz 2003), i.e., the willful restriction of knowledge to politically acceptable scientific findings.

4.2 PROSPECTS FOR INTEGRATED ASSESSMENTS AND POLICY ANALYSES

Integrated Assessments

Integrated assessment models attempt to functionally link the various components discussed so far: atmospheric chemistry modules, climate modules (including oceans, ice, and land responses), terrestrial ecosystem modules, and human activity modules reflecting both driving forces of change as well as responses to climate change (an example of such an integrated assessment model is depicted in Figure 19)

Recent, more sophisticated integrated assessment models (IAMs) account for at least some of the unknowns (using appropriate probabilistic approaches) by propagating parameter uncertainty through the model. For example, the MIT model presented in Figure 19 accounts for economic and technological uncertainties through probability distributions of future labor productivity growth, the autonomous energy efficiency improvement rate, or various emissions factors for industrial pollutants. These are derived from the literature and through expert elicitation (see Chapter 1). Climate uncertainties accounted for in this IA model include those associated with climate sensitivity, heat uptake of the deep oceans, and the strength and sign of aerosol forcings, where the requisite pdfs are developed from ongoing climate change detection research and then combined with expert judgments.

> It is entirely possible that even as scientific uncertainty about vulnerability and adaptive capacity is reduced in the future, policy options may be constrained by ignore-ance – the willful restriction of knowledge to politically acceptable scientific findings.

Integrated assessment models are used as policy analysis tools that can produce probabilistic climate change projections (temperature change, sea-level rise, etc.) for selected policy options (e.g., no additional climate policy or various paths of GHG reduction). In addition, IAs can be used to assess the uncertainties in abatement costs associated with different policy pathways, to examine the implications of social learning over time, or to study the implications of various interactions among strategic actors.

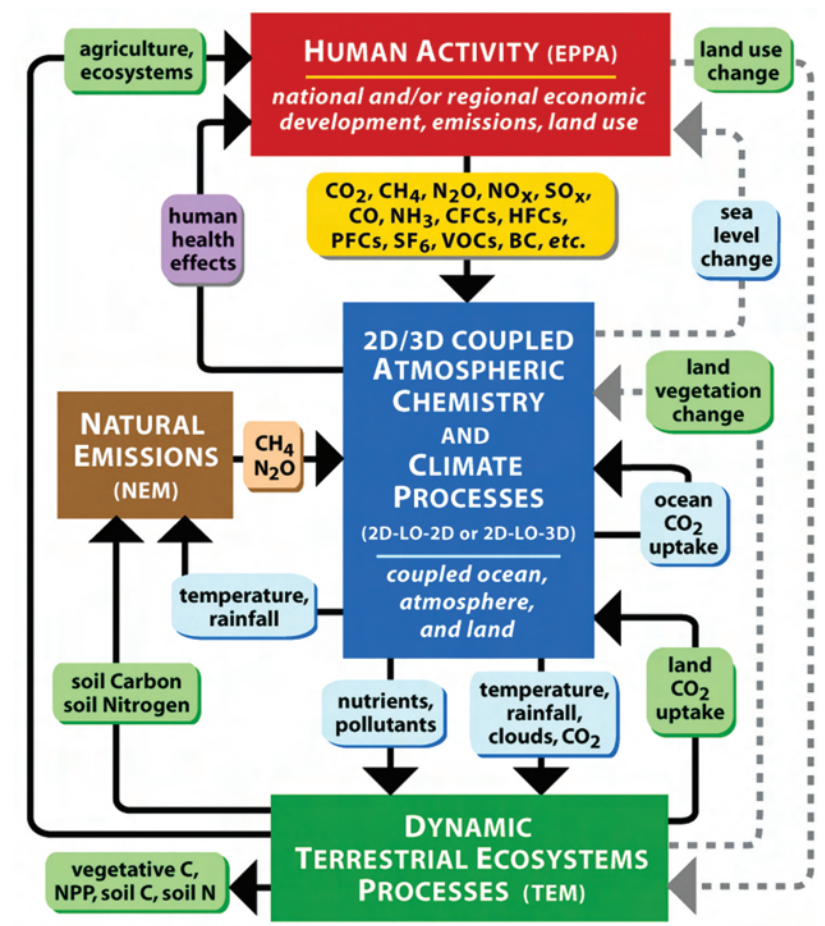


FIGURE 19: **The MIT Integrated Global System Model:** Example of a Complex Integrated Assessment Model (Source: Prinn et al. 1999; reprinted with permission)

To estimate the probabilities of extreme outcomes, many IA simulations are required, thus demanding significant time and computational resources. To speed up the development of extreme probabilities analyses, an alternative technique, importance sampling, long used for other problems could be used in climate model studies. In this approach, uncertain parameters are disproportionately sampled from the range that produces extreme outcomes for the variable of interest (e.g., temperature change) (i.e., more from the 'tail' of the distribution). This sample is then re-weighted on the basis of the parameters' actual probability distributions to arrive much more quickly at an estimate of extreme probabilities with minimal variance.

Uncertainty in IAMs faces several serious challenges, however. The first set of challenges is empirical: parameterization (or "reduced form" as it is know in economic modeling) often is scale-independent *in* models, even though in reality, small-scale processes may function quite differently from processes at broader scales. Secondly, IAM parameterization typically assumes constancy from the past into the future, but of course, past behavior never fully determines the future. Some parameterizations of physical processes can be validated on past observations and assumed to behave the same in the future such as reaction rates of a given chemical species. Other processes essential to IAMs, however, involve those that may differ in the future from the past, for example human behavior affecting the rate and form of technological development. Even some physical systems behave in ways that may prevent extrapolation, for example if a system moves to a different equilibrium behavior from that for which we have observations.

While parameterizations can allow the future to be different from the past, different *in what way* is obviously the major unknown. Moreover, even if parameterization allows for different futures, the structural form of a model typically remains the same unless there is specific knowledge or good reason to change it.[5] Parameterization is also – as previously discussed – hampered in its accuracy by sparse or lack of high-quality data. To make up for such uncertainties, IAMs may rely on expert judgment, thereby introducing cognitive biases of the experts into the analysis.

The second set of challenges to uncertainty analysis in IAs is methodological in nature and echoes previously discussed challenges in combining expert opinion and model uncertainties (see previous chapters for more detail).

The final set of challenges focuses attention on the subjective dimension of integrated research (and uncertainty analysis within it). These challenges revolve around the following questions: How should we structure formal assessment processes? Should we focus on developing consensus results or allow (possibly vastly) divergent views? How should we handle expert judgments in the political context? How can we adjudicate between differing views on future social development? And finally, how can we reconcile between frequentist and Bayesian approaches to uncertainty analysis (for further elaboration on the latter question, see Berk 1997)? These questions reflect deep philosophical differences in the assessment community; they can also manifest in institutional obstacles, e.g., when research institutions or federal agencies have a long history in a particular approach and resist innovation or shifts in direction.

[5] This is part of a general modeling philosophy to keep the representation as simple as possible to represent the process under study.

Many of these research challenges have been discussed in more detail in previous chapters (see also discussion in Parson 1996). Specifically, however, workshop participants urged future IAM research to focus on the following aspects:

- ***Constructing probability distributions for socio-economic parameters***, using historical data to inform such parameterization, but avoiding the pitfall of assuming that the future will be similar to the past. Especially in the human context where behavior can change easily, this assumption can easily produce misleading results.
- ***Greater focus on higher-order impacts*** beyond the most immediate climatic changes.
- More effort to ***link standard SRES scenarios with probablistic information.***
- ***Explicit focus on nonlinearities*** (in any component module of the IAM model).

In addition, as discussed in this section, integrated assessments frequently contain elements built on expert judgment. Careful elicitation of expert judgments regarding the uncertainty in key parameters and inputs from a wider range of experts (broader disciplinary representation) (see Chapter 1, Box 1) will remain an important and necessary element of integrated assessments. Such efforts need to be mindful of the challenges of combining expert judgment and be strictly transparent about how the combination was done. Interestingly, according to a study presented by John Weyant, private sector analyses rely to a greater extent (~80%) on expert judgment regarding the probabilities of key uncertainties and far less (~20%) on deterministic modeling. By comparison, in the public sector, the relative reliance on expert judgment about key uncertainties versus large scale deterministic modeling (with some sensitivity analysis) is just the opposite, and in fact even more strongly polarized (5% and 95%, respectively). The private sector studies are often proprietary and done in situations where it is clear that there is a single decision-maker. Nonetheless, exposure to this practice has lead some observers to conclude that refinements and extensions to the studies by Morgan and Keith, and Nordhaus cited above and the initiation of similar studies in other areas would have a high payoff to the climate policy analysis community and those who rely on it for information in making investment decisions.

The extent to which different sector rely on different methods reflects the dichotomy of opinions that expert elicitation is either absolutely critical, or entirely unreliable in the process of uncertainty assessment (see also the discussion on frequentist versus Bayesian approaches in Chapter 1; for a more detailed discussion, see Schneider 2005a). In the absence of a viable, more promising alternative, significant improvements in expert elicitation can help shore up against some of this technique's critics. Expert elicitation may be most useful for the deep mining of useful information from existing data. Great care must be taken in selecting and calibrating experts to eliminate strongly biased or insufficiently qualified experts, as well as in the combination of expert opinion (using a variety of methods). Different approaches – averaging, weighting, with or without contact and exchange between experts during the elicitation – will yield very different results.

Robust Decision-Making

In recent year, alternatives to integrated assessments and other predict-then-act approaches to policy analysis have been developed under the rubric of Robust Decision- Making (RDM) (see, e.g., Lempert, Popper, and Bankes 2003; Lempert et al. 2004). Most traditional analytic methods characterize uncertainties as a prelude to assessing alternative decisions, i.e., they view resolution, or at least specification of uncertainty, as a step prior to deciding between evaluating policy alternatives. Obviously, climate change confronts decision-makers with deep uncertainty (ignorance) where they do not know or do not agree on (disagreements) the system model, prior probabilities, and/or cost functions (trade-offs). Even in instances where uncertainties are quantified, decisions in this deeply uncertain context can go awry if decision-makers assume that risks are well characterized even if they are not. Uncertainties may be underestimated; competing analyses can contribute to gridlock; and misplaced concreteness can blind decision-makers to potential surprises.

Under such conditions of deep uncertainty, decision-makers often try to reduce uncertainty by choosing among alternative strategies (identifying hedges and reducing conflict) rather than by obtaining additional information. The preferred strategy in such a situation – a robust one – would perform reasonably well compared to the alternatives across a wide range of plausible futures. Robust adaptive planning then is an iterative, analytic process used to identify robust strategies, which are relatively insensitive to most uncertainties. The approach also helps characterize the small number of uncertainties to which the selected strategies remain sensitive.

The four key elements of robust decision-making are:

- Consider large ensembles (hundreds to millions) of scenarios.
- Seek robust, not optimal strategies.
- Achieve robustness with adaptivity (learning over time).
- Design analysis for interactive exploration of a multiplicity of plausible futures.

A robust decision-making analysis begins with a large ensemble of plausible futures generated by scanning over a wide range of parameter inputs to one or more computer simulation models. One or more candidate robust strategies are identified, which can be either strategies proposed by parties to the debate and/or ones generated by the analyst assuming some initial probability weighting across plausible futures. Through data-mining methods, one then identifies "breaking scenarios," i.e., clusters of futures where the strategies perform poorly independent of the assumed probability weighting. These clusters denote scenarios, readily understood by decision-makers, which represent potentially important vulnerabilities of the proposed strategies. The analysis then identifies potential hedging actions and/or alternative strategies that can address these vulnerabilities. It also generates trade-off curves, which help decision-makers decide which hedging actions they wish to take. The process then repeats to make the candidate strategies increasingly more robust against a wider range of poorly characterized uncertainties.

The analysis typically includes visualizations, called landscapes of plausible futures, which compare the performance of alternative policies across a wide range of uncertainties. The visualizations can help parties to a decision with different expectations about the future buy-in to analysis because each can see that the analysis can reproduce their view of the world, and can help decision-makers consider potentially unpleasant or inconvenient assumptions which they otherwise may not be willing to discuss.

In essence, robust decision-making provides a means for reducing highly complex problems with many dimensions of poorly characterized uncertainty into a small number of simple wagers among different strategies which can be presented to decision-makers. That is, "unknowable" uncertainties are characterized by first identifying robust strategies whose good performance is insensitive to the outcome of most these uncertainties and then by focusing decision-makers' attention on the small number of residual uncertainties most important to the choice among these robust strategies.

In situations where multiple decision-makers with very different objectives are involved (e.g., decision-makers in developing versus developed countries, or decision-makers with widely varying attitudes toward risk) the approach can also help identify near-term policies which are robust across different value systems as well different expectations about the future.

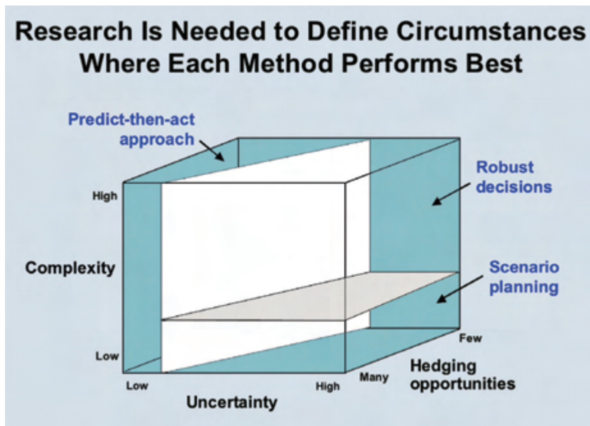


FIGURE 20: **Analytic Approaches to Policy Problems Characterized by Varying Degrees of Uncertainty, Complexity, and Hedging Opportunities** Robust decision-making may be most useful for decision problems with deep, rather than well-characterized, uncertainty; where there are substantial opportunities for hedging against those uncertainties; and where the system is sufficiently complex so that decision- makers cannot easily trace the potential effects of alternative policy choices. Decision situations characterized by other combinations of conditions are best served by alternative analytic decision-support approaches. (Source: Lempert; reprinted with permission)

As shown in Figure 20, robust decision-making seems most appropriate for supporting decisions in situations characterized by deep uncertainty. Decision-making in deep uncertainty is defined as a situation where the parties to the decision do not know or cannot agree upon the system model, prior probabilities for the inputs to the system model(s), and/or the value function. Additionally, further obstacles for a knowledge expert include a rich enough array of potential hedging options to make it possible to discover robust strategies, and a sufficiently non-intuitive connection between alternative policy decisions and their impacts. In situations where the uncertainties are well characterized, more traditional probabilistic decision "predict-then-act" decision methods should be used. Scenario planning approaches may be more appropriate in situations where experts can easily understand the potential consequences of alternative choices. Further research is needed to understand the precise boundaries and conditions where these different methods are most appropriate.

4.3 TOWARD DEFINITION OF DANGEROUS ANTHROPOGENIC INTERFERENCE WITH THE CLIMATE SYSTEM

As stated in the Preface as well as in the introduction to this chapter, policy-makers and the wider public tend to be most interested in how climatic changes might affect their lives, livelihoods, and the environment on which they depend. The ultimate international policy context for such concerns is the United Nations Framework Convention on Climate Change (UNFCCC). Article 2 of that document states that,

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

It further states,

Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

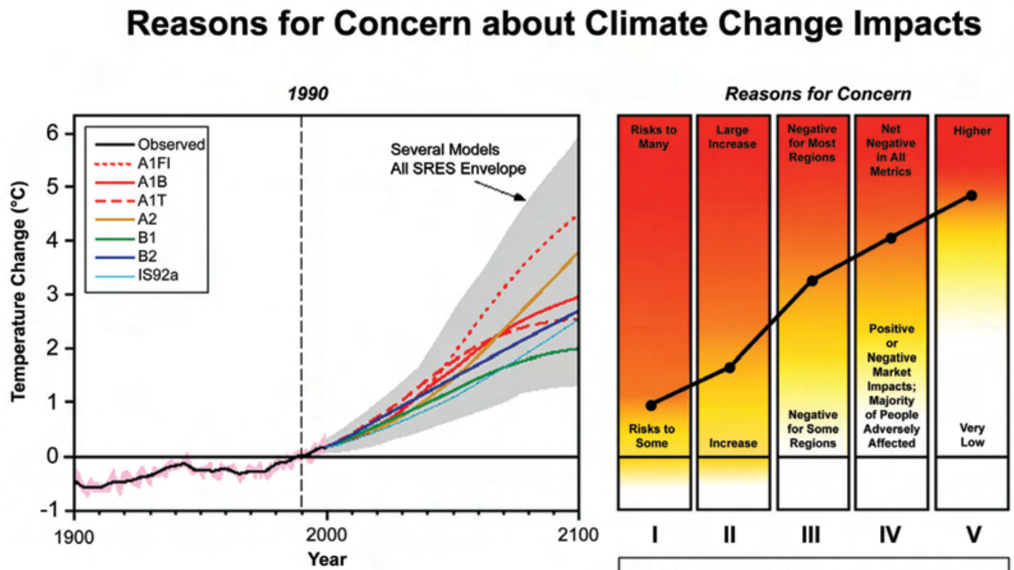


FIGURE 21: **Reasons for Concern about Climate Change: An Approximation of Dangerous Climate Change** This figure is an adaptation of the IPCC Reasons for Concern figure (IPCC 2001b, Figure SPM-2), with the thresholds used to generate our cdf for dangerous anthropogenic interference (DAI). The IPCC figure conceptualizes five reasons for concern, mapped against climate change through 2100. As temperature increases, colors become redder: White indicates neutral or small negative or positive impacts or risks, yellow indicates negative impacts for some systems, and red means negative impacts or risks that are more widespread and/or greater in magnitude. The risks of adverse impacts from climate change increase with the magnitude of change, involving more of the reasons for concern. For simplicity, we use the transition-to-red thresholds for each reason for concern to construct a cdf for DAI, assuming the probability of DAI increases by a quintile as each threshold is reached. (Source: Mastrandrea and Schneider 2004; reprinted with permission)

The challenge to determine – if possible, probabilistically – when dangerous climate change might occur depends fundamentally on the answers to the following three questions:

- What is dangerous climate change?
- What climate change scenarios currently exist, and how can we assign probabilities to them?
- What solutions have been proposed, and how are they affected by projected probabilities and consequences (or lack thereof)?

While the answer to the first question is ultimately a value judgment (see Dessai et al. 2004), it can be assigned agreed-upon measurable thresholds that are not to be exceeded. The IPCC in its most recent assessment approximated danger by identifying reasons for concern (Figure 21), i.e., criteria indicating danger based on potential consequences: risks to unique and threatened systems (e.g., small islands or vulnerable ecosystems), risks from extreme climate events, equitable distribution of impacts, aggregate impacts, and risks from future large-scale discontinuities or surprises.

In the IPCC's Third Assessment, each of these reasons for concern was addressed independently and thus could be viewed as equally important (i.e., no differential weights). The degrees of dangerousness simply accumulated across the five dimensions. Moss and Schneider (2000) thus called for traceable, transparent ways of aggregating and weighting these five dimensions, suggesting that the development of such alternative approaches should be an important goal of impacts research.

Steve Schneider introduced one possible approach at the workshop (for additional detail see Mastrandrea and Schneider 2004). The basic idea underlying this approach is to construct cumulative probability distributions built for each reasons of concern (Figure 20) by determining a threshold temperature (above which each temperature turns red), and assuming a cumulative increase in dangerousness of 20% at each next threshold (an all-weights-are-equal assumption). The identified threshold temperatures are then used for systematic sensitivity analyses to answer the question of which climate change scenario leads to a crossing of the threshold, given uncertainties in climate sensitivity, climate damages, and discount rate (three of the most critical determinants of policy outcomes). The approach allows the identification of policies that can avoid dangerous anthropogenic interference with the climate system at some level of probability. Expressed in a probablistic sense, the approach allows analysts to project by how much the risk of dangerous climate change could be reduced if certain policy actions were taken. They found that ordinary climate policies like carbon taxes could dramatically reduce the probability of crossing specific percentile levels of dangerous warming. Although warning that their specific numerical results were model dependent, Mastrandrea and Schneider argued that their framework was robust and could be used to show policy-makers how to lower risks of crossing a range of dangerous warming thresholds by various degrees of policy stringency, represented in this simple highly reduced form model as a global carbon tax.

Already, great scientific attention is being devoted to one of the five reasons for concern, namely the risk of large-scale discontinuities, such as rapid sea-level rise associated with the disintegration of the Greenland or West Antarctic ice sheets, or with a possible shutdown of the North Atlantic thermohaline circulation (Box 4). Future work on the dangerousness of climate change will have to connect approaches like the one offered above to the SRES scenarios and the underlying assumptions about adaptive capacity and behavior. Workshop participants also considered an expert solicitation on these five – and maybe other, currently missing – dimensions of dangerousness a high priority for further research, hopefully becoming available in time for use by IPCC Lead Authors writing the AR4.

Clearly, defining dangerous anthropogenic interference in the climate system (in terms of certain impacts) and assigning probability distributions of their occurrence are the essential underpinnings of a climate policy that aims to prevent or reduce the likelihood of such dangerous climate change (Grubler and Nakicenovic 2001). It would offer a risk-management framework familiar to many policy-makers that is directly linked to the policy goals identified and agreed upon by the 190 signatories to the UNFCCC (e.g., see Chapter 1 in IPCC 2001b).

Box 4: Low-Probability – High Consequence Events: The Example of a Possible Shutdown of the North Atlantic Thermohaline Circulation

Changes in the ocean-atmosphere system that are currently understood to have a low probability of occurring in this century, but if and/or when they do, are likely to have high consequences are clear candidates for “dangerous” types of climate change. Such abrupt nonlinear events are sometimes called imaginable surprises (Schneider, Turner and Morehouse-Garriga 1998; Schneider and Turner 1995).

One frequently discussed candidate for such an imaginable surprise is the shutdown of the thermohaline circulation (THC) in the North Atlantic (the Gulf Stream or “conveyor belt”), which transports heat from the tropics to northern latitudes. The resulting warm sea surface temperatures provide heat and moisture to the atmosphere, causing Greenland and Western Europe to be roughly 5-8 °C warmer than they would be otherwise. THC also increases precipitation throughout the region (NRC 2002, Rahmstorf 2002, Stocker and Marchal 2000, Rahmstorf 1999, Broecker 1997; see also a discussion of the mechanism propelling the THC and the state of the science by Schneider 2004). Complex GCMs of the atmosphere and oceans now allow scientists to explore emergent properties in the climate system – such as a possible shut-down of the conveyor – resulting from interactions between the atmospheric, oceanic, biospheric, and cryogenic components. This has allowed them to observe processes that exhibit complex, nonlinear behavior. Simpler, more computationally affordable models that can be run over very long times show multiple stable equilibrium states of the THC in the North Atlantic.

Paleoclimatic reconstruction and model simulations suggest that there are multiple equilibria for the THC, including one that completely collapses the circulation. Switching between the equilibria may occur as a result of temperature or freshwater forcing at higher latitudes and the concomitant reduction in the equator-to-pole temperature gradient. There is some evidence now that changes in Atlantic currents are indeed occurring (Curry et al. 2003).

However, some coupled models of the atmosphere and oceans (e.g., Yin et al. 2005) do *not* produce a THC collapse from global warming due to yet unknown feedback processes in the models. Schlesinger reported at the workshop that in model simulations he has undertaken the shutdown may occur, but may also be reversible.

These findings from various simulations point to why it is so difficult to assign any confident probabilities to the possibility of a THC collapse. Our understanding of the coupled ocean-atmosphere-cryosphere-hydrosphere system in the North Atlantic is insufficient at this time to fully understand the processes and feedbacks in this system. We therefore cannot yet say with confidence whether the simulated results (of shutdown or reversibility of a shutdown) are merely model artifacts or possible realities. But workshop participants agreed that the current unknowns are at least knowable to some extent in the future.

4.4 KEY RESEARCH TASKS: A SUMMARY

The search for more accurate scientific understanding of the impacts from climate change is pursued through top-down (emissions to global climate to regional impacts) and bottom-up (societal factors determining sensitivity, adaptive capacity and thus vulnerability to climate risks) approaches. The complementary insights derived from these approaches can serve to prevent or minimize negative impacts on the environment and on people. Much progress has been made in recent years to integrate impact analyses and to address explicitly and – where possible – quantitatively the uncertainties associated with assessments of the impacts and potential dangers from climate change. Workshop presentations and discussion, however, revealed numerous areas where progress can and must be made, before highly confident assessments will emerge.

Economic Impact Assessments

Overall, workshop participants urged that economic models be subjected to a more stringent quality review empirical testing and inter-model comparisons, similar to the kind of review to which climate models are regularly subjected. Specific improvements could be achieved through research focus on the following aspects:

- ***Improvements in the measurement of impacts:*** Who or what is impacted by what requires careful specification. In addition, the measurements themselves are non-trivial challenges, especially at high spatial resolution and greater disaggregation of impacts and commodities. How to measure impacts and indicators, integrate them into models, and assess their relative importance should be a major focus in future economic research.
- ***Development of non-equilibrium models:*** Most current economic models are general equilibrium models. The highest costs from climate change, however, are expected from the temporary out-of-equilibrium behavior of systems, depending on how long it takes for technologies, institutions, societal values, or individual behaviors to change. Thus, we need models that are better able to capture system behavior and impacts during these transition times.
- ***Greater attention to and integration of adaptation:*** The transition from one equilibrium state to a new one should focus economists' attention on adaptation, especially its rate, efficiency, and effectiveness. Economics must better understand the determinants of change in technology and in human preferences in order to produce more confident, realistic impact assessments.
- ***Improvement in model specification:*** Model specification is a critical step toward reducing uncertainty in economic impacts assessments. Currently, knowledge of human behavior and preferences among disaggregated commodities, of the relevant attributes and how they are perceived, the choice set, and the degree of heterogeneity among decisions, decision-makers, and within specific sectors is quite limited. Most current models also do not allow for what might be called regime changes – i.e., fundamental changes in model structure resulting from changes in institutions, changes in perceptions, or changes in behavioral patterns.
- ***Improvement in model calibration/estimation:*** While general guidance as to the correct form of economic models cannot be given because it depends on the specific modeling purpose, improvements in this area may be achieved through statistical approaches such as mixture model estimation (McLachlan & Peel, 2000) and Bayesian model averaging (Raftery et al. 1997; Hoeting et al. 1999).
- ***Improvements in model forecasts:*** Backcasting exercises or starting models in the past and forecasting the (already realized) future could help assess and improve the forecasting skill of economic models. Testing model responses to known shocks is a good empirical test of model sensitivity to stressors.

Ecological Impact Assessments

Among the important scientific challenges ahead in ecological impact studies are the following:

Examination of synergistic impacts: Ecologists face crucial challenges in moving from single-driver impact studies to ones that examine and project the synergistic impacts of climate change and other drivers of change, such as land use change or mitigation actions (e.g., forest protection). For example, major questions remain as to species ability to adapt to rapid climate change. Probing the simplistic notion of pole- or upward species migration, possible obstacles, availability of analogue habitats, and possible changes in migration behavior and patterns (drawing on data and insights from people studying biodiversity hotspots and other observation networks) will provide critical insights into ecological adaptive capacity and offer policy-relevant information for ecosystem and land use management. Progress in this area will also help make modeling studies, which currently are still rather simple, more sophisticated.

Examination of not only single-species but ecosystem impacts: Until now, most ecological impact studies have examined single-species impacts. With individual species responding differentially to climate change, analysis of the breakdown and reassembly of species communities and, in turn, ecosystems (rather than single-species impacts assessments) is a critical future research challenge. Progress in this area is important for the development of more reliable predictions as to where or in which cases this breakdown and reassembly will be ecologically catastrophic or successful.

Exploration of impacts not only of single variables but of climate: The clearest signal observed in ecological impacts studies to date is the response to temperature change. However, climate change involves more than temperature increases, and a focused research effort is required to understand in a more holistic fashion the ecological response to synoptic climate change.

- ***Better integration of non-traditional data sources with scientific information:*** Given the sparse archive of observational data, ecologists face the challenge of integrating scientific information with non-traditional empirical observations (e.g., native knowledge, lay observers). Progress may be made more quickly through collaboration with anthropologists, who are developing integrative approaches in their work with native peoples (e.g., in the Arctic regions). Certainly, more reliable long-term data will allow a better understanding by ecologists of how ecosystems reacted in the past to climatic changes, which in turn will help us to better understand how species might shift with future warming.

Vulnerability and Adaptive Capacity Assessments

Drawing general, transferable conclusions from the myriad of case studies produced to date, and then feeding the emergent findings into the development of adaptation strategies, are the overarching challenges faced by researchers conducting vulnerability and adaptive capacity assessments. Specific research tasks include the following:

- ***Identification of vulnerability/adaptation assessment users and their information needs:*** Many vulnerability and adaptive capacity assessments to date have not paid careful attention to the key users of vulnerability/adaptation information. Depending on the scale for which studies and/or scenarios are produced, the sets of information users will differ substantially, as will their capacity to use that information. A careful identification of users needs and perceptions prior to the study can influence the type of study and the range of information products arising from it, to say nothing about its utility to various decision-makers and stakeholders.
- ***Development of a conceptual framework of adaptive capacity:*** Reflecting the presence of multiple theoretical schools of thought on vulnerability and adaptation, a coherent, and yet sufficiently flexible, conceptual framework of adaptive capacity has yet to be developed. While a single correct framework is unlikely to emerge, systematic evaluation of different frameworks is needed to develop criteria for when and why particular frameworks should be applied, and their strengths and weaknesses.
- ***Improvement in the measurement of vulnerability:*** Against the backdrop of sometimes significant data limitations, more research is required on identifying proxy variables of sensitivity, vulnerability, and coping/adaptive capacity (which would enable a comparative assessment informed by underlying causal factors). Improved measurement and mapping of current vulnerability and adaptive capacity will provide a baseline against which improvements or declines in the future can be measured.
- ***Development of indicators of adaptive capacity and vulnerability:*** Indicators suffer from a variety of uncertainties, including inaccurate or incomplete data, mismatches between proxies and the target variables researchers would like to measure, incompletely understood functional relationships among variables, lack of specificity, and uncertainties associated with forecasting human choices and relationships. Both probabilistic and scenario approaches may yield interesting and complementary results and both should be pursued.
- ***Greater focus on inequality and the causal mechanisms producing vulnerability:*** While politically sensitive and frequently controversial, better knowledge about inequality in and between societies now and in the future is required to assess who in a society is vulnerable, to what degree, and to which stressors. Future research on vulnerability and adaptation will have to focus specifically on the question of inequality and the specific mechanisms creating different degrees of vulnerability. Such improved theoretical understanding will help in the projection of future vulnerabilities and adaptive capacity, and in generating scenarios.
- ***Greater focus on cost and effectiveness of adaptation options:*** Vulnerability research at times is narrowly focused on reducing vulnerability or enhancing adaptive capacity only, but it does not always ask whether the suggested remedies would actually constitute effective responses to climate change, how much they would cost and to whom, to be effective. Future research must pay greater attention to costs and effectiveness of adaptation responses.
- ***Greater focus on synergisms between different types of global change:*** Similar to the critical issues raised around synergisms in ecological impact studies, vulnerability and adaptation research must also pay greater attention to the socio-economic and political context of climate change impacts, and tackle the critical synergisms arising from multiple stressors. For example, how does economic globalization affect the degree of vulnerability or the ability of local decision-makers to implement adaptation strategies? Or: how do regional wars or unrest undermine efforts to prepare for or respond to climate change impacts?

Integrated Assessments and Policy Analyses

Many of the specific research questions pertaining to integrated assessments are derivatives of the research challenges discussed in previous chapters. In addition, workshop participants urged research focus on the following aspects:

- ***Construction of probability distributions for socio-economic parameters:*** Probabilistic projection of socio-economic behavior ultimately requires far greater understanding of the causal loops producing stability and change in human behavior. Historical data (i.e., empirical data of past behavior) informs our theoretical understanding of socio-economic behavior and thus the parameterization in models, but researchers must avoid the pitfall of assuming that the future will be similar to the past and that human behavior and preferences will remain constant. In some instances, such projections might have to be based on sparse observations (see March, Sproull and Tamuz 1991). Single pdfs can be placed over these projections if they are based on reliable information (see IPCC 2005); alternatively, researchers could parameterize models for a wide variety of cases from different countries, regions and/or time periods. In addition, the limited amount of historical information can be used in focused expert elicitation to elicit subjective uncertainty ranges for the behavior of the variable of interest in the future. Finally, the alternative projections and probability distributions should be tested for robustness (i.e., a "red team" approach in which analysts ask if there is some plausible path into the future that would be particularly troubling for the policy recommendations that emerge from the analysis, and how likely this path would have to be in order to change the policy recommendation).

- ***Greater focus on higher-order impacts:*** Current IA models are still limited in their capacity to project higher-order impacts (i.e., the more complex ecological and societal impacts) beyond the most immediate climatic changes. Too many IAMs still project climate outcomes as global mean temperature change or as an aggregate economic loss based on a simple damage function of global mean temperature change. More specificity of impacts in time, space, and type would be extremely valuable, including primary impacts variables such as regional temperature and precipitation changes, and changes in weather/climate variability for a region, as well as secondary impacts changes in water supplies, impacts on agriculture, sea-level rise impacts on coastal areas, and loss of biodiversity from climatic shifts. Workshop participants considered these critical areas where resources should be invested to improve the usefulness of IAMs.
- ***Integration of scenarios with probabilistic approaches:*** What-if scenarios yield important insights into the dynamics of ecological and societal dynamics. Virtually all impact assessments to date are based on scenarios whose probability is undetermined. From a policy-making perspective, however, these insights are only – or more likely – taken seriously, if scientists can say how likely certain impacts are to occur. Thus, more effort is needed to move toward assigning probabilities to the SRES scenarios (if only over the relative near-term) and thus toward probabilistic forecasting of impacts.
- ***Greater focus on nonlinearities:*** Current IA models combine linear and – at least some, if maybe not enough – non-linear components. Many already-known nonlinearities, however, are either neglected or treated only very simply (e.g., THC collapse, induced technological change, utility functions). Nonlinearities, and non-equilibrium states, however, may be the most interesting and the most challenging future changes, and hence of greatest interest to policy-makers. Their treatment in IAMs need to become more central and sophisticated.
- ***Careful expert elicitations:*** In the absence of a viable, more promising alternative, expert judgment will remain a critical input in integrated assessments. Improving expert elicitations can help shore up against some of the technique's critics to improve confidence in conclusions. Greater care must be taken in selecting and calibrating experts to eliminate strongly biased or insufficiently qualified experts, as well as in the combination of expert opinion (using a variety of methods). Different approaches – averaging, weighting, with or without contact and exchange between experts during the solicitation – will yield very different results, and the maximum insights from this may well follow from the differential comparisons of elicitations of various groups.
- ***Analysis of robust policies and the applicability of this type of analysis:*** Robust adaptive planning has recently emerged as a promising new approach in policy analysis. Research is needed to determine those circumstances where predict-then-act versus robust adaptive planning versus scenario planning approaches perform best, or at least, how they alter the risks of climate change.

Dangerous Anthropogenic Interference with the Climate System

To meet the objectives of the UN Frameworks Convention on Climate Change, significant research attention is needed to help define the criteria for dangerous anthropogenic interference in the climate system, to assess the probabilities with which such thresholds of danger may be crossed, and what policy options are available to remain below them. Workshop participants suggested the following areas of research:

- ***Development of a traceable account for weighing the reasons for concern:*** To advance beyond the IPCC's five highly qualitative reasons for concern, a traceable, transparent way of aggregating and weighting these five (or additional ones that may emerge from additional research and assessment) dimensions is needed.
- ***Connection of dangerousness with scenarios and adaptive capacity:*** Future work on the dangerousness of climate will have to connect emerging probabilistic approaches to the SRES scenarios and the underlying assumptions about adaptive capacity and behavior. An expert solicitation on these five – and maybe other, currently missing – dimensions of impacts that could constitute dangerousness would be a viable approach to advancing the discussion.

Defining what is dangerous about climate change, however, cannot remain a scientific discussion alone. Given the unavoidable and necessary value judgments involved in defining danger, a scientifically informed public discourse will have to be generated and facilitated. This brings to the forefront the question of how best to communicate climate change and its inherent dangers and uncertainties. The following chapter summarizes workshop discussions on this issue.

5. COMMUNICATING THE KNOWN, UNKNOWN, AND UNKNOWABLE

Chapter 5 summarizes contributions by Miles, de la Chesnaye, Janetos, Moss, Moser, Surles, and Bisset.

Linking the scientific knowledge base concerning global climate change with public policy decision-makers continues to be a daunting problem. Properly linking this information with the general public is even more daunting. For while there is general public acceptance that climate change is a problem – and real, there is not even a reasonable public understanding of the causes and related individual contributions.
– Terry Surles, Director of the Public Interest Energy Research (PIER) Program, California Energy Commission

The first task of any communication effort is to identify and know the intended audience, so that the information can be tailored in a way that can be heard by those listening. At the workshop, participants focused on three main audiences of concern: public policy-makers, resource managers, and the broader public. From the perspective of the public, the need expressed by scientists to reduce uncertainty and to further define it appears too nuanced and is frequently perceived as self-serving, i.e., as an attempt to ascertain more funding. The general public may not see the necessity for further reduction of uncertainties given that the scientific consensus seems to already make the most important point (to them): the globe is warming and will continue to do so unless emissions are substantively reduced. Being accustomed to public decision-making where options are uncertain and outcomes not guaranteed, the public thus has a difficult time appreciating the need for further reducing scientific uncertainties. Realistically, lack of certainty has never prevented individuals or governments from taking action, except when uncertainty was used as an excuse to delay action.

Thus, the guiding question of how best to speak to potential users about climate change and the inevitable, and in some cases irreducible, ignorance and uncertainty in it becomes less a technical and more a strategic question: Who needs to know, what specifically, for what purpose, and when? Identifying the specific goal of the communication and the relevant constituencies that need to be reached and mobilized will go a long way toward developing the appropriate message, determining what about climate change uncertainties needs to be told, and how this information should best be delivered (see Box 5 for the policy and resulting communication challenges currently faced by California decision-makers and public audiences).

The public and state officials are, of course, only some of the many potential audiences for climate (and uncertainty) information. There is no one-size-fits-all set of rules or approaches for communicating to different audiences. What may seem like arcane scientific debates in professional fora are necessary conversations. Eventually their content becomes the stuff for popular dissemination, albeit packaged differently for different groups. The only ethical and professional imperative for scientists is to ensure that the same message emerges about what is well known, what is partially known, and what remains speculative at this time.

It is critical to recognize, however, that once outside the scientific arena uncertainty takes on a life of its own. Effective communication thus requires not only consistency and clarity, but also a keen understanding of the policy and political context into which scientific information and uncertainty enters.

5.1 THE KNOWN, UNKNOWN, AND UNKNOWABLE IN THE POLITICAL CONTEXT

The particular alignment of qualities that characterize climate change as a global policy problem could lead observers to believe that it is virtually hopeless to make meaningful political progress. Uncertainty about the seriousness and drivers of the problem, combined with a malign configuration of actor interests are major hurdles in international regime building. This particular constellation makes global climate change the ultimate collective action problem. Past studies of international regimes have shown that for such collective action problems to be addressed, two conditions have to be met: either a disaster has already occurred or there is a consensus that a disaster of significant scale is uncomfortably probable in the short run (Warrilow 2004). These conditions reflect a significant dependence by international regimes on the rate of environmental change and on the immediacy and saliency of perceived effects. These conditions therefore do not bode well for climate change, at least not in the near-term.

Realistically, lack of certainty has never prevented individuals or governments from taking action, except when uncertainty was used as an excuse to delay action.

Experience and studies of national policy regimes (e.g., comparing U.S. and European responses to climate change) also reinforce the importance of political culture and leadership for political action to occur. Skillful, persistent, and strategic framing of what is known and not known can take advantage of a particular

Box 5: Current Communication Challenges in California

Contributed by Terry Surles, CA Energy Commission

In California at present, our biggest communication challenge is how to develop the right message to sway public opinion to more aggressively support action on climate change in such a way that elected representatives will be prodded into action. One means is to take advantage of what is already occurring at a state and local level. California is already taking advantage of positive public opinion to catalyze new legislative initiatives and actions, as well as to promulgate regulations that lead the way in changing the world energy use paradigm. Efficiency standards, the Renewable Portfolio Standard, and tailpipe emission legislation (the Pavely bill) demonstrate that the body politic on a state level can and will effect change. Many similar activities are occurring in the U.S. Northeast and in other West Coast states.

Now our challenge is to raise public awareness and support even further in order to promote additional efforts. While we recognize that we need a scientific "uncertainty police" to improve the accuracy and precision of climate change predictions, we also know that this refinement will not affect the overall debate. Instead, we need to "get the message out" in a way that better frames the public debate. First, this message must be in conversational English – not in "bureaucratese" or "technocratese." Scientific jargon dies a quick death. And second, we need to better connect climate change to what people really care about in order to increase the number of supportive constituencies: economic impacts, equity, health, energy security, and education.

It would be extremely informative to conduct public surveys within the states and regions that are most aggressively pushing for a governmental response to climate change to better understand why the public supports specific initiatives. It would be particularly helpful to better understand which constituencies are strongly for, somewhat for, neutral, and somewhat to strongly against these initiatives. This would put us in a better position to package information in a way that informs and influences public opinion.

People want to know about economic impacts, both positive and negative, on the state and on their lives. Most of the explicit arguments against climate change action revolve around these subjects. If we could better quantify these impacts by region and by constituency group, and compare them to "no action" economic impacts, we might be able to demonstrate that it is in our self-interests to effect policy changes now.

We also must be more precise in terms of the information that is needed to sway various constituencies' opinions. Which information is really needed? We know not to dwell on scientific nuance and to speak in jargon. And while we know that the public is generally supportive and what they are concerned about, we have yet to learn how to refine and target our message to take advantage of this support and how to allay people's fears.

For California, the time is now. With a popular governor in office who is extremely interested in the environment and in the technologies that can be made available to improve the environment, we need immediate answers: What is the best way to provide information to him and his advisors that will demonstrate the overall collateral benefits from existing and enhanced state strategies to combat global warming? And how do we parlay California and other state activities to effect change on a national level?

political or institutional culture, or at least penetrate to willing audiences. This framing can also enable a political actor willing to assume leadership to garner support from colleagues and the general public for a particular course of action (or inaction). Both proponents and opponents of climate change action face the challenge of appropriate framing to reach actors in positions of power and to achieve their political goals.

While scientists typically abhor being pulled into what they perceive as spin doctoring and political rhetoric, strategically selected scientific information will be used by all sides for varying political purposes whether or not scientists approve. In the U.S., even if scientists prefer to remain outside the political fray, they can improve communication of climate change by providing sounder scientific underpinnings for future policy and reducing opportunities for naysayers or alarmists to misuse the scientists' information (Box 6).

> Scientists can improve communication of climate change by providing sounder scientific underpinnings for future policy and reducing opportunities for naysayers or alarmists to misuse the scientists' information.

Cognizant of the political context, and of the fact that decision-makers and the general public listen to many messengers (e.g., the media, NGOs, climate contrarians), scientists (or their expert communicators) can nonetheless greatly improve their presentation of what is known, what is currently unknown, and what is fundamentally unknowable. Specific guidelines emerged from the workshop discussions and are summarized in the following section.

Box 6: Rules of Thumb for Communicating about the IPCC, the Scientific Consensus on Climate Change and Policy Options

The following suggestions reflect both experience with past shortcomings in communication and the new communication needs at this time:

- Better representation of the IPCC process and conclusions can support political acceptance of this international assessment.
- Support of further research to reduce specific, policy-related uncertainties can be presented as one important, albeit insufficient, component of sound public policy.
- At the same time, uncertainties are not sufficient reasons to defer action. Scientists can improve the presentation of climate change knowledge for which high levels of evidence and scientific consensus exist (see Section 5.2), while also improving public understanding of the scientific process.
- Policy and economic analyses can illustrate whether and when concerted international action is more cost-effective than piecemeal approaches. The backing of national action with the international consensus view of the climate problem can also play an important role in mobilizing the necessary political support for action.
- By determining probabilities of potential impacts, scientists can provide essential information for public debate about unrestrained climate change and the unacceptable risks it entails.
- Scientific impact analyses can demonstrate that global control of greenhouse gas emissions is necessary to stabilize concentrations at levels below "dangerous anthropogenic interference in the climate system." At the same time, such analyses can demonstrate that the Kyoto Protocol is only a first step.
- Given the evidence of already occurring climate change and the commitment to some additional climate change due to our past emissions, scientists can also facilitate public discussion about the need for adaptation strategies (along with mitigation actions). This will turn attention to the regional and local level where climate change impacts can be made more "real."

Source: Adapted from Warrilow 2004

5.2 GUIDELINES FOR BETTER COMMUNICATION OF SCIENTIFIC KNOWLEDGE

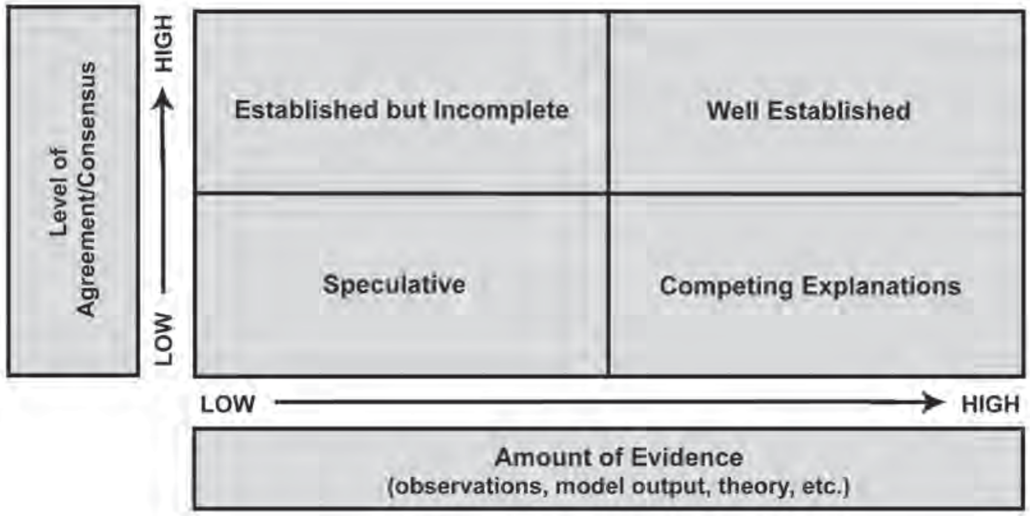
Two-Way Communication

Workshop discussions repeatedly affirmed that scientists would be well advised to take seriously the old adage that "communication is a two-way street." Embracing this notion instantly makes communication with stakeholders not an auxiliary add-on at the back end of research, but an early and continuous element of the research and assessment process. As experience with the U.S. National Assessment demonstrated, involvement of stakeholders improved the focus of the subsequent analyses, even if the stakeholders were not involved in or did not specifically improve the technical quality of the analyses. But careful listening and engagement generally led to a better fit of the scientific analysis with real decision-making needs. IPCC leaders should seriously assess whether the sole reliance on a review of the scientific literature without front-end consultation with technical and policy communities is the most effective way to proceed with these global climate assessments. At a minimum, such inputs should be sought in reviews of early drafts of the Fourth Assessment report (AR4). In particular, could the IPCC envision an alternative process for developing scenarios that would involve practitioners?

Simple, Consistent, and Transparent

The communication of uncertainty in knowledge can be made far more effective by using simple terms, consistently applied. Attempts to standardize uncertainty terminology in the U.S. National Assessment (see Chapter 1), the IPCC, and in the U.S. Climate Change Science Program's guidance for decision-support are quite successful efforts in this direction. Clear and consistent terminology alone will enhance public understanding of uncertainties. In addition to associating certain qualitative terms consistently with specific quantitative levels of uncertainty, scientists can also help people understand what type of, and how much, evidence supports certain conclusions, thus giving the audience a sense of the level of consensus in the scientific community (Figure 22).

For certain audiences, it may also be helpful to discuss the underlying reasons for why something is currently unknown or ultimately unknowable. For example, something might be understood in general terms, but unknowable in specific instances; there may be limits to accuracy and certainty because of the nature of what is being forecast (such as human behavior);



Supplemental Qualitative Uncertainty Terms

Key to qualitative "state of knowledge" descriptors:

Well Established: models incorporate known processes; observations largely consistent with models for important variables; or multiple lines of evidence support the finding

Established but Incomplete: models incorporate most known processes, although some parameterization may not be well tested; observations are somewhat consistent with theoretical or model results but incomplete; current empirical estimates are well founded, but the possibility of changes in governing processes over time is considerable; or only one or a few lines of evidence support the finding

Competing Explanations: different model representations account for different aspects of observations or evidence, or incorporate different aspects of key processes, leading to competing explanations

Speculative: conceptually plausible ideas that haven't received much attention in the literature or that are laced with difficult to reduce uncertainties or have few available observational tests

FIGURE 22: **Qualitative Distinctions of Different Degrees of Uncertainty Reflecting the Amount of Available Evidence and the Level of Scientific Consensus** (Source: Moss and Schneider 2000, and after Moss and Schneider 1997; reprinted with permission)

or something may be uncertain due to the multiple influences on future social and/or economic conditions. Such information will help people assess both the degree and source of uncertainty, and typically help them be more at ease with uncertainty.

In short, statements on uncertainty should be made more transparent. First, scientists need to clearly document where and why a certain type of uncertainty exists. This will also help direct future research to reduce it (if indeed, it is important to reduce). Second, scientists and policy analysts should give decision-makers and the public a better sense in which ways uncertainties matter to the kinds of decisions they may choose to make. Not all uncertainties matter equally in terms of decision-making, however interesting they may be scientifically. Third, communicators can make uncertainties more understandable to decision-makers and lay audiences by using common metaphors of risk assessment issues like highway safety, health risks or air pollution epidemiology. Finally, analysts should also document how the assessment of uncertainty was done. Being transparent and forthcoming about uncertainty will help information users assess the degree of uncertainty, and – maybe counter-intuitively – build trust between scientists and practitioners (see below).

Leading with Certainty

Most scientists feel uncomfortable making statements that suggest a high degree of confidence and scientific certainty. This is especially true in the context of global climate change. Thus, many couch their assertions and findings in caveats of ever-present uncertainty – with the demonstrable effect that the audience remains tentative and interprets the entire issue as continuing to be so incompletely understood as to not warrant any action – or, sadly – even attention. Workshop participants acknowledged that the typical form and framing of scientific communication thus contributes in no small measure to the persistent public perception of an unsettled scientific debate, and hence to public inaction on anthropogenic climate change.

Clearly, scientists can improve their communications without violating appropriate caution or scientific credibility by stating upfront and clearly where the underlying science and economics are pretty well settled (e.g., the observed increases in atmospheric CO_2 and other GHGs, the sources of these GHGs, and hence the non-negligible role of human activities in altering the global atmosphere and climate), and why that is the case. This would give a sense of perspective to subsequent statements about intrinsic and irreducible uncertainty (e.g., the "missing" terrestrial sink for CO_2 – an issue currently unknown but in principle knowable; the lack of specificity for particular impacts – in some cases knowable, in others unknowable in principle).

IPCC leaders should assess whether the sole reliance on a review of the scientific literature without front-end consultation with technical and policy communities is the most effective way to proceed with these global climate assessments.

Clear Link between Science and Common Experience

Climate change is progressing rapidly outside the envelope of recorded and – more importantly – experienced reality by present-day decision-makers and the general public. This suggests that most of us have to draw on the imagination or on analogs to comprehend what may be in store as global warming proceeds. Scientists therefore must find creative ways to communicate that which is beyond immediate grasp. Communication can be more effective when it uses historical or geographical analogies, or employs commonly understood metaphors to relate complex, unfamiliar concepts and processes to common and culturally relevant experiences. A frequently discussed but not yet widely used example is the "insurance" concept. Most Americans have a clear understanding of the principles, goals, and social contract underlying the notion of "insurance," which is all about spreading risk, thus it might be successfully used to explain climate policies. Deterrence is a related concept, going beyond the risk-spreading notions underlying insurance. Deterrence implies reducing risks. Both are widely accepted principles in public policy and private choices, and metaphors that help convey these ideas can help make uncertainties less daunting to the public.

For decision-makers, scientific information has to clearly connect with the decisions (at the spatial and temporal scales) over which they have control. Experience has shown that it helps if the information producer takes the first step toward potential information users by trying to understand the decision problems the users face (including the institutional and political context). Communicators (not necessarily just scientists) must be able to show how the scientific approaches and results can help the decision-maker solve real problems. Some of this mutual learning will take place in face-to-face interactions; regular (annual) workshops offer additional important contacts. Such individual or group interactions can provide opportunities for informal teaching about probabilistic techniques. Personal trust will grow along with trust in heretofore unfamiliar scientific approaches, but this may require that information producers spend considerable time explaining the approaches. It may also require that scientists fulfill the decision-makers' more immediate needs first (such as largely deterministic short-term forecasts and assessments of risks) before introducing challenges associated with long-term climate change. In short, scientists must provide added value to the decision-maker and foster two-way dialog.

A cautionary note should be added on stakeholder–scientist interactions. How best to design such interactions, in what roles to involve stakeholders in scientific or assessment processes, and how to weigh stakeholder versus scientific priorities and insights are all questions of practical and social-scientific concern (see e.g., the study currently underway at the U.S. National Research Council's Human Dimensions of Global Change Committee). These questions directly affect the legitimacy/fairness, relevance, and credibility of such processes, and cannot be avoided by the scientific community, if it wants to take stakeholder involvement seriously.

Shoring up the Risk-Taking Decision-Maker

Clearly, even close collaboration and connectivity to the decision problem does not guarantee the use of scientific information in decision-making. Convincing a technical operations manager of the benefits of using new scientific information does not automatically mean that the organization within which this manager is embedded will accept the innovation. The process is one of diffusion of innovations through a particular institutional context with numerous barriers. Understanding these barriers and working through and around them takes time and effort on both sides. However, building communication bridges between the peculiar perspectives of scientists and decision-makers is an essential first step. Then scientists must provide the tools, insights and data from which decision-makers will choose courses of action that correspond with their degree of risk-averseness or risk-taking attitudes.

5.3 THE OVERRIDING IMPORTANCE OF TRUST

Trust is essential.
– James Boyd, Commissioner, California Energy Commission

The mutuality, respectfulness, and complementarities of skills and insights that characterize effective interactions between scientists and stakeholders are necessary ingredients to build trust. This process takes time and effort from both sides; thus, time-pressured interactions generally fail to establish trust. The overriding importance of trust in the effective communication between scientists and practitioners was demonstrated, more than discussed, in this workshop itself.

One participant, for example – an outsider to both the science and the decision-making worlds – observed how the revelation of the many unknowns about future climate over the course of this three-day conference could have easily led anyone to dismiss climate projections as "absolute hogwash." Instead, the open and honest struggle with uncertainties during the workshop helped this participant not only build trust with the attending scientists as human beings deeply concerned with the well-being and survival of the planet, but in the process also completely convinced this participant of the seriousness of the climate problem.

Uncertainty does not necessarily undermine decision-making or public discourse.

This observation was echoed by numerous practitioner participants. Given that uncertainty is nothing new for decision-makers, the difference between what they are accustomed to already and what climate change to the best of our current knowledge entails is mostly a matter of degrees. The uncertainties embedded in the complexity and long time horizon of the issue become more manageable (and politically defensible) for decision-makers, when they have access to trusted experts who can explain the uncertainties, and are willing to help solve difficult decision-problems. "Trust," as California Energy Commissioner James Boyd said, "is essential. Probably the most essential."

Experience in the U.S. National Assessment supports the observation that uncertainty does not necessarily undermine decision-making or public discourse. Scientists involved in that large-scale effort found the U.S. public to have a tremendous appetite for straightforward discussion of climate-related issues. Open and honest discussion about scientific evidence (or the lack of evidence) for climate change, the remaining unknowns, how observed changes compared to natural variations, and why the findings might matter to people was almost always well received. That assessment, of course, framed the question of impacts through the particular lens of existing vulnerabilities and other stresses, and how climate change may ameliorate or exacerbate them. This entry point for discussion allowed sincere exchange without having to know the exact extent or regional manifestation of climate change, suggesting that a society more resilient to climate variability and extremes was likely to be less vulnerable to climate change. Importantly, most people did not want to be preached to and persuaded, but they did want a sense that the scientist could be trusted. Various audiences hearing the findings of the National Assessment seemed perfectly comfortable in accepting the immense complexity of the climate issue and that perfect predictions were simply unobtainable.

The communication challenge surrounding uncertain scientific knowledge is at once technical and strategic, as well as ultimately personal. Understanding communication as a two-way process aimed at mutual learning and trust-building will create a discursive environment, in which climate change knowns, unknowns, and unknowables can be told *and* heard. Simple and consistent terminology should be accompanied by transparent explanations about the nature, degree, and sources of uncertainty. If the aim of such communication is to supply the scientific underpinnings for sound decision-making, then scientists would be well advised to lead with certainty, speak through familiar metaphors, connect with the common experiences, language, and decision problems at hand, and provide those decision-makers willing to take political risks with the necessary backing so that they are equipped to take action when windows of opportunity arise.

6. LESSONS FROM CALIFORNIA FOR PROJECTING REGIONAL CLIMATE FUTURES – A SUMMARY

California is unique in many respects. Climatologically, it combines a unique set of characteristics – its coastal location with strong influence from the Pacific Ocean, its complex topography leading to a highly varied regional climate, and its latitudinal expanse across hundreds of miles. As a consequence, California is extremely rich in natural resources and ecological diversity. Politically and culturally, it is also distinct from the rest of North America. The state frequently leads the U.S. in policy and technological innovations, and climate change is a good example of its environmental leadership. California is also the only state in the nation with an ambitious state-funded climate change research program to support its innovative policy and management efforts. Thus, there are already important opportunities for close collaborations between scientists and decision-makers to implement research findings. With a rather pro-environmental governor in office at this time, more such opportunities are likely to open up in the future.

Given these unique features of California's political and geographic environment, to what extent and in what ways can the methods and lessons learned in this workshop specific to the California case be transferred to regional climate forecasting and decision-making efforts elsewhere? Some cautious answers are provided below. These answers entail larger conclusions from this workshop about the known, unknown, and unknowable about our future climate.

LESSON 1: **California is harder than some and easier than other regions, requiring care in transferring lessons.**

The first and most obvious answer to the transferability question is that California's enormous climatological, geographic, and ecological diversity makes climate projections for the region particularly difficult. Not all, but many other regions will face fewer challenges, e.g., in regional downscaling or in ecological impacts analyses.

On the other hand, the remarkable political interest, openness, technical sophistication among managers, and willingness to take political risks make California an easier place to communicate climate change and to foster science–policy collaborations. While the basic principles of effective communication and collaboration are the same everywhere, far more patient groundwork and political advances have yet to be made in many other regions of the country and the world for climate science to enter effectively into the decision-making process.

LESSON 2: **The complexity of models should be inversely related to the decision time horizon.**

There are practical limitations to a scientifically accurate specification of future emissions, climate, and impacts projections that must be respected. For example, forecasts of technological change beyond 30 years quickly reach the limits of "knowability." While significant progress can be made in increasing our understanding of any one component of emission scenarios, global and regional modeling, and impacts assessments, not all will move from the "unknown" into the "known" category; some will remain "unknowable." As a general rule of thumb then, the internal complexity of scenarios and models which include deep uncertainty should be inversely proportional to the timescale (i.e., for near-term projections complex; for long-term projections simpler). Workshop participants argued that while this general rule of thumb may well apply to all modeling efforts, it may seem more reasonable to keep adding complexity to physically-based models where the realism of the added complexity can be directly tested. Adding complexity to long-range socio-economic models, on the other hand, may not yield results in which analysts can have greater confidence. For century-scale socio-economic scenarios, instead, greater progress is likely to be made by focusing on the complexities and uncertainties associated with a few key parameters such as wealth and its distribution, fertility rates, the dominant technology for supplying primary energy etc. Surely, simply increasing socio-economic complexity of models without seriously taking account of the uncertainty associated with the added complexity will undermine scientific credibility.

LESSON 3: **The choice of downscaling method should be guided principally by the ability of the approach to replicate influences on regional climate.**

Given the specific interest of decision-makers in regional climate changes, the experience in California suggests that promising scientific progress over the next few years will produce more relevant, higher-resolution climate information. The plethora of downscaling approaches, regional climate models, global models feeding them, and underlying emissions scenarios offers rich scientific opportunities and insights. For regional decision-makers, however, who are faced with the difficult choice among the many possible combinations of scenarios, models, and methods, this range of choices is daunting. As a general rule, which GCM should drive the regional model, should depend on how well the combination replicates historical climate, including the influence of extra-regional phenomena (such as PDO or ENSO) that influence regional climate. Validation, however, is crucial and should be done carefully for a range of climate variables, temporal climate variability, and with various validation metrics. If resources are available, using both dynamical and statistical downscaling methods is preferable to reliance on only one approach.

LESSON 4: Scientists can do far more to make their knowledge more useful to decision-makers.

Science–policy collaboration is a bridge-building effort across worldviews, institutional cultures, problem definitions, goals, notions of success, data, and models. Mutual effort and learning is required to bridge these differences effectively. Offering relevant information products that match the time horizons over which decisions are being made, and making them available in a timely manner; focusing on those impacts variables that decision-makers are concerned about and have control over; developing tighter bounds around projections or eliminating unlikely climate futures; explaining the nature and sources of uncertainty; identifying no-regrets strategies in the face of uncertainty; identifying critical institutional thresholds or the most climate-sensitive elements in a managed system; and post-hoc evaluations of the science–policy interaction are all examples of making scientific information more useful to decision-makers.

LESSON 5: More effective communication of uncertainty can be achieved through technical, strategic, and personal improvements.

Understanding and taking seriously the notion that communication of scientific information is a two-way street makes the interaction at once more personal and – with sufficient mutual teaching and learning – more effective and thus satisfying. As previously found, the communication of uncertainty will be made more effective by using simple terms, consistently applied. In addition, scientists can help people understand what type and how much evidence supports certain scientific conclusions, thus giving the audience a sense of the level of consensus and confidence in the scientific community. Sometimes it can also be helpful to discuss the underlying reasons for why something is currently unknown or ultimately unknowable.

Not all scientists will feel comfortable or qualified to handle this type of two-way communication and interaction with representatives from other disciplines, potential information users, stakeholders, or the broader public. Clearly, there is no need for everyone to be an expert at such communication. In those cases, it may be more important to embed scientists in teams where someone else is responsible for the bridge-building communication effort.

For whoever takes the role of such a "go-between," the key is to be mindful of the audience: who needs to know what, and at what level of detail. For many audiences, the finer nuances of scientific understanding are irrelevant to what they need or want to know, and, in fact, may distract from their understanding of the primary message. Not all uncertainties matter equally in terms of public understanding or even decision-making, however interesting they may be scientifically. Omitting detail when it is appropriate is for most scientists an acquired skill. In particular, scientists can improve their communication without violating appropriate caution or scientific credibility by leading with what is well established and supported in the scientific literature to put subsequent statements about intrinsic and irreducible uncertainty in perspective.

Most importantly, scientists/communicators must find creative ways to convey that which is beyond immediate grasp in ways that link with people's everyday experience, cultural knowledge, and language. For example, reasoning by analogy or explaining complex, unfamiliar concepts and processes through commonly understood metaphors will greatly increase the likelihood of being understood. Finally, the scientific community and/or their communicators must provide the tools and evidence that will allow and back up the risk-taking decision-makers, when the officials step forward to take political action.

LESSON 6: Better communication – while much needed – is not a sufficient condition for better decision-making under uncertainty.

The use of probabilities to represent uncertainties in climate change projections will help users make more informed decisions. Moreover, it is better for experts to make these subjective judgments than non-experts. At the same time, scientists have to recognize that scientific information – probabilistic or not – is only one ingredient, and sometimes not the most important one in the decision-making process. Better understanding of the decision process, constraints, institutional or other barriers, turf issues, and the political context and strategically working through and around these contextual factors may be as important as better scientific information itself to foster policy action on climate change. Particularly under conditions of deep uncertainty, decision-makers frequently try to find hedging strategies and options that minimize conflict, rather than more information. Thus, analysts will do better helping decision-makers identify robust adaptive strategies than producing ever more fine-tuned predictions.

LESSONS 7: The public and decision-makers are hungry for frank information.

It is important to recognize that the public does not expect deterministic predictions for the next 100 years. People know intuitively and readily accept that things won't stay the same, and that the future cannot be predicted with certainty. As workshop participants reiterated, much of the interested public would rather have an honest discussion than a perfect forecast.

Realistically, lack of certainty does not stop public or governmental action as long as there are people willing to take political risks and a broader (than at present) public to support it. To mobilize wider support, however, communication about climate change does not necessarily have to be more specific about uncertainties, but connect more directly with constituencies' interests (e.g., the economy, health, the environment, equity, security, and education).

Thus, it is critical to educate people about the causes, solutions, and complexities involved in climate change, and – equally vital – to link climate to what people care about. Too many scientists and communicators forget sometimes that climate is not front and center on lay people's daily agendas. Clearly linked to those more pressing daily concerns and appropriately presented, many would listen and like to learn. The need for education is huge and should be fulfilled in formal and informal settings, for young and old. The scientific community – broadly writ – could do even more by providing credible information for K-12 education.

> Much of the interested public would rather have an honest discussion than a perfect forecast.

LESSON 8: **Probability "über alles"? No! Non-probabilistic approaches remain important complements.**

Reducing uncertainty, specifying and quantifying it, and communicating it better to various audiences are worthy, even imperative, and certainly obtainable goals. Particularly advances on the uncertainties in the human driving forces underlying future emissions and in climate sensitivity are critically important. At the same time, non-probabilistic approaches, such as scenario analysis, will continue to be important and should not be neglected. Developing richer storylines should be a high priority.

And while a consistent "uncertainty language" marks desirable progress in scientific communications, more assistance is needed for decision-makers to interpret the implications of uncertain future events for their current decisions.

Better specification of uncertainty and ever-finer detail on climate change should not allow us to get lost in this complex problem. Practical detail at policy-relevant resolutions must be balanced with a clear message about the enormity of this long-term challenge. What is just as important as refining our understanding is a focus on creating options for the future: additional mitigation solutions, more effective adaptation strategies, and more people mobilized to take these next steps. Analysts can do their part in helping society get to the social tipping point that makes inaction on climate change publicly unacceptable. Science needs to create the analytical basis so that political actors have a solid foundation for action when policy windows open.

LESSON 9: **The scientific prospects are positive, but for our future to be so also, decisions will have to be made under great uncertainty for years to come.**

This workshop illustrated where scientific progress is most needed and possible. Clearly, the outlook is positive, the enormity of the challenge notwithstanding. However, breakthrough advances and widespread production and use of regional climate projections, are years to decades away. In the meantime, many decisions will have to be made whose impacts will be felt for decades to centuries, reaching into a future that will most certainly be different socially and climatologically than the present. Many of these decisions will be practically irreversible. Dams will stand over a person's lifetime; emissions released from coal-fired power plants will remain in the atmosphere for decades to centuries. To retain flexibility, enhance societal resilience, and avoid "dangerous anthropogenic interference in the climate system," many decisions will have to be made – now and in the coming years – where what is unknown and unknowable may change over time, but not necessarily become less problematic. In fact, climate change may create a world, in which uncertainty – maybe more so than ever before – is the most commonly experienced condition of human existence. This uncertainty, however, is not – and should not be construed as – a paralyzing impediment to actions that will reduce the likelihood of dangerous outcomes for humanity and the environment on which we depend.

BIBLIOGRAPHY

Adger, W.N., and K. Vincent (2005). Uncertainty in Adaptive Capacity. Comptes Rendus Geoscience 337: 399-410.

Allen, M. (1999). Do-it-yourself Climate Prediction. Nature 401: 642.

Andronova, N.G., M.E. Schlesinger, S. Dessai, M. Hulme, B. Li (forthcoming). The Concept of Climate Sensitivity: History and Development. In: Human-Induced Climate Change: An Interdisciplinary Assessment, M.E. Schlesinger et al. (eds.). Cambridge University Press, New York.

Andronova, N.G. and M.E. Schlesinger (2001). Objective Estimation of the Probability Density Function for Climate Sensitivity. Journal of Geophysical Research 106: 22605-22612.

Andronova, N.G. and M.E. Schlesinger (2000). Causes of Global Temperature Changes During the 19th and 20th Centuries. Geophysical Research Letters 27(14): 2137-2140.

Azar, C. and S.H. Schneider (2002) Are the Economic Costs of Stabilizing the Atmosphere Prohibitive? Ecological Economics 42: 73-80.

Bankes, Steve (1993). Exploratory Modeling for Policy Analysis. Operations Research 41(3): 435-449.

Berk, R. (1997). "Bayesian Approaches to Characterizing Uncertainty." In: Elements of Change 1996, Hassol, S.J. and J. Katzenberger (eds). Aspen Global Change Institute, Aspen, CO, pp. 136-139. Paper available at: http://www.agci.org

Berkhout, F. (2002). Technological regimes, path dependency and the environment. Global Environmental Change 12(1): 1-4.

Broecker, W. (1997). Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO_2 Upset the Current Balance? Science 278: 1582-1588.

Brooks, N., W. Neil Adger, and P. Mick Kelly (2005). The Determinants of Vulnerability and Adaptive Capacity at the National Level and the Implications for Adaptation. Global Environmental Change 15: 151-163.

Budnitz, R.J. et al. (1995). Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and the Use of Experts. Lawrence Livermore National Laboratory, UCRL-ID 122160.

Casman, E.A., M.G. Morgan and H. Dowlatabadi (1999). Mixed Levels of Uncertainty in Complex Policy Models. Risk Analysis 19(1): 33-42.

Castles, I., and D. Henderson (2003a). Economics, Emissions Scenarios and the Work of the IPCC. Energy & Environment 14(2-3): 415-435.

Castles I., and D. Henderson (2003b). The IPCC Emission Scenarios: An Economic-Statistical Critique. Energy & Environment 14(4): 159-185.

Curry, R., et al. (2003). A change in the freshwater balance of the Atlantic Ocean over the past four decades. Nature 426: 826-829.

Dessai, S. and M. Hulme (2003). Does Climate Policy Need Probabilities? Tyndall Centre for Climate Change Research, Working Paper #34. Tyndall Centre, University of East Anglia, Norwich, UK.

Dessai, S., et al. (2004). Defining and Experiencing Dangerous Climate Change: An Editorial Essay. Climatic Change 64: 11-25.

Dettinger, M. (2004). From Climate-Change Spaghetti to Climate-Change Distribution. Discussion Paper prepared for the CA Energy Commission/PIER, La Jolla, CA.

Dowlatabadi, H. and M.G. Morgan (1993). A Model Framework for Integrated Studies of the Climate Problem. Energy Policy 21(3): 209-221

Easterling, W.E. et al. (2001). Comparison of Agriculture Impacts of Climate Change Calculated from High and Low Resolution Climate Model Scenarios, Part II: The Effect of Adaptations. Climatic Change 51: 173-197.

Evans, J.S., J.D. Graham, G.M. Gray, and R.L. Sielken, Jr. (1994a). A distributional approach to characterizing low-dose cancer risk. Risk Analysis 14: 25-34.

Evans, J.S. et al. (1994b). Use of probabilistic judgment in uncertainty analysis of carcinogenic potency. Regulatory Toxicology and Pharmacology 20: 15-36.

Fischer, C and R.D. Morgenstern (2003). Carbon Abatement Costs: Why the Wide Range of Estimates. Resources for the Future Discussion Paper 03–42. RFF, Washington, DC.

Forest, C.E., et al. (2002). Quantifying Uncertainties in Climate System Properties With the Use of Recent Climate Observations. Science 295:113-117.

Funtowicz, S.O. and J.R. Ravetz (1990). Global Environmental Issues and Post-Normal Science. London: Council for Science and Society.

Giles, J. (2002). When Doubt is a Sure Thing. Nature 418: 470-478.

Glantz, M. (1996). Currents of Change: El Niño's Impact on Climate and Society. Cambridge University Press, Cambridge; New York.

Glantz, M. (2003). Climate Affairs: A Primer. Island Press, Washington, DC.

Goulder, L.H. and S.H. Schneider (1999). Induced technological change and the attractiveness of CO_2 abatement policies. Resource and Energy Economics 21:211-252.

Gritsevskyi, A. and N. Nakicenovic (2000). Modeling uncertainty of induced technological change. Energy Policy 28(13): 907-921.

Grubler, A. and N. Nakicenovic (2001). Identifying dangers in an uncertain climate. Nature 412: 15.

Haddad, B.M. (2005). Ranking the Adaptive Capacity of Nations to Climate Change When Socio-Political Goals Are Explicit. Global Environmental Change 15: 165-176.

Ha-Duong, M., E.A. Casman and M.G. Morgan (in press). Bounding poorly characterized risks: A lung cancer example. Risk Analysis.

Hanks, T.C. (1997). Imperfect science: Uncertainty, diversity, and experts. EOS 78(35): 369, 373, 377

Harvey, L.D. (1998). "Upscaling in global change research." In: Elements of Change 1997, Hassol, S.J. and J. Katzenberger (eds.). Aspen Global Change Institute, Aspen, CO, pp. 14-33. Paper available at: http://www.agci.org

Harvey, L.D. (2000). Upscaling in global change research. Climatic Change 44(3): 225-263.

Hawellek, J., Kemfert, C. and Kremers, H. (2004). A Quantitative Comparison of Economic Cost Assessments Implementing the Kyoto Protocol. Carl von Ossietzky Universität: Oldenburg, Germany. Paper first presented at the EAERE XIII Annual Conference, Budapest.

Hoeting, J.A., Madigan, D., Raftery, A.E., and Volinsky, C.T. (1999). Bayesian model averaging: a tutorial. Statistical Science 14(2): 382–417.

Holtsmark, B. J., and K. H. Alfsen (2004). PPP-correction of the IPCC emission scenarios - does it matter?

IPCC (2005). Guidance Notes for Lead Authors of the IPCC Fourth Assessment Report on Addressing Uncertainties. IPCC, Geneva.

IPCC (2001a). Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report. Cambridge University Press, Cambridge, UK.

IPCC (2001b). Climate Change 2001: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Third Assessment Report. Cambridge University Press, Cambridge, UK.

Lempert, R.J., N. Nakicenovic, D. Sarewitz and M. Schlesinger (2004). Characterizing Climate-Change Uncertainties for Decision-makers. Climatic Change 65: 1-9.

Lempert, R.J., Popper, S.W. and S.C. Bankes (2003). Shaping the Next One Hundred Years: New Methods for Quantitative Long-Term Policy Analysis. RAND, Santa Monica, CA.

Lempert, R. J. and M.E. Schlesinger (2000). Robust Strategies for Abating Climate Change. Climatic Change 45(3-4): 387-401.

Liverman, D.M. and K. O'Brien (1991). The impacts of global warming on Mexico. Global Environmental Change 2: 351-364.

March, J., L. Sproull, and M. Tamuz (1991). Learning from Samples of One or Fewer. Organizational Science 2(1): 1-13.

Mastrandrea, M.D. and S.H. Schneider (2004). Probablistic integrated assessment of dangerous climate change. Science 304: 571-575.

BIBLIOGRAPHY

McKibbin, W. J., D. Pearce, and A. Stegman (2004). Can the IPCC SRES be Improved? Lowy Institute Working Paper. Lowy Institute for International Policy & Center for Macroeconomic Analysis, Australian National University, Canberra, AU.

McLachlan, G. and Peel, D. (2000). Finite Mixture Models. Wiley Series in Probability and Statistics. John Wiley & Sons, New Cork.

Mesarovic, M., and Pestel, E. (1974). Mankind at the Turning Point. E. P. Dutton, New York.

Morgan, M.G., et al. (1978a). A probabilistic methodology for estimating air pollution health effects from coal-fired power plants. Energy Systems and Policy 2: 287-310.

Morgan, M.G., et al. (1978b). Sulfur control in coal-fired power plants: A probabilistic approach to policy analysis. Journal of the Air Pollution Control Association 28: 993-997.

Morgan, M.G., et al. (1984). Technical uncertainty in quantitative policy analysis: A sulfur air pollution example. Risk Analysis 4: 201-216.

Morgan, M.G., et al. (1985). Uncertainty in environmental risk assessment: A case study involving sulfur transport and health effects. Environmental Science and Technology 19: 662-667.

Morgan, M.G. and D. Keith (1995). Subjective judgments by climate experts. Environmental Science and Technology 29(10): 468-476.

Morgan, M.G. and H. Dowlatabadi (1996). Learning from integrated assessment of climate change. Climatic Change 34(3-4): 337-68.

Morgan, M.G. (2001). The neglected art of bounding analysis. Environmental Science and Technology 35: 162A-164A.

Morgan, M.G., L.F. Pitelka and E. Shevliakova (2001) Elicitation of expert judgments of climate change impacts on forest ecosystems. Climatic Change 49: 279-307.

Moss, R.H. and S.H. Schneider (1997). Characterizing and communicating scientific uncertainty: Moving ahead from the IPCC Second Assessment. In: Elements of Change 1996, Hassol S.J. and J. Katzenberger (eds.). Aspen Global Change Institute, Aspen, CO, pp.90-135.

Moss, R.H. and S.H. Schneider (2000). Uncertainties in the IPCC TAR: Recommendations to Lead Authors for More Consistent Assessment and Reporting. In: Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC, Pachauri R., T. Taniguchi, and K. Tanaka (eds.). World Meteorological Organization, Geneva, Switzerland, pp.33-51.

Moss, R.H., A.L. Brenkert, and E.L. Malone (2001). Vulnerability to Climate Change: A Quantitative Approach. Report prepared for the U.S. Department of Energy, PNNL-SA-33642, Pacific Northwest National Laboratory.

Moss, R.H., B. Lim, E.L. Malone, and A.L. Brenkert (2002). Developing Socio-Economic Scenarios for Use in Vulnerability and Adaptation Assessments. United Nations Development Programme, NY.

Murphy, J., et al. (2004). Quantification of modelling uncertainties in a large ensemble of climate change simulations. Nature 430: 768-772.

Nakicenovic, N., et al. (2000). Special Report on Emissions Scenarios. Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Nakicenovic, N., et al. (2003). IPCC SRES Revisited: A Response. Energy & Environment 14 (2-3): 187-214.

National Assessment Synthesis Team (2001). Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change. Foundation. Report for the U.S. Global Change Research Program, Cambridge University Press, Cambridge UK.

National Research Council (2002). Abrupt Climate Change: Inevitable Surprises. Committee on Abrupt Climate Change, Ocean Studies Board, Polar Research Board, Board on Atmospheric Sciences and Climate. National Academy Press: Washington, D.C.

Nordhaus, W.D. (1994). Expert opinion on climatic change. American Scientist 82: 45-51.

Parmesan, C. and G. Yohe (2003). A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37-42.

Parson, E.A. (1996). Three dilemmas in the integrated assessment of climate change: An editorial comment. Climatic Change 34: 315-326.

Pielke Sr. et al. (2002). The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases. Phil. Trans. R. Soc. London A 360: 1705-1719.

Prinn, R. et al. (1999). Integrated Global System Model for Climate Policy Assessment: Feedbacks and Sensitivity Studies. Climatic Change 41(3/4): 469-546.

Raftery, A.E., Madigan, D., and Hoeting, J.A. (1997). Bayesian model averaging for linear regression models. Journal of the American Statistical Association 92 (March): 179–191.

Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. Nature 419: 207-214.

Rahmstorf, S. (1999). Rapid Transitions of the Thermohaline Ocean Circulation - A Modelling Perspective. In: Reconstructing Ocean History: A Window Into the Future, F. Abrantes and A.C. Mix (eds.). Dordrecht (The Netherlands): Kluwer Academic/ Plenum Publishers, pp. 139-149.

Rao, A.B., E.S. Rubin and M.G. Morgan (2003). Evaluation of Potential Cost Reductions from Improved CO_2 Capture Systems. Proceedings of the 2nd National Conference on Carbon Sequestration, Alexandria, VA, May 5-8, 2003.

Repetto, R. and D. Austin (1997). The Costs of Climate Protection: A Guide for the Perplexed. World Resources Institute, Washington, DC.

Root, T.L., D.P MacMynowski, M.R. Mastrandrea, and S.H. Schneider (2005). Human-modified temperatures induce species changes: Joint attribution. Proceedings of the National Academies of Science 102: 7465-7469.

Root, T.L., et al. (2003). Fingerprints of global warming on wild animals and plants. Nature 421: 5760.

Root, T.L. and S.H. Schneider (2003). Strategic cyclical scaling: Bridging five orders of magnitude scale gaps in climatic and ecological studies. In: Scaling Issues in Integrated Assessment, Rotmans J. and D.S. Rothman (eds.). Swets and Zeitlinger Publ., Lisse, The Netherlands, pp. 179-204.

Rothman, D.S. and J.B. Robinson (1997). Growing pains: A conceptual framework for considering integrated assessments. Environmental Monitoring and Assessment 46: 23-43.

Schlenker and M. Hanemann (2005). Will U.S. Agriculture Really Benefit from Global Warming? Accounting for Irrigation in the Hedonic Approach. American Economic Review 95 (1): 395-406.

Schlesinger, M.E. and N.G. Andronova (2005). Climate sensitivity: Uncertainty and learning. Proceedings of the World Climate Conference, Moscow, September 29 - October 3, 2003, in press.

Schneider, S.H. (1997). Integrated assessment modeling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions? Environmental Modeling and Assessment 2(4): 229-248.

Schneider, S.H. (2002). Can we estimate the likelihood of climatic changes at 2100? Climatic Change 52(4): 441-451.

Schneider, S.H. (2004). Climate Impacts: Climate Surprises and a Wavering Gulf Stream? Available at: http://stephenschneider.stanford.edu/Climate/Climate_Impacts/CliImpFrameset.html

Schneider, S.H., and B.L. Turner (1995). "Anticipating Global Change Surprise." In: Elements of Change 1994, Hassol, S.J. and J. Katzenberger (eds.). Aspen Global Change Institute, Aspen, CO, pp. 130-145. www.agci.org

Schneider, S.H., B.L. Turner, and H. Morehouse-Garriga (1998). Imaginable surprise in global change science. Journal of Risk Research 1(2): 165-185.

Schneider, S.H., W.E. Easterling, and L. Mearns (2000). Adaptation: Sensitivity to natural variability, agent assumptions and dynamic climate changes. Climatic Change 45(1): 203-221.

Schneider, S.H. (2005a) with J. Lane. The Patient From Hell: Getting the Best That Modern Medicine Can Offer. Da Capo Lifelong Books, Cambridge, MA.

Schneider, S.H. and J Lane (2005b). Dangers and Thresholds in Climate Change and the Implications for Justice. MIT Press, in press.

BIBLIOGRAPHY

Stainforth, D.A. et al. (2005). Uncertainty in predictions of the climate response to rising levels of greenhouse gases. Nature 433: 403-406.

Stocker T.F. and O. Marchal (2000). Abrupt climate change in the computer: Is it real? Proceedings of the National Academy of Sciences 97: 1362-1365.

UK Climate Impacts Programme (2001). Socio-Economic Scenarios for Climate Change Impact Assessments: A Guide to Their Use in the UK Climate Impacts Programme. UKCIP, Oxford.

UNFCCC (1992) New York, Article 2.

Wallsten, T.S., D.V. Budescu, A. Rapoport, R. Zwick, and B. Forsyth. (1986). Measuring the vague meanings of probability terms. Journal of Experimental Psychology,General 115(4):348-365.

Warrilow, David (2004). "The UK's Approach to Climate Change." Presentation at AAAS Meeting, Seattle, WA, February 13.

Webster, M. et al. (2003). Uncertainty analysis of climate change and policy response. Climatic Change 61(3): 295-320.

Weyant, J.P. and J.N. Hill (1999). Introduction and overview. In: The Costs of the Kyoto Protocol: A Multi-Model Evaluation, Special Issue of The Energy Journal, John Weyant (ed.).

Wigley, T.M.L. (2004). Input Needs for Downscaling of Climate Data. Discussion Paper prepared for the CA Energy Commission/PIER, Louisville, CO. Paper available at: http://www.agci.org/

Wigley, T.M.L. and S.C.B. Raper (2001). Interpretation of high projections for global-mean warming. Science 293: 451-454.

Yin, J. et al. (2005). Is a shutdown of the thermohaline circulation irreversible? J. Geophys. Res. (submitted).

Yohe, G., and R. Tol (2002). Indicators for Social and Economic Coping Capacity—Moving Toward a Working Definition of Adaptive Capacity. Global Environmental Change 12: 25-40.

APPENDIX A: MEETING AGENDA

Aspen Global Change Institute
Climate Scenarios and Projections: The Known, the Unknown, and the Unknowable as Applied to California
11-14 March 2004
Co-chairs: Stephen Schneider and Richard Moss
Convenor: John Katzenberger

AGENDA

Note: PDFs of presentations and DVDs of many of the talks are available through AGCI's website.
See http://www.agci.org.

Thursday 11 March

Opening Reception

Friday 12 March

8:30am	John Katzenberger: Welcome & opening remarks
8:40am	Steve Schneider and Richard Moss: Introduction and meeting overview
Theme I: Decision Context and Uncertainty	
9:10am	Granger Morgan: Known, unknown, and unknowable in decision-making
9:40am	Roger Pulwarty: Nexus of resource management and science: Re-visiting adaptive management and decision-making environments
10:00am	Discussion
10:35am	Guido Franco: Key California Issues in a changing climate from a CA perspective
10:55am	Tony Janetos: Evaluating and communicating the known and speculative: the case of the U.S. National Assessment
11:15am	Francis Chung: What do water resource mangers need to know to manage well?
11:35am	James Boyd: If downscaling were solved, how would California managers and policy-makers respond?
11:55am	Discussion: Focusing on needs, approaches that have been used.
Theme II: Socio-Economic Futures and Their Uncertainties	
1:15pm	Naki Nakicenovic: Path-dependencies, emerging properties and treatment of uncertainties in emissions scenarios
1:35pm	Richard Richels: Probabilistic treatment of elements of emissions scenarios (or integrated assessment?)
1:55pm	Discussion
2:20pm	Alan Sanstad: Assumptions and parameterizations in energy-economic models
2:40pm	Art Rosenfeld: An Apollo-scale Energy Efficiency Scenario, with no Hydrogen Distraction
3:00pm	Discussion
3:35pm	David Keith: Future uncertain: Big tent vs. winner takes most
3:55pm	Hugh Pitcher: Crafting scenarios as if integrated assessment mattered-key issues
4:15pm	Discussion
4:45pm	Session adjourns

Saturday 13 March

Theme III: Characterizing Climate Futures and Their Uncertainties

8:00am	Michael Schlesinger and Natasha Andronova: Climate sensitivity: uncertainties and learning
8:20am	Tom Wigley: Downscaling GCMs to produce meteorological variables at regional scales
8:40am	Discussion
9:10am	Dan Cayan: Improving confidence in the California regional modeling efforts and assessment strategies
9:30am	Michael Dettinger: From climate-change spaghetti to climate-change distributions
9:50am	Phil Duffy: Model inter-comparisons/validation at all scales
10:10am	Discussion

Theme IV: Uncertainties in Assessing Consequences

10:55am	Michael Hanemann: Uncertainties in Economic Costs of Climate Change
11:15am	Terry Root: Surprise from the biosphere?
11:35am	Discussion
1:15pm	Richard Moss: Scenarios of Adaptive Capacity
1:55pm	Discussion

Theme V: Integrated Treatment of Uncertainty

2:15pm	Mort Webster: Coupling models across disciplines
2:35pm	Rob Lempert: Robust strategies--creating conversation between modelers and managers
2:55pm	Discussion
3:30pm	John Weyant: Expert opinion for fun or profit
3:50pm	Steve Schneider: Uncertainty framework for dangerous climate change
4:10pm	Discussion
4:30pm	Session adjourns

Sunday 14 March

Theme VI: Communicating Across the Science/Policy Divide

8:30am	Ed Miles: Politics of science policy: whos listening?
8:50am	Paco Delachesnaye: The importance of comprehensive analyses for policy-makers
9:10am	Discussion
9:30am	Synthesis roundtable: Where do we go from here? Granger Morgan, Tom Wigley, Terry Surles, and Peter Frumhoff Improving best practice: evaluating uncertainty; constructing scenarios; meeting user needs; setting research agendas; communication
10:45am	Susanne Moser and Annie Bissett: Key themes and final products
11:15am	Steve Schneider and Richard Moss: Concluding remarks
11:45am	Meeting adjourns

APPENDIX B: PARTICIPANT ROSTER

Aspen Global Change Institute
"Climate Scenarios and Projections: The Known, the Unknown, and the Unknowable as Applied to California"
11-14 March 2004
Co-chairs: Stephen H. Schneider and Richard Moss
Convenor: John Katzenberger

Natalia Andronova
Department of Atmospheric Sciences
University of Illinois at Urbana-Champaign
105 S. Gregory Ave.
Urbana, IL 61801

Annie Bissett
Freelance Graphic Illustrator
156 Crescent St.
Northampton, MA 01060

James D. Boyd
Commissioner
California Energy Commission
1516 Ninth Street, MS-34
Sacramento, CA 95814

Dan Cayan
Climate Research Division
Scripps Institution of Oceanography-UCSD
9500 Gilman Drive
La Jolla, CA 92093

Francis Chung
California Dept. of Water Resources
Bay-Delta Office Modeling Support Branch
P.O. Box 942836
Sacramento, CA 94236

Paco Delachesnaye
U.S. Environmental Protection Agency
Office of Atmospheric Programs
1200 Pennsylvania Ave., NW
Washington DC 20460

Michael Dettinger
U.S. Geological Survey and
Climate Research Division/
Scripps Institution of Oceanography
UC San Diego, 9500 Gilman Drive
La Jolla, CA 92093-0224 USA

Phillip Duffy
Lawrence Livermore National Laboratory
Deputy Division Leader, Atmospheric Science Division
7000 East Ave. L-103
PO Box 808
Livermore, CA 94551

Guido Franco
California Energy Commission
Project Manager
1516 Ninth Street, MS-29
Sacramento, CA 95814-5512

Peter Frumhoff
Senior Scientist and Director
Global Environment Program
Union of Concerned Scientists (UCS)
Two Brattle Square
Cambridge, MA 02238

Michael Hanemann
Chancellors Professor
Public Policy/ Agricultural & Resource
Economics
UC Berkeley
207 Giannini Hall
Berkeley, CA 94720-3310

Anthony Janetos
Vice President
The H. John Heinz III Center for Science,
Economics and the Environment
1001 Pennsylvania Ave., NW
Suite 735 South
Washington, DC 20004

David Keith
Dept. of Engineering and Public Policy
Carnegie Mellon University
129 Baker Hall
Pittsburgh, PA 15213-3890

Rob Lempert
Senior Physical Scientist
RAND Science and Technology
1700 Main St.
PO Box 2138
Santa Monica, CA 90407-2138

Ed Miles
Bloedel Professor of Marine Studies and
Public Affairs
School of Marine Affairs
University of Washington
Box 355685
Seattle, WA 98105

Granger Morgan
Head of Dept. Engineering and Public Policy
Carnegie Mellon University
Baker Hall 129
Frew St.
Pittsburgh, PA 15213-3890

Susanne Moser
Research Scientist
Institute for the Study of Society and Environment (ISSE)
National Center for Atmospheric Research (NCAR)
PO Box 3000
Boulder, CO 80301

Richard Moss (Co-Chair)
Director of the Office
U.S. Climate Change Science Program Office
1717 Pennsylvania Ave NW Suite 250
Washington, DC 20006

Nebojsa (Naki) Nakicenovic
Professor of Energy Economics, Vienna
University of Technology
Transitions to New Technologies Project,
International Institute for Applied Systems Analysis
A-2361 Laxenburg, Austria

Hugh Pitcher
Staff Scientist
Joint Global Change Research Institute
Pacific Northwest National Laboraory
8400 Baltimore Avenue, Suite 201
College Park, MD 20740-2496

Roger Pulwarty
NOAA/ CIRES/ CDC
University of Colorado
325 Broadway R/ CDC 1
Boulder, CO 80305

Rich Richels
EPRI
3412 Hillview Ave.
Palo Alto, CA 94304

Terry Root
Senior Fellow
Center for Environmental Science and Policy
Stanford Inst. for International Studies
Stanford University
Stanford, CA 94305

Arthur Rosenfeld
California Energy Commission
1516 Ninth Street, MS-35
Sacramento, CA 95814

Alan H. Sanstad
Staff Scientist
Environmental Energy Technologies
Lawrence Berkeley National Laboratory
90-4000,#1 Cyclotron Rd.
Berkeley, CA, USA 94720

Michael Schlesinger
Professor of Atmospheric Sciences Department of Atmospheric Sciences
University of Illinois @ Urbana-Champaign
105 S. Gregory St. Urbana, IL 61801

Stephen Schneider (Co-Chair)
Professor, Dept. of Biological Sciences
Stanford University
371 Serra Mall
Stanford, CA 94305-5020

Terry Surles
Public Interest Energy Research (PIER)
Program Director
California Energy Commission
1516 Ninth Street, MS-51
Sacramento, CA 95814-5512

Mort Webster
217 Abernethy Hall, CB# 3435
Department of Public Policy
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599-3435

John Weyant
Professor
Dept. of Management Science and Engineering
Stanford University
Stanford, CA 94305-4026

Tom Wigley
National Center for Atmospheric Research
(NCAR)
PO Box 3000
Boulder, CO 80307-3000

Convener:
John Katzenberger
AGCI Director
100 East Francis St.
Aspen, CO 81611

Conference Coordinator:
Sue Bookhout
AGCI
100 East Francis St.
Aspen, CO 81611








AGCI
100 East Francis Street
Aspen CO 81611
http://www.agci.org
970 925 7376
agcimail@agci.org

ISBN 0-9741467-2-2

ISBN 0-9741467-2-2
9 780974 146720

THIS PUBLICATION IS PART OF THE
ASPEN GLOBAL CHANGE INSTITUTE'S ELEMENTS OF CHANGE SERIES