WMO INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE UNEP

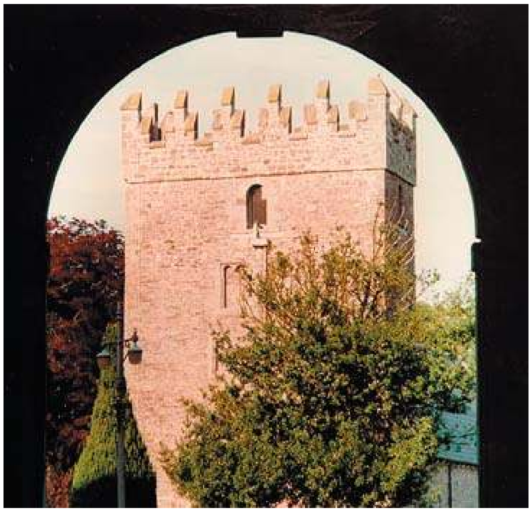
IPCC Workshop on

Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options

National University of Ireland, Maynooth,
Co. Kildare, Ireland
11–13 May, 2004

Workshop Report

Edited by
Martin Manning, Michel Petit, David Easterling, James Murphy,
Anand Patwardhan, Hans-Holger Rogner, Rob Swart, Gary Yohe



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Supporting material prepared for consideration by the Intergovernmental Panel on Climate Change. This material has not been subjected to formal IPCC review processes.

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IPCC Workshop on

Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options

11–13 May, 2004, National University of Ireland, Maynooth, Co. Kildare, Ireland

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Executive summary

This IPCC workshop was convened in order to consider past experience and new developments in the determination and communication of uncertainties in order to make that knowledge available to Lead Authors of the AR4 in useful form. It was attended by experts from all areas of climate change as well as users of climate change information and researchers in assessment and communication methods.

Results of plenary and breakout discussions are presented in sections 3 and 4 of this report. The main results emerging from these are as follows

General

There was strong support for consistency in describing uncertainty across all parts of the AR4. This requires that specific words used to describe levels of uncertainty or of confidence in understanding should have the same agreed meanings throughout. Such an approach will also reduce linguistic imprecision and facilitate accurate translation into other languages. At the same time, agreed methods of expressing uncertainty should be sufficiently flexible to allow all disciplines to use them.

It was agreed that brief guidance notes should be prepared for incoming Lead Authors of the AR4 that would summarize key material from Moss and Schneider (2000) together with results from this workshop. A draft version of such notes will be prepared by the organizers of the workshop and then subjected to wide review before the first Lead Authors meetings.

There was general support for the use of targeted expert reviewers, operating within the standard IPCC review process, to provide comments to the author teams on how issues of uncertainty were being treated and the degree of consistency in approach and language across different parts of the report. These expert reviewers could consider several chapters dealing with similar material, or could review chapters across more than one Working Group for consistency in approach and language. They would be selected by the Working Group Bureaux, taking advice from experts in communication and uncertainty.

The relationship between uncertainty and risk presented in the concept paper for the Uncertainty and Risk theme was recognized as helpful in communicating uncertainty. The increasing use of probability distribution functions in the literature allows a more focused approach to considering a range of possible outcomes rather than a single most likely one, e.g. through estimated probabilities of exceeding critical thresholds. This approach also links to risk management and associated decision making processes in the insurance industry and in other areas of environmental management. However, it should be noted that the tails of estimated distribution functions are sensitive to assumptions made and approaches used and so require careful description taking into account their relevance to decision making.

Because estimating and communicating uncertainty raise complex issues, some of which are fairly generic across disciplines, it was felt that consideration should be given to preparing an "uncertainty primer" for readers of the AR4. However, there may be procedural difficulties in preparing a cross-WG primer as a formal part of the assessment report. An alternative approach would be to use boxes in different parts of the report to cover issues of uncertainty in relation to specific results. The latter option could tie the elaboration of uncertainty methods to matters of direct interest to the reader.

Across all areas of climate change it is found that uncertainty tends to increase going from global to regional scales. Regional information is clearly highly relevant to policy, but is generally much less precise and can be ambiguous and confusing, thus a careful balance is needed when considering the scale at which policy relevant information can be provided.

Assessing and communicating uncertainty

Any assessment of uncertainties and confidence in climate change must begin by identifying and explaining the determinants of uncertainty including underlying assumptions together with any conceptual or structural limits in the methods used, as well as the sources of uncertainties that can be treated specifically by those methods. There are many different classifications or typologies for sources of uncertainty and while the appropriate choice may vary from one discipline to another such typologies should be used to develop a comprehensive view of all plausible sources of uncertainty.

Two broad classes of uncertainty are "statistical" uncertainty associated with parameter or observational values that are not known precisely, and "structural" uncertainty where important relationships between variables or their functional form may not have been identified correctly. Assessing structural uncertainty is generally more difficult and can normally only be done to a limited extent through comparison of models with observations or with one another. In general there has been a demonstrable tendency for structural uncertainty to be overlooked by expert groups.

There are important differences between descriptions of uncertainty in terms of "likelihood" or in terms of "level of understanding" of the science. Likelihood, defined as the chance of a defined occurrence or outcome, can be a valuable construct where results are available from formal probabilistic analyses or can be expressed in a probabilistic way and such language is familiar to those working with risk analysis using probability distribution functions. "Level of confidence" refers to the degree of belief or confidence in a science community that available models or analyses are accurate and will generally be determined by a combination of the amount of evidence or information available and the degree of consensus in the interpretation of that information. Both ways of describing uncertainty are needed but they should be used in different circumstances and not confused.

Cognitive biases such as anchoring, where judgment is overly influenced by a starting point, and a tendency for over-confidence among expert groups are well established but their effect can be reduced through careful design of expert elicitation techniques.

Although use of probability distribution functions is increasing in the expert communities it is not clear to what extent this way of presenting uncertainties would be broadly understood by all readers of the AR4. Presentation of standard graphical PDFs might be more appropriate for the underlying chapters in the AR4 while some less technical presentation style, e.g. using color shading, might be more appropriate for the SPM. It was agreed that PDFs should only be shown where there was high level of confidence in the underlying science.

Specific issues in considering uncertainty in climate change

One of the key uncertainties for projections of climate change is that in climate sensitivity. The same range (1.5 to 4.5°C) for the equilibrium warming caused by a doubling of CO_2 has been quoted in all assessments since the Charney report (National Academy of Sciences, 1979). However, new studies are now producing PDFs for this quantity using combinations of observational constraints and ensembles of model runs. This raises the prospect of a more probabilistic treatment of climate sensitivity emerging from the WG1-AR4.

Large differences between models simulating the effects of climate change indicate the existence of significant structural uncertainties in this area. Although some projects are carrying out model intercomparisons, and most crop yield studies use more than one crop response model, there appears to be a need for more widely and better coordinated model intercomparisons in order to obtain better estimates of these uncertainties. For natural (i.e. unmanaged) ecosystems studies seldom use more than a single response model so that knowledge of structural uncertainties is more limited.

At a system level, approaches to uncertainty in the effects of climate change include considering thresholds, such as points at which impacts become non-linear or where adaptive capacity might be exceeded. Alternatively consideration can be given to discontinuities in the trajectories of prices or impacted populations.

The knowledge base for assessing uncertainty in socio-economic factors remains limited but there are still options for stimulating additional research work on probabilities of socio-economic scenarios to assist the AR4.

Grafting of adaptation scenarios onto the SRES scenarios should be considered. Options would include: use of the natural hazards & disasters literature, especially emergency responses; learning from early adopters to disasters and champions of new options; and the future based scenario planning & development literature that links global science to local decision making.

Probability distributions should be considered for the drivers of emissions and the determinants of mitigative and adaptive capacity. There are functional relationships and interdependencies between these underlying factors which are important, affect considerations of uncertainty, and need to be accounted for in the AR4.

The authors of the WG3-AR4 face several challenges in trying to apply the same approach as WG1 and WG2 authors to describing uncertainty. For example, economists and social scientists do not usually treat uncertainty in terms of probabilistic scales used in the natural sciences. Similarly there is very little literature to support estimates of uncertainty in areas such as costs of policies and measures, mitigation potentials and estimates of future emissions or drivers. Uncertainties in these factors are mostly determined by the boundaries of the methods used (what is and what is not included), and definitions of the variables, in addition to structural uncertainties related to socio-economic processes and variability of parameters. Rather than using likelihood or confidence terminology, this kind of uncertainty can be addressed by evaluating and describing the definitions of the variables and limitations of the methodologies applied.

1 Introduction

1.1 Genesis of the workshop and issues covered

The purpose of this workshop was to develop the cross-cutting theme of Uncertainty and Risk being considered for the IPCC Fourth Assessment Report (AR4). Initial ideas for this theme were covered in a concept paper that was prepared and reviewed by the IPCC in 2003. The concept paper included a proposal to hold a workshop as a means of summarizing experience from the IPCC Third Assessment Report (TAR) and considering relevant new developments.

The specific aims of the workshop were to:

- consider examples of how information on uncertainties is taken into account by users of IPCC assessments;
- review new developments in techniques for characterizing and describing uncertainties with particular reference to their utility in risk analyses;
- consider the extent to which different techniques for dealing with uncertainty in different disciplines can be harmonized so as to maximize consistency and comparability throughout the AR4; and
- review the treatment of uncertainty in the IPCC Third Assessment Report with a view to improving on that for the AR4.

The seminal work that underlies any consideration of uncertainties in climate change science is the guidance paper prepared by Moss and Schneider (2000) for authors of the TAR. The workshop considered carefully how the recommendations of that paper were used and what might be learned in light of that. For example, there was some divergence in the definition and use of standard terms to describe uncertainty between Working Groups I and II which appeared to arise from underlying differences in the traditional approaches used by different expert communities and expressed in their corresponding literature. The workshop considered how to take the best features of each approach into the AR4.

The concept paper for the Uncertainty and Risk theme posed as a general coordinating principle, that consideration be given to how users might use uncertainties in analyzing risks. Risk can be defined in several ways but is broadly defined as a combination of the likelihood of an outcome or event and some quantitative measure of the consequences of that outcome or event. Many analyses of risk consider a simple product of probability and consequence and in that sense are used broadly in decision making for environmental and other issues. Considering climate change in this context enables users of the IPCC assessments to more easily relate effects of climate change to other risks, and to integrate decision on climate change with existing decision making frameworks for dealing with risks.

Recognition of the importance of uncertainties for risk analysis can also improve communication by more clearly distinguishing between uncertainty in whether, or how frequently, certain events or outcomes might occur and uncertainty in their consequences. Risk analysis also provides a framework in which a range of outcomes can be considered with different probabilities and consequences. This perspective shows that when faced with uncertainty it is not sufficient to identify only a most likely outcome to the exclusion of other perhaps less likely but more consequential outcomes. Figure 1-1 shows a schematic view of the relationship between probability of outcomes, consequence, and risk.

Experience with the TAR showed that choice of language is critical in describing uncertainties in ways that will be properly understood. While authors of the AR4 are likely to be aware of the literature that covers determining uncertainties in their fields, they may not be so well aware of studies of communication, interpretation of language, and cognitive biases in how people approach uncertainty. Thus an important contribution of this workshop was to consider options for communicating, including language and graphical presentation techniques.

The different approaches taken in the TAR by WGs I and II highlights some implications of choice of language. The WG I use of *likelihood* as a basis for approaching uncertainty focuses on probability of outcomes, and was clearly intended to be interpreted that way despite the definition in the WG I Summary for Policymakers referring to “judgmental estimates of confidence”. The WG II use of *level of confidence* focused on degree of understanding and consensus, but at times was used as a proxy for the probability of an outcome. In retrospect both likelihood and level of confidence may need to be addressed and the language used should not confuse the two.

An emerging feature of all aspects of climate change science is the growing use of probability distribution functions (PDFs) which can provide detailed quantitative descriptions of uncertainties. However, this raises issues in using PDFs to communicate both between different areas of science and externally to the different audiences of the assessment report. This is considered further throughout this report.

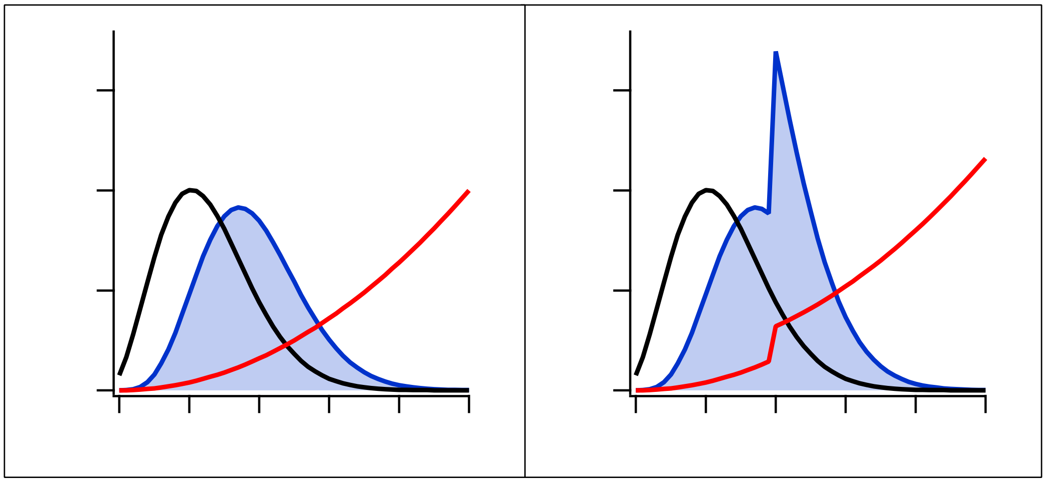

Figure 1-1. Schematic of probability, consequence and risk. In the left hand panel the horizontal axis denotes a magnitude of change in arbitrary units, the black curve represents a probability distribution for change, the red curve a magnitude of consequences associated with change, and the blue curve shows risk as the product of those. To consider the full spectrum of outcomes the total risk can be taken as the integrated area under the blue curve. The right hand panel shows the same constructs for the case where there is a threshold in consequence and shows that the probability of exceeding the threshold contributes significantly to the total risk.

1.2 Organization of the workshop

The IPCC Workshop on Uncertainty and Risk was hosted by the Irish Environmental Protection Agency and the Geography Department of the National University of Ireland, Maynooth campus, over three days from May 11 to 13, 2004. The workshop was attended by 79 experts representing all areas of climate change science, some user communities, and those working broadly on communication and assessment of uncertainties.

The workshop was opened by Dr Seamus Smyth on behalf of the University and addressed by Dr Mary Kelly, Director General of the Irish EPA. Dr Susan Solomon, co-chair of IPCC WG I, thanked the host organizations and presented an IPCC perspective on the issues to be covered.

The workshop was organized with plenary sessions alternating with breakout sessions. The initial plenary session provided several different perspectives on how the use of uncertainty has evolved in IPCC assessments and how uncertainty affects decisions beyond the science community. This was followed by four thematic breakouts covering:

- Determining and describing uncertainty in socio-economic factors.
- Determining and describing uncertainty in observed climate change and its effects.
- Effective communication of uncertainty.
- Determining and describing uncertainties in projections of climate change and its effects.

Each of these was introduced in plenary beforehand and their presentations and discussions were summarized in plenary subsequently. On the final day separate breakouts considered aspects of uncertainty specific to each of the three IPCC Working Groups and these were then summarized in plenary.

Further details of the workshop, including electronic copies of this workshop report, are available from the IPCC WG I web site at http://ipcc-wg1.ucar.edu/meeting/URW/.

2 Using Information in an Uncertain World

Five different perspectives were presented on the evolution and use of uncertainties in climate change. Some of the key points made by the different speakers are summarized below. These do not necessarily represent a consensus view of the workshop participants or of the breakout sessions which are summarized in the following sections.

2.1 Evolution in the communication and use of scientific uncertainties – G. McBean

Describing uncertainty honestly is an important part of communicating science in a balanced way and is essential to maintaining trust between scientists and the broader community. This has been recognized in previous IPCC assessments, particularly in the approach to formulating the Summaries for Policymakers and the Synthesis Report.

However, it is also important that experts understand the uncertainties that matter to people and the impact these may have on social and political decision making. One of the challenges in achieving this comes from the fact that scientists tend to think differently to the general public, particularly in their own areas of expertise.

There are a number of different approaches to assessing risk, from formal and quantitative to largely personal responses based on experience and perceptions. All these deal with uncertainty in one way or another and the qualitative and contextual aspects are always important. For example, asymmetry is often recognized in the sense that being wrong in one direction may have more serious consequences than being wrong in the other.

The need to develop a more formal approach to defining uncertainties in IPCC assessments, particularly in key parameters such as climate sensitivity was specifically noted in the IPCC's Second Assessment Report (chapter 11). The subsequent development of the TAR Guidance paper was a reflection of the need to place estimates of uncertainty on a more formal basis, and more still needs to be done.

2.2 Helping UK decision-makers deal with climate risks and uncertainties: The UKCIP approach – R. Connell

The UK has developed an extensive program for advising local decision makers on climate change impacts and this requires presentation of material from IPCC assessments and UK climate research to the broader community. Based on experience some standardized features have been built into the way that the science is presented. For example, results in the future are shown for specific time periods and for 4 scenarios.

Figure 2-1 provides a broad classification of areas of risk management and a structure for identifying those where climate change may be more or less relevant. Treating management of climate risks within a broader context of existing decision making frameworks means that these are brought into a mainstream of existing processes and structures for risk management. The

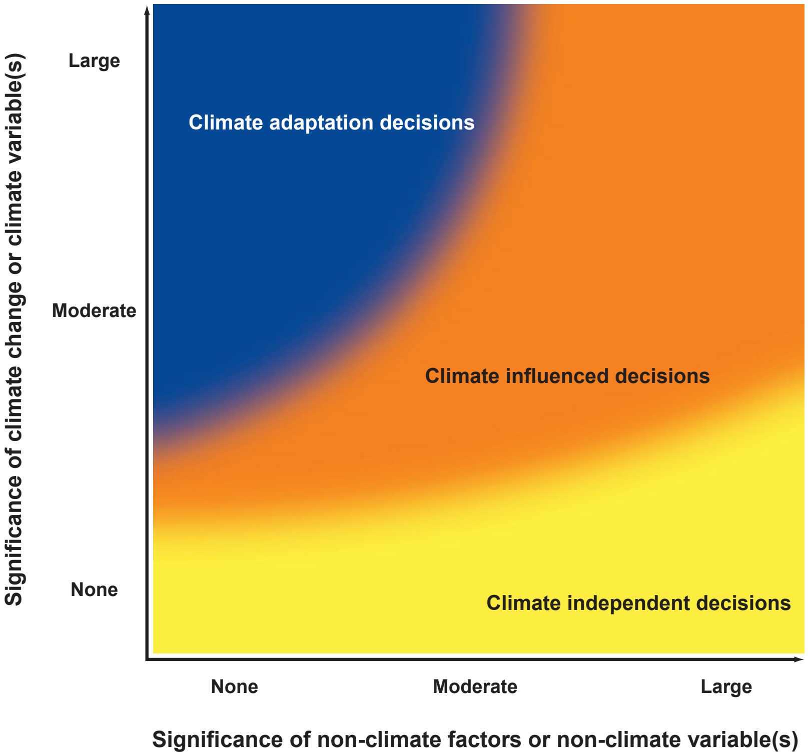

Figure 2-1. Climate change in a broader decision making context. Placing climate change in a broader context, and recognizing that there is a spectrum of issues ranging from those that are independent of climate change to those that are critically dependent on adaptation, enables a balanced approach to be taken to managing climate related and non-climate related risks. From Willows and Connell (2003).

types of decision making framework normally used adopt iterative approaches which are quite appropriate for dealing with climate change risks.

Many approaches to dealing with uncertainty are based on attitudes or perceptions such as being optimistic, risk averse, or adopting a least regret strategy. In addition the apparent magnitude of uncertainty and whether or not it is quantifiable influence the approaches taken. For example, local policy in the UK now makes specific allowance for climate change in many respects, but does not do so where uncertainties are large.

The policymaker's view of uncertainty focuses on: valuation of outcomes, whether or not there are conflicting objectives, and assessments of priorities and interests. The risk assessor's view is generally quite different and emphasizes cumulative model uncertainties and the robustness of conclusions to changes in assumptions made. Thus the scientific assessment of uncertainties has to feed into a wide range of both qualitative and quantitative approaches.

Senior decision makers generally want to know a best guess together with high and low bounds. For example, responses tend to be based on simple bottom line questions such as "how much?", "by when?" and "what are the options?". However, in some areas (e.g. flood management) analysis techniques can make use of PDFs and these are requested for climate change. Simple descriptions of the level of relative confidence among scientists as either *high*, *medium* or *low* have been developed by the UK program and are seen to be useful.

As many decision makers are focused on near term considerations, there would be value in the IPCC presenting a single PDF for temperature change incorporating all uncertainties (scenario and science based) as far as 2030, and then complementing that with separate PDFs for different scenarios beyond 2030.

2.3 A reinsurer's view of weather and climate – S. Smith

The reinsurance industry acts as a risk manager of last resort by dealing with risks that individual insurance companies do not want to cover in full. This means the industry is generally focused on catastrophic property losses and has to manage a balanced portfolio of business through detailed analysis of risk in complex situations across many countries.

Increasing use is made of catastrophe models which cover event generation (e.g. storm magnitude and frequency), hazard simulation (wind stresses), damage modelling (extent of structural damage), and financial modelling (costs). Stochastic modelling is used to generate thousands of simulated events and develop probabilistic approaches to quantifying the risks.

Typically event generation is based on use of historical data in the form of PDFs but there may be sampling problems in determining the tails of such PDFs and they may make no allowance for differentiation by modes of climate variability or of long term trends. The industry is now recognizing such patterns – e.g. relationships between Atlantic basin hurricanes and ENSO, or European winter storms and NAO – and the risks to the industry associated with clustering of severe weather events.

A key issue for the industry is whether and how climate change might affect the frequency and severity of extreme weather events. Information on such change presented in probabilistic fashion – e.g. as PDFs or changes in PDFs for recurring events – would be readily assimilated by the industry into existing decision making.

2.4 Living with uncertainty: From the precautionary principle to the methodology of ongoing normative assessment – A. Grinbaum and J.-P. Dupuy

It is suggested that there are three components to dealing with uncertainty in a broad based issue such as climate change: gauging the types of uncertainty correctly; taking into account cognitive barriers; and dealing with ethical problems.

Different typologies of uncertainty generally cover areas such as epistemic uncertainty due to lack of knowledge and deterministic chaos that places limits on the precision of predictions. However another factor in the climate change context is that society is not an independent observer of the system but an intrinsic part of it.

Cognitive barriers to objective decision making arise in various ways. People have a preference for certainty in outcomes they can influence, choosing smaller but certain benefits over larger benefits associated with some degree of risk, even where on average the latter option should be to their advantage. Similarly there is a preference to choose situations in which there is some information even if that information might be unreliable. A third cognitive barrier to effective decision making comes from the difficulty people have in believing that the worst is going to occur – as shown in cases where accurate predictions have been ignored. Similarly recognition of the existence of a risk appears to be determined by the extent to which solutions are perceived to exist.

Finally climate change raises ethical issues in relation to responsibility for decisions. There are different views as to the level of responsibility of scientists and these may change depending on when such judgments are made, what changes actually occur and how serious their impacts are. The approach called for is one in which the public and scientists are both consciously engaged in an ongoing normative assessment of scientific understanding of climate change.

2.5 An overview of some issues in uncertainty and climate change – G. Morgan

Probability is the basic language of uncertainty and was originally developed to describe the chance of different outcomes for processes that are stationary over time (such as throws of dice) where observed frequencies are equivalent to probabilities. In general, assigning probabilities to future outcomes can not assume stationarity or be based entirely on past observations. This leads to the subjective view of probability as a statement of the degree of belief that a person has, that a specified event will occur given all the relevant information currently known by that person. Such subjective probabilities have wider utility and are more relevant to the climate change context.

Using common language terms to characterize uncertainty is problematic because different people will interpret the same word in very different ways. A recognized way of dealing with this is to use standardized terms such as *likely* or *very likely* that are defined in terms of a probabilistic scale. This was recommended in Moss and Schneider (2000) for use in the TAR and also adopted in the US National Assessment.

There are two basic types of uncertainty:

1. Where the relevant variables and functional relationships are known but values of key coefficients (e.g. climate sensitivity) are not.
2. Where it is not clear that all relevant variables and functional relationships are known. (Referred to as structural uncertainty through much of this report.)

Assessing either type of uncertainty calls for expert judgment. Eliciting subjective probabilistic judgments across a group of experts requires careful preparation and execution. There is now a useful base of experience in such elicitation techniques both for climate change (see Figure 2-2) and in other areas. This has shown that interview protocols need to be developed and tested carefully and then require several hours per expert.

Interview protocols for expert elicitation need to address sources of potential bias such as overconfidence and the use of common mental rules of thumb known as “cognitive heuristics”.

Three forms of cognitive bias are:

- *Availability*: probability judgment is driven by ease with which people can think of previous occurrences of the event or can imagine such occurrences.
- *Anchoring and adjustment*: probability judgment is frequently driven by the starting point which becomes an "anchor".
- *Representativeness*: people judge the likelihood that an object belongs to a particular class in terms of how much it appears to resemble that class.

Quantifying structural uncertainty is done using different plausible alternative formulations for relationships that are not well known. For example, some integrated assessment models are

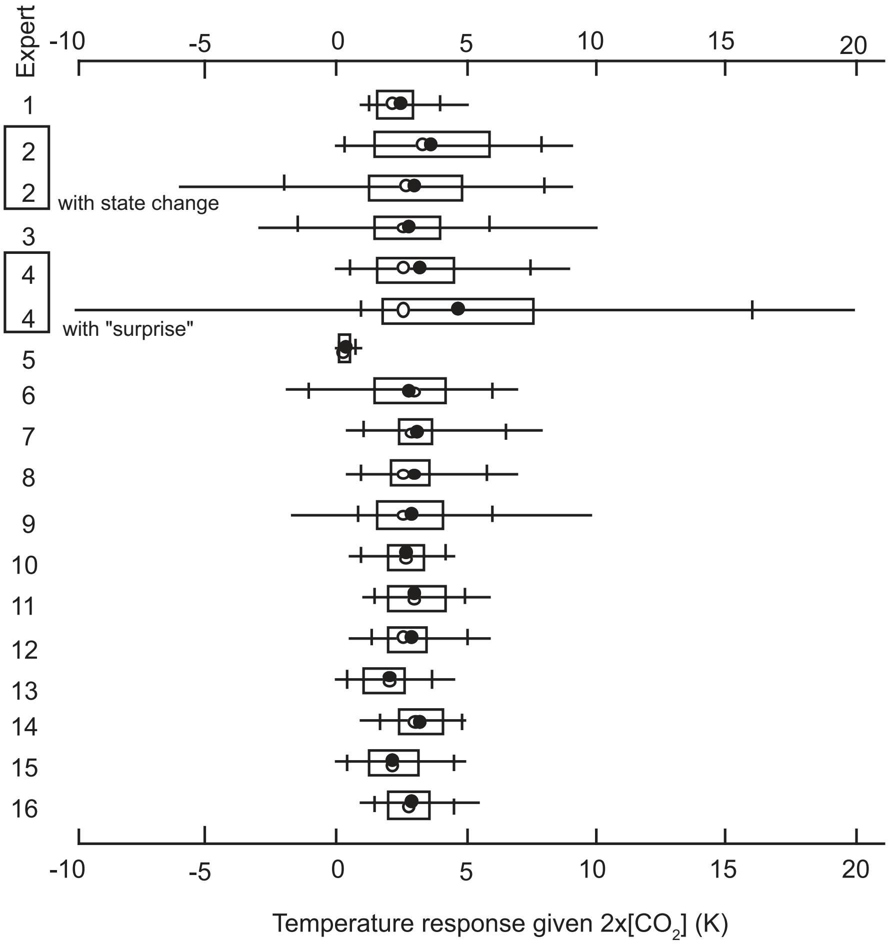

Figure 2-2. Box plots of elicited probability distributions of climate sensitivity, the change in globally averaged surface temperature for a 2xCO$_2$ forcing, shown for 16 experts. Horizontal line denotes range from minimum to maximum assessed possible values. Vertical tick marks indicate locations of lower 5 and upper 95 percentiles. Box indicates interval spanned by 50% confidence interval. Solid dot is the mean and open dot is the median. (From Morgan and Keith, 1995).

designed to allow switching between various sub-models to explore structural uncertainties. Results from such studies tend to show wide ranges for regional outcomes and high sensitivity to choice of metrics for aggregate utility. These difficulties have led away from seeking optimal policies towards identifying policies that are robust in the sense that they avoid problems for wide ranges of assumptions.

Uncertainty in socio-economic variables has generally been treated through the use of scenarios. While scenarios can be a useful device to help think about the future, they can also be susceptible to problems of cognitive heuristics. A single scenario that describes one point in a multi-dimensional space of outcomes is of limited use and logically cannot be assigned a probability. Thus scenarios are better used to span a space of interest and by assigning probabilities to regions within this space. An advantage of the scenario approach is that it enables consideration of path dependencies as well as the outcomes for each path.

Finally it is felt that those who do climate impact assessment have an obligation to:

- summarize what we know;
- describe research needed to improve that knowledge; and
- identify what we are unlikely to be able to know before the changes actually occur.

So far the assessment community has not done very well in addressing this last point.

3 Thematic Sessions

3.1 Determining and describing uncertainty in socio-economic factors

3.1.1 Introduction to the issues

Uncertainties in socio-economic factors underlying future scenarios and treatment of adaptive and mitigative capacity were not explained in the TAR as well as they might have been.

The AR4 provides an opportunity to consider more carefully the relative importance of various sources of uncertainty for socio-economic variables, particularly in determining key assessment outputs. In addition there is an opportunity to improve the way in which uncertainties were dealt with through the assessment process and the way in which those uncertainties were reported.

The breakout session considered the following types of socio-economic factors in relation to climate change:

- Demographics
- Affluence/income
- Technological change
- Scenarios (emissions, impacts & adaptation)
- Costs (mitigation, damage, adaptation)
- Mitigative and adaptive capacity

For each of these areas the sources of uncertainty, and ways of characterizing those uncertainties, were discussed using the following approach:

- Measuring and monitoring: how accurate are data, statistics?
- Modelling dynamics: how adequate do models describe reality (structure, parameters)?
- Indicator selection: how representative are the selected (input and output) indicators?
- The role of expert judgement, in particular for future assumptions: i.e. how will the future evolve? And how is it influenced by human choices?

3.1.2 Summary of discussions

The TAR noted that uncertainty in projected climatic changes is about equally attributable to uncertainties in emission scenarios and uncertainty in climate models implying that both contributions need careful re-consideration in the AR4.

Probability distributions should be considered for the drivers of emissions and the determinants of mitigative and adaptive capacity. There are functional relationships and interdependencies between these underlying factors which are important and need to be accounted for in the AR4.

By considering such distributions, tail regions with lower probability but with greater changes in socio-economic variables such as emissions, scenarios and costs, can be identified and can provide important perspectives for decision makers. Approaches to probabilities for these types of variables and their drivers are necessarily based on subjective views, usually of a group of experts, on how the future may evolve, and can be quite different to the approaches used to estimate probabilities in the natural sciences.

The factors which determine the likelihood of extreme outcomes should be identified where possible. However, reliable characterization of extremes using models typically requires large numbers of model runs and the use of multiple models and ranges of scenarios.

Uncertainty tends to increase when going from global to regional scales, however, development of regional information increases the policy relevance of the assessment. Thus careful balance is needed.

For emission scenarios the key determinants are: population, economic development and technological change. However, for mitigative and adaptive capacity other factors are important such as governance, education, trust, health, and accessibility of information. These additional factors increase uncertainty in projections of vulnerability and mitigation and adaptation options.

It should be noted that frequency distributions of model results are often dependent on previous work, and that a distinction should be drawn between the frequency distributions of model outcomes and a hypothetical subjective frequency distribution for multiple instances of the real world.

There is a recognized cascade of uncertainty when proceeding through projected climate change, projected effects of that change, and projected adaptation or mitigation responses. See Figure 3-1. Dealing with this uncertainty cascade is complex and it should not be assumed that uncertainties add in the sense of being statistically uncorrelated. Identification of thresholds and sensitivity analyses are important from a policy perspective. Thus each Working Group should focus on its own part of this causal chain without attempting to fold in uncertainties from the other Working Groups. An integrated assessment of uncertainties can only been done clearly in a synthesis report.

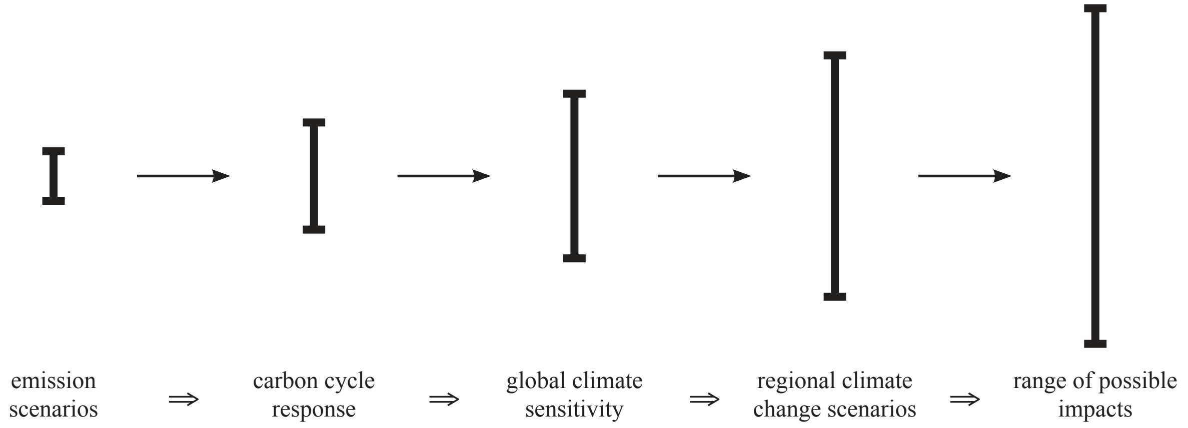

Figure 3-1. Cascade of uncertainties in the relationship between emissions and impacts.

3.1.3 Recommendations from the breakout session

1. A consistent methodology should be adopted across all WGs for describing confidence and likelihood in socio-economic factors. For specific socio-economic variables such as costs and benefits, mitigation and adaptation potentials and scenarios, qualitative explanations of uncertainty determinants may be more appropriate than quantitative confidence or likelihood estimates.

2. As compared to unrestricted (no-policy) scenarios, mitigation/stabilization scenarios are bounded by GHG emissions constraints and hence the scope of technological options is reduced and technology uncertainty is reduced. However, uncertainty about the potential and costs of particular technologies becomes more important for policy support (i.e. which technology choices are robust for different population/economic futures)

3. Assessment of co-benefits of adaptive/ mitigative policies in the AR4 requires attention to the associated uncertainties, especially where policies are implemented mainly for reasons other than climate change.

4. From an uncertainty perspective, the assessments of different WGs cannot be separated – e.g. there are common determinants of vulnerability and adaptive/ mitigative capacity, and of cascading uncertainties.

5. There should be a clear assignment of responsibility for implementing uncertainty assessments in WGs and chapter teams.

6. In dealing with uncertainty the AR4 should give special attention to those issues most relevant for policymakers (e.g. those addressed in the SPMs) .

7. The knowledge base for assessing uncertainty in socio-economic factors remains limited but there are still options for stimulating additional research work on probabilities of socio-economic scenarios to assist the AR4.

8. Grafting of adaptation scenarios onto the SRES scenarios should be considered. Options would include: use of the natural hazards & disasters literature, especially emergency responses; learning from early adopters to disasters and champions of new options; and the future based scenario planning & development literature that links global science to local decision making.

9. While consensus PDFs for socio-economic variables and scenarios would be desirable, they are unlikely to become available, e.g. via expert elicitation of subjective probabilities, unless the scientific community were to do this quickly.

10. A balance needs to be set between quantitative and qualitative ways of presenting uncertainties recognizing different audiences for the assessment. While PDFs may not be appropriate for inclusion in the SPM there is an audience for such information and where

possible they should be included in the underlying chapters. Other ways of communicating probabilities across a range of outcomes (e.g. color codes, uncertainty bars, etc) should be evaluated.

11. Where results are more directly relevant to decision making options, authors should consider formulation of their results in terms of robustness and not just in terms of probability and uncertainty.

12. Consideration should be given to preparing a succinct guide on uncertainty for WG2 and WG3 authors building on the Moss-Schneider paper and taking into account the specific culture of social scientists and economists. This might be done by a subgroup of LAs. In addition the proceedings of this workshop would provide valuable input to the first LA meetings.

3.1 Determining and describing uncertainty in observed climate change and its effects

3.1.1 Introduction to the issues

The TAR included a detailed treatment of uncertainty in many aspects of observed climate change and its effects. WG1 approaches to uncertainty were generally based on mathematical-statistical methods and estimates of uncertainty in raw data. WG2 included rather less material based on statistical methods and gave rather more consideration to levels of confidence among experts.

Approaches to determining uncertainty in the WG1-TAR included:

- Statistical estimation of uncertainty in global and regional anomalies: mainly covariance-based techniques.
- Restricted Maximum Likelihood and other techniques for estimating uncertainty in linear trends.
- Physical consistency.
- Consensus.

Areas where statistical estimation of uncertainty were used include: instrumental records of global mean surface temperature, time series for paleoclimatic temperature and ENSO index derived from proxy data, time series for changes in ocean heat content, and reconstructed surface temperatures from borehole data. Temperature trend analyses were based on restricted maximum likelihood techniques to take account of time-varying uncertainties, data gaps, potential biases, and serial correlation. The significance of precipitation trends was established by concurrence between t-tests and a non-parametric tests, while for extremes trends were estimated by weighted linear regression.

More general consideration of uncertainties were influenced by physical consistency between independent observations in areas such as: change in cloud cover vs diurnal temperature range, snow cover vs land temperature, and worldwide glacial retreat. Uncertainty was generally expressed in terms of probabilistic likelihoods of outcomes using a 7-level scale. The main reason for extending the scale proposed in Moss and Schneider (2000) was to express much higher confidence using a *virtually certain* (probability greater than 99%) category.

Structural uncertainties associated with analysis techniques in the literature were not considered explicitly. This may have led to more apparent certainty being given to results where only one or very few independent analyses had been carried out. For example, in the area of interpreting temperature trends from the MSU satellite records, recent analyses of the MSU data using different approaches have produced trend estimates which differ by more than their estimated uncertainties, suggesting that structural uncertainty arising from choice of analysis method dominates instrumental uncertainties in the data.

The MSU example suggests that structural uncertainty needs greater recognition and that data which has not been subject to multiple calibration and validation should not be given the same level of confidence as data that has – particularly when addressing key issues such as the detection and attribution of climate change.

3.1.2 Summary of discussions

Observed change in physical climate

Consideration of uncertainty in observed climate change needs to take into account limitations of the observing network. The present and historical network is better able to determine some changes (e.g., in global mean surface temperature) than others (e.g. trends in upper atmosphere temperature). Determination of reliable confidence intervals is complicated by the existence of time dependent biases and data density. These issues require careful treatment but are amenable to a range of statistical techniques and confidence can be gained from independent analyses, e.g. see Figure 3-2 for uncertainties in global annual temperature anomalies. Seemingly small persistent errors in data can have very significant effects on inferences drawn from them (e.g. estimates of climate sensitivity and aerosol forcing taken from inter-hemispheric temperature differences).

The variance of climate parameters increases as the spatial averaging scale decreases, making determination of trends or systematic patterns of behaviour more uncertain at regional scales. Similarly greater spatial and temporal variance leads to larger uncertainty in determining trends of extremes or more heterogeneous variables such as precipitation. However, the limitations of the present observational networks have been subject to many independent analyses and are generally well understood.

Observational constraints on future climate change

Studies have shown a linear relationship between warming attributed to greenhouse gases over the 20th century and projected warming over the 21st century. Thus for a range of model parameters, projected warming over 1990–2100 in the A1FI scenario is about 4 times the 20th

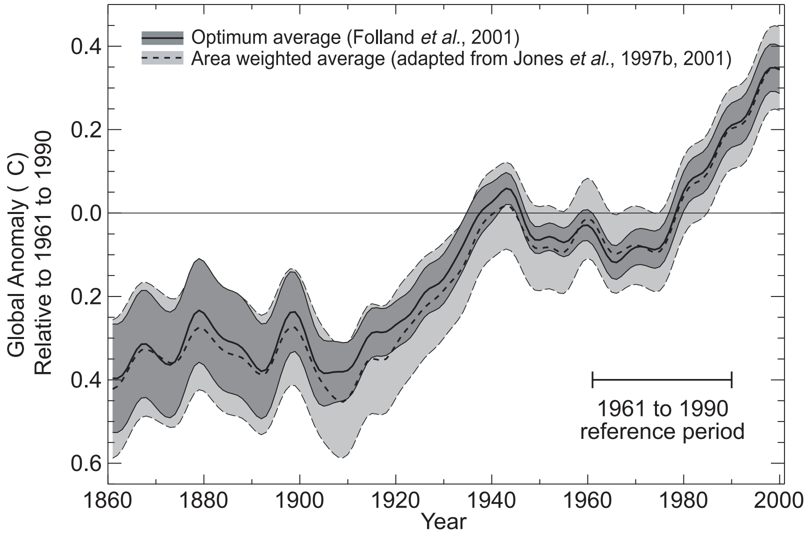

Figure 3-2. Smoothed annual anomalies of global combined land-surface air and sea surface temperatures relative to the 1961–1990 reference period. Note that the uncertainties change with time and depend on the analysis method used. From Folland et al. (2001)

century warming attributable to greenhouse gases, and for the B1 scenario is about 2 times the attributable warming.

Although the fraction of observed warming attributable to greenhouse gases has a higher relative uncertainty than the total observed warming, it is better defined by detection and attribution studies than the temperature response due to other forcing agents such as aerosols, or than equilibrium climate sensitivity.

This linkage between detection and attribution of climate change and projection of future climate change suggests that a common approach should be used in the treatment of uncertainty. This was not the case in the TAR where a probabilistic approach was taken to detection and attribution whereas projections were shown as single model runs or ranges given without defined confidence intervals. There is now a growing body of literature covering ensemble modelling that will allow probabilistic approaches to be taken for climate projections in the AR4.

Although PDFs for climate sensitivity and warming are available from single model studies further consideration needs to be given to developing multi-model PDFs and whether and how estimates of PDFs derived from very different sets of prior assumptions can be combined.

Identifying effects of climate change on biological systems

In order to assess the effects of climate on biological systems it is necessary to consider three related issues:

- Data and analysis – are changes real?
- Attribution – how can cause be inferred?
- Projection – how good are available methods?

In addition to problems of sampling quality and density, biological data tend to be based on localized studies, have high variability, and often high levels of autocorrelation. Assessments of the literature need to also consider a possible positive publication bias, as studies showing null results are less likely to appear in the literature.

However, recent work has developed approaches that deal with such difficulties. In particular hierarchical Bayesian models appear to deal with many issues of varying data density and statistical properties and there is experience in using these for interpreting both physical and biological data. Similarly multi-species studies can be used to reduce the effect of positive publication bias.

The term “attribution” applied to biological responses in the WG2 TAR was used to denote a causal link between observed change in a biological system and observed local climate change. It needs to be noted carefully that this is a different use of the term than in WG1 where attribution refers to a causal link between anthropogenic forcing factors and climate change.

Attribution in the WG2 sense is based on an understanding of biological responses to environmental factors derived from laboratory experiments, field manipulations, and observation of “natural experiments” in the form of response to climate variability and extreme events. Long term records increase the ability to remove confounding effects due to other factors influencing the system. Objective approaches are being developed to assign statistically derived confidence levels to situations where there are possibilities of competing explanations for change.

Multi-species studies generally provide greater confidence in determining attribution or the lack of it. In addition growing recognition of “sign switching” situations, such as opposite responses of polar and temperate species at the same site, or opposite responses during periods of warming and cooling, can differentiate between climate change and alternative explanations.

Diagnosing effects of climate change

Projected effects of climate change can differ significantly from one impact model to another, e.g. see Figure 3-3 showing changes in crop yields for two models. This indicates significant structural uncertainties in modelling biological responses which appear to be largely due to different assumptions about physiological parameter-processes relationships and poorly known parameters. However, crop yields are non-linearly dependent on localized precipitation, soil moisture, and radiation and on the temporal variability in each of these. Thus an additional source of model differences arises from the methods used to derive local environmental conditions. Monte-carlo techniques are now being used to determine sensitivities of impact models to inputs and have shown significant differences between assuming fixed or changing variability in climate parameters.

Although some projects, such as the European PRUDENCE project, are carrying out model intercomparisons, and most crop yield studies use more than one crop response model, there appears to be a need for more widely and better coordinated model intercomparisons in order to obtain better estimates of structural uncertainties. For natural (i.e. unmanaged) ecosystems

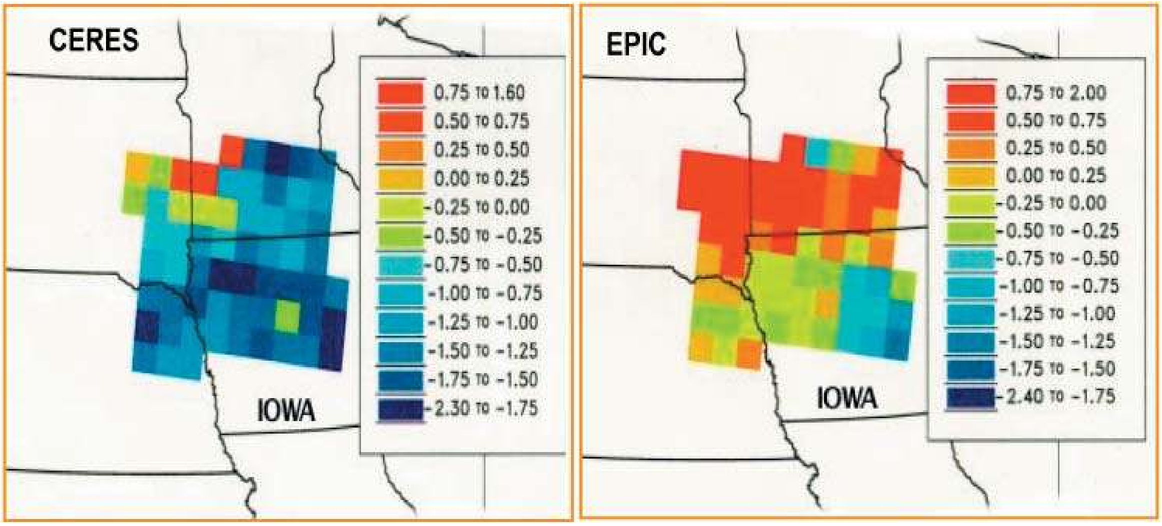

Figure 3-3. Change in model simulated yield using the CERES and EPIC crop models for the RegCM scenario and taken from Mearns *et al.* 1997. The left hand panel shows results for the CERES model and the right hand panel for EPIC. The same color scale is used in both cases and indicates change in yield in Mt/ha.

studies seldom use more than a single response model so that knowledge of structural uncertainties is more limited.

The choice of emission scenario has little effect on projected climate in the near term (up to *ca* 30 years) so that corresponding uncertainties in ecosystem responses are determined by the uncertainty in climate models and are effectively scenario independent. However, different emission scenarios affect longer term responses both through climate change and the proximate effects of different atmospheric CO_2 concentrations.

Most impact modelling studies have been carried out for industrialized countries. A lack of corresponding studies in developing countries may affect the level of confidence in the types of global scale statements that can be made.

At a broader system level, the approach to uncertainty in the effects of climate change has often been to consider thresholds such as points at which impacts become non-linear, or where adaptive capacity might be exceeded. Alternatively consideration can be given to discontinuities in the trajectories of prices or impacted populations.

Use of PDFs

There are different views on whether presentation of results using PDFs would be widely or narrowly understood. Presentation of standard graphical PDFs might be more appropriate for the underlying chapters in the AR4 while some less technical presentation style, e.g. using color shading, might be more appropriate for the SPM. An alternative view was that use of PDFs in the SPM would reduce a tendency for verbal caveats to be expressed differently from those in the underlying chapters. It was agreed that PDFs should only be shown where there was high level of confidence in the underlying science.

3.2 Effective communication of uncertainty

3.2.1 Introduction to the issues

IPCC assessments support a wide range of users and simple characterization of the audience is not practical, however, public and private sector decision makers are key users. Such decision makers adopt approaches to problems which are different to those in the scientific community. For example, science focuses on testing hypotheses to high levels of confidence rather than on setting a time frame for results. Decision makers on the other hand are often familiar with a requirement to act with "best estimates" that are available within a time table and accept that these have a degree of uncertainty. In addition, decision makers are often interested in complex questions which require aggregation of information from several different scientific disciplines or studies.

In this context it has been argued that the role of a climate change assessment is to distinguish between:

- Known: summarize present knowledge;
- Unknown: describe research needed to improve that knowledge
- Unknowable: summarize what we are unlikely to be able to know before the changes actually occur.

Issues of uncertainty raise challenges for communication that begin within the assessment process itself. Thus determining expert judgment across a group is subject to cognitive processes and group dynamics that tend to introduce imprecision, bias, and overconfidence (Morgan and Henrion, 1990). In the IPCC context communicating across interdisciplinary boundaries can add additional difficulties. However, awareness of these issues in itself can increase the rigor of group judgments.

Studies of the language used to express varying degrees of certainty have shown that commonly used words, such as *virtually certain*, *likely*, *probable*, *possible*, are interpreted very differently by different people as shown in Figure 3-4. Such differences in interpretation will be even wider in the multicultural and multilingual context of an IPCC assessment translated into many different languages.

Moss and Schneider (2000) provided general guidance for authors of the TAR on addressing the above issues. This paper did not specify any particular statistical or estimation procedures and recognized that different areas of climate change science require different approaches as reflected in the corresponding literature. Rather, the two aims of Moss and Schneider (2000) were to provide advice on improving internal processes for making expert judgments, and to provide an approach for calibrating and standardizing language used to communicate uncertainties.

The recommended 7-step process arising from Moss & Schneider (2000) is summarized in Box 1.

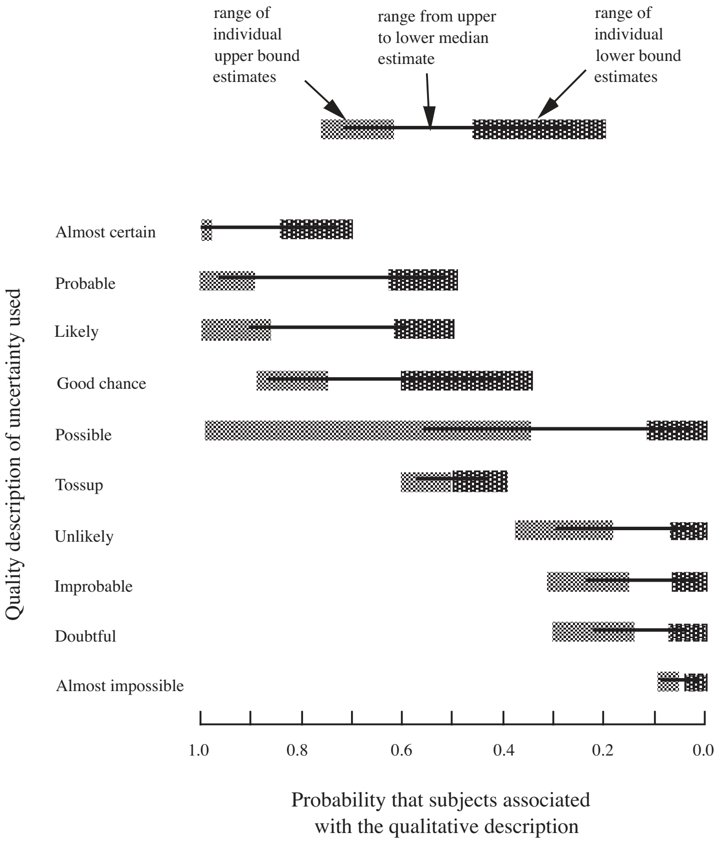

Figure 3-4. Interpretation of common words used to express degrees of certainty or uncertainty. From G. Morgan adapted from Wallsten *et al.* 1986.

Box 1. *Seven Step Process for Describing Uncertainty (based on Moss and Schneider, 2002)*

1. Identify the most important factors and uncertainties that are likely to affect the conclusions
2. Document ranges and distributions in the literature
3. Make an initial determination of the appropriate level of precision
4. Characterize the distribution of values that a parameter, variable, or outcome may take
5. Rate and describe the state of scientific information (using recommended terminology)
6. Prepare a “traceable account”
7. OPTIONAL: Use formal probabilistic frameworks for assessing expert judgment

Moss and Schneider (2000) proposed two standardized sets of uncertainty terms as a basis for communication. In cases where authors felt that scientific understanding allowed it, a quantitative assessment for the level of confidence in a finding was proposed using 5-point scale as follows:

- *Very high confidence* – greater than 95% confidence
- *High confidence* – between 67% and 95% confidence
- *Medium confidence* – between 33% and 67% confidence
- *Low confidence* – between 5% and 33% confidence
- *Very low confidence* – less than 5% confidence

In cases where scientific understanding was not sufficiently developed to merit this approach, a qualitative approach was proposed that would give simple high or low ratings to each of the level of agreement or consensus in the expert community and to the amount of available supporting evidence including observations, theory and models. As a supplement, in the latter case a diagrammatic way of denoting independently the extent of consensus, theory, observations and model results, using "radar diagrams" was proposed.

As noted earlier, descriptions of uncertainty in the WG1-TAR used a 7-point scale to describe likelihood of an outcome rather than the level of confidence in the finding. While WG II used the 5-point scale and referred to levels of confidence, some uncertainty statements appeared to be trying to denote the likelihood of an outcome. This suggests that both concepts need to be addressed as appropriate.

Since the TAR there have been several new studies on communicating uncertainty in environmental and climate change issues. For example, experience with the US National Assessment has further promoted classification of expressions of expert judgment into broad categories rather than giving single point estimates or specific ranges for each issue addressed. This work introduced the notion of fuzzy boundaries in the standard scales used so as to avoid a false sense of precision, but also appears to use these to describe likelihoods rather than levels of confidence as shown in Figure 3-5.

The NUSAP typology for describing uncertainty has been used in different contexts and more recent work has led to the development of an Uncertainty Matrix (e.g. Sluijs *et al*., 2003) which summarizes the sources of uncertainty against a typology of both statistical and structural factors.

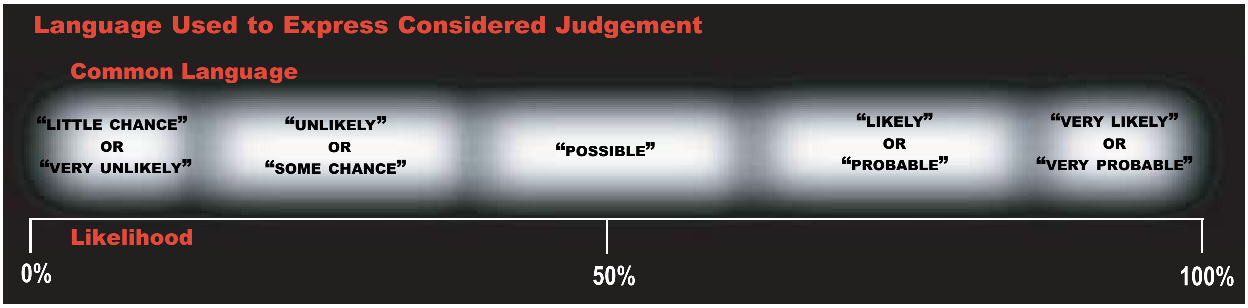

Figure 3-5. "Pillow diagram" used in the US National Assessment to denote fuzzy boundaries to the categories of certainty and uncertainty used. From National Assessment Synthesis Team (2001).

Finally it is noted that improving the treatment of uncertainty in the AR4 will require commitment, resources and the allocation of time for implementation.

3.2.2 Summary of breakout presentations

Breakout presentations addressed an approach to risk using probabilities of exceeding specific thresholds and results from studies of how the likelihood language used by WG I was interpreted by different groups. It was noted that the probability of exceeding a threshold was often fairly consistent within a few percent over a range of PDFs for the magnitude of change and that this provided a possibility for simplifying descriptions of future risk.

Studies of communication show that most people remember risk information in words rather than in numbers. In addition when people translate from words to numbers the translation is affected by event consequence or magnitude. This latter magnitude-influence on the perceived relationship between words and probabilities has been shown to be symmetric in the sense that, for the same context, speaker and listener each make similar adjustments. However, the use of words to denote a probability independent of magnitude can lead to misinterpretation (Patt and Schrag, 2003).

3.2.3 Summary of discussions

General discussion of communicating uncertainty indicated that among workshop participants there was a range of views on several issues. However, key points that emerged were:

- Trying to describe both likelihood and level of confidence for the same issue may be confusing and there was no agreement on how to approach this.

- It is extremely important to have consistent language throughout the report and it should be possible to design one scale that is flexible enough for all to use.

- There is no simple rule for when to use quantitative or qualitative descriptions of uncertainty – this is a matter for the judgment of the author teams.

- The term risk is used in different ways and it should not be assumed that the likelihood times consequence definition will be immediately recognized by readers or suit all situations.

- There seems to be no experience with using PDFs at the level of a Summary for Policymakers to judge how effective that would be. Alternative and simpler presentational forms such as Tukey plots should be kept in mind.

- Structural uncertainty needs to be addressed to avoid under-representing the actual uncertainties.

- Experience of LAs from the TAR suggests that the medium confidence level (33% to 67%) was too broad to be useful.

- Identifying and explaining the determinants of uncertainty including such issues as: definitions of variables, assumptions regarding system boundaries affecting the methods used, and existence of competing conceptual frameworks, is often more relevant than trying to quantify those uncertainties.

- The breakout session suggested that a short (2-page) document be prepared to provide some key guidance to incoming LAs. The intent would be to assist the writing teams by providing some practical advice based on previous experience. Such a document would note what was done in the TAR and provide a brief summary of revisions using input from this workshop and relevant recent studies.

- Further consideration should be given to the development of a consistent set of options for describing uncertainty in different contexts relevant to the AR4. This should include revisiting the scale used and requesting that where possible authors identify what is "unknowable" within the time frames affecting climate change decision makers.

- CLAs should be advised to consider their approaches to uncertainty early in developing their chapters and e.g. identify a set of key issues on which the author team would have to decide on likelihood or level of confidence. Where possible this should include key statements likely to appear in the SPM.

- A separate "primer" for readers of the AR4 should be considered in order to provide background material on the types of approaches taken by authors in describing uncertainty.

3.3 Determining and describing uncertainties in projections of climate change and its effects

3.3.1 Introduction to the issues

The main sources of error for projections of physical climate change considered in the TAR were:

- the range of emission scenarios;
- model uncertainty including errors in radiative forcing;
- parameterization of physical processes, and omitted processes; and
- neglected feedbacks including biogeochemical cycles.

Approaches used to estimate these uncertainties were to provide ranges from the literature, consider statistics of variability, and make expert judgments using the likelihood language adopted throughout the WG1-TAR.

One of the key uncertainties for projections of climate change is that in climate sensitivity. The same range (1.5 to 4.5°C) for the equilibrium warming caused by a doubling of CO_2 has been quoted in all assessments since the Charney report (National Academy of Sciences, 1979). A number of new studies are now producing PDFs for this quantity using combinations of observational constraints and ensembles of model runs. Figure 3-6 shows examples from work done in the UK.

Many studies now use ensembles of runs from a single model spanning a range of physics parameters or range of initial conditions. Fewer studies have considered ensembles combining different models. Appropriate use of multi-model ensembles might involve expert judgment in the WG1-AR4. In this respect it will be important to recognize that the range of ensemble results from one or more modelling studies does not necessarily span the full range of uncertainty.

The development of PDFs for key aspects of climate change is leading to new considerations of the high-impact-low-probability tail. While this is very important for risk assessment the details are very sensitive to assumptions made and have been shown to depend on the metrics used.

3.3.2 Summary of discussions

Ensemble based projections will need to sample uncertainties in model formulation, emissions and initial conditions. Approaches for sampling modelling uncertainties would include use of: multi-model ensembles; ensembles sampling different parameterisations; and ensembles sampling different parameter values.

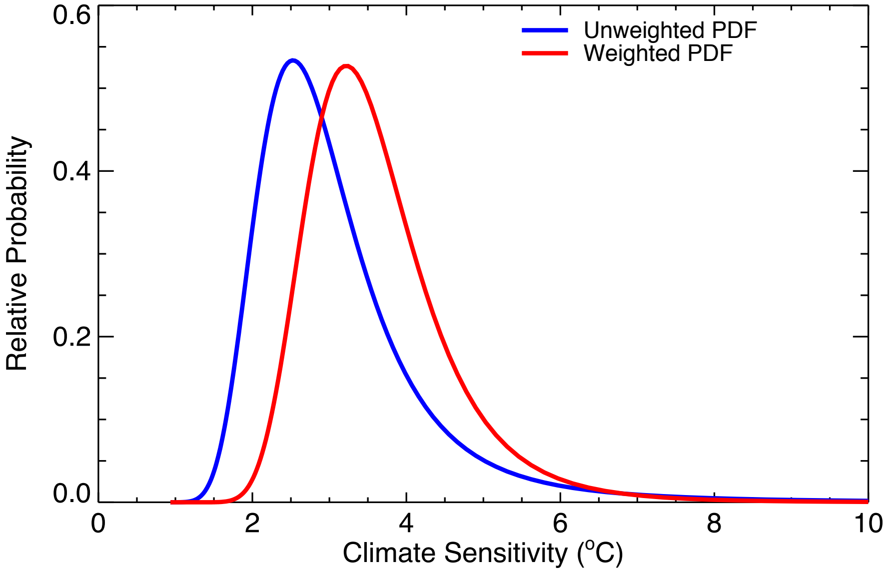

Figure 3-6. Examples of probability distribution functions for climate sensitivity (warming caused by a doubling of CO_2 concentrations). The blue curve shows results from an ensemble of model runs spanning ranges of parameters judged to be plausible by a group of experts, the red curve shows results based on weighting members of this ensemble according to their ability to reproduce metrics of observed climate. From Murphy *et al.* 2004.

Structural uncertainties will remain. For example, the use of deterministic bulk formula parameterisations is often not physically justified. New techniques may identify structural issues, e.g. a stochastic-dynamic approach could lead to reduced bias, increased variability and a more complete representation of uncertainty. But such approaches may not be available until the AR5.

As was done for the WG1-TAR it is expected that core material for projections in the WG1-AR4 will come from:

1. Individual runs of GCMs from different centres, for selected scenarios
2. Small ensembles of runs of a subset of GCMs, distinguished by different initial states

In addition developments since the TAR will allow inclusion of:

3. Large perturbed parameter ensembles of at least one GCM (HadCM3)
4. Methods of weighting or scaling projections from different GCMs according to goodness of fit to observations.

There will be a need to coordinate these four sources of projections in order to provide the best possible basis for construction of probabilistic projections. One requirement for such coordination that is already being addressed is to use common scenarios and types of model output.

Probabilistic projections based on different methods for obtaining PDFs are appearing in the literature, and will be available for the AR4 for both global and "large scale" regional climate change. For example, Figure 3-7 shows results from a recent multi-model ensemble approach

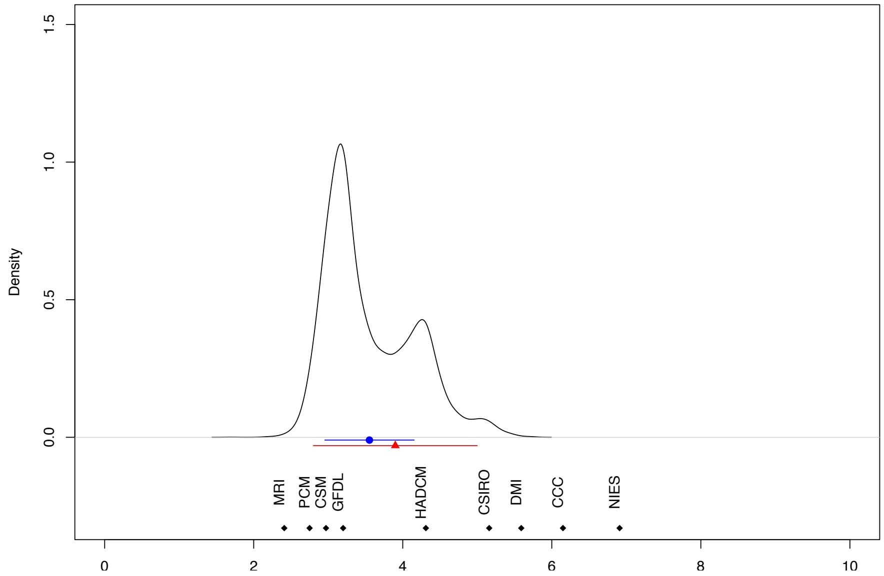

Figure 3-7. A posterior probability distribution constructed for winter time warming in central Asia based on a multi-model ensemble using a Bayesian method (Tebaldi et al, 2004) taking into account natural variability, model bias, and the spread in model results. The blue dot and bar show the mean and standard deviation of this distribution. The red triangle and bar show estimated warming and variability estimated from the same model results using an earlier weighting technique (REA method, Giorgi and Mearns, 2002). Black dots show the results for individual models. The x-axis represents change in temperature (future-present) in degrees Celsius.

to large scale regional climate change. Communication of the necessary caveats and the assumptions underlying such PDFs will be crucial to avoid any overconfidence that may arise from this way of presenting results. Some of the issues that will need to be covered are:

- what range of modelling uncertainties is sampled in the ensemble;
- what criteria are used to quantify reliability and weight or scale predicted changes;
- the role of expert judgement (choice of priors, parameters etc); and
- are the model projections contingent on an assumption of no surprises.

This leads to a need to distinguish between confidence and likelihood. Developing confidence in probabilistic projections raises several basic issues such as how do we measure confidence in unfalsifiable probabilities of future climate change? To what extent does convergence determine confidence. Demonstration that probabilities remain stable when new information (e.g. new runs of improved models) is added, and verification of probabilities from seasonal-decadal hindcasts, are necessary but not fully sufficient conditions for confidence.

This is an area where subjective judgement of confidence will be needed in the WG1-AR4. For this reason PDFs should not be presented when the confidence in the methods used is low. However, in some applications, it may only be necessary to demonstrate that the tails of PDFs are not implausible.

PDFs also raise issues of presentation. Simple approaches are to be preferred – e.g. giving the probability of exceeding some specific threshold, or of exceeding a range beyond which we cannot cope. Alternative techniques for presenting PDFs as colour density or scatter plots should be investigated.

Uncertainties in the projected effects of climate change involve many of the same issues as those given above for projections of physical change. However, impact models cover a wide range of structural types, introducing new issues in describing associated uncertainties. Furthermore the way in which uncertainties in projected effects are communicated should take account of the decision making process that they are intended to inform.

Studies of decision making in the presence of uncertainty suggest alternatives to the “predict then act” paradigm. In particular, incremental or iterative decision making through learn then act strategies may be better for complex systems where there are deep uncertainties (i.e. uncertainties due to lack of consensus on comprehensive conceptual frameworks and model structures). This suggests that the communication of significant or structural uncertainties should be designed to be useful for the development of robust strategies that may not be optimal but would work reasonably well across a wide range of outcomes.

The breakout session considered a relevant example where, using the Moss and Schneider (2000) qualitative confidence scale, confidence in the numerical results of an analysis was *speculative*, but confidence in the overall conclusion was *established but incomplete*. This result was demonstrated by considering the inclusion of additional potential sources of uncertainty and finding that the nature of the conclusion was not significantly changed.

A review of how uncertainty and consideration of confidence interacts with decision making can be an means by which policy analyses can be assessed within the AR4 without being policy prescriptive.

Finally it was felt that there was a serious need for communication and integration of the treatment of uncertainty across working groups as the assessment process proceeds. Ways of achieving that might include an ongoing liaison process, presentations at authors' meetings, or asking bureau members to convey common interests.

4 Working Group Sessions

4.1 Working Group I perspective

Previous guidance. The Moss and Schneider (2000) document had provided a valuable input to the treatment of uncertainties in the WG1-TAR. Decisions to adopt a 7-level scale for describing likelihood were taken primarily to introduce a descriptor for a very high level of likelihood expressing results from observational studies involving large amounts of information.

Development of PDFs. Increasingly the literature that will be assessed by WG1 for the AR4 is using probability distribution functions to express model projections and model based analyses of observational data. While use of PDFs in the underlying report may increase clarity for expert readers, it is unclear whether or how PDFs should be presented in the Summary for Policymakers for more general audiences. This is potentially a bigger issue for Working Group I than for either of the other Working Groups.

Scenario vs model probabilities. Uncertainties in climate model projections due to model uncertainties should be distinguished carefully from those due to the emission scenario assumed. In particular, it should be made clear which uncertainties are being covered by a PDF.

Presentational techniques. Innovative graphical techniques for presenting results and associated uncertainties should be considered. Some of the workshop presentations provide examples that might be adapted for the AR4. Alternatively, provision of web based tools, allowing users to probe the data that is assessed in the AR4, using different thresholds or spatial and temporal ranges, could provide a richer understanding of associated uncertainties.

Qualitative descriptions of confidence in the science. The WG1-TAR used a LOSU (level of scientific understanding) terminology to describe uncertainties in radiative forcing. It appears that the qualitative description of confidence presented in Moss and Schneider (2000) was not used because of some discomfort with the specific wording given there. However, it was agreed that providing separate indications of the amount of information available and the degree of unanimity in the expert community on its interpretation, is appropriate. In areas where there is still significant lack of knowledge that should be acknowledged clearly rather than through arbitrarily extended uncertainty ranges.

A primer for the reader. There is a need to develop a clearer understanding among readers of IPCC reports of how uncertainty is determined and described. However, it is not clear that an uncertainty primer would actually be read – particularly in connection with the SPM where it might be most needed. An alternative approach would be to cover uncertainty issues in boxes closely linked to key sections of the report.

Types of uncertainty. There needs to be clearer recognition of the difference between structural and statistical uncertainties in the AR4. There is a large WG1 related literature on model intercomparisons which provides some information on structural uncertainty, however, convergence among models is not the same as reducing uncertainties.

Regional vs global. Uncertainties in analysing observed changes or projecting future changes in regional climate are larger than those that apply at the global scale. The reasons for this will need to be communicated clearly in the AR4. A related issue is that of attribution of observed or projected changes in extremes, where the additional difficulty arises of analysing probabilities of infrequent events.

Approaches in chapter teams. CLAs should consider how their chapters would address uncertainty at an early stage. The development of a short guide for AR4 LAs and review of that by CLAs would provide a useful way of summarizing past experience and capturing the results of this workshop.

Use of Expert Reviewers. The assessment process would be helped by use of targeted expert reviewers, who would consider the ways in which uncertainty was being addressed and consistency of that between different parts of the report.

4.2 Working Group II perspective

Consistent treatment of uncertainty. A consistent treatment of uncertainties in the Report is important. This treatment should include language, graphics, and "traceable accounts" of how the authors arrived at particular uncertainty estimates.

Consistent language. Both a qualitative and a quantitative standard scale of uncertainty language are needed in order to cover the wide range of research that WGII assesses. Authors should be free to choose the scale with which they are most comfortable.

Author involvement. A consistent treatment of uncertainty throughout the Report will succeed if authors feel comfortable with the need for consistency and with the range of options available to them. Therefore it is important to introduce authors to these issues as soon as possible.

Guidance notes. There is a need for guidance notes for authors on how to treat uncertainty. The Moss and Schneider guidelines for the treatment of uncertainty in the TAR are a good starting point.

Incorporating discussions of uncertainty into the Report. A methodological discussion of uncertainty would be considered in Chapter 2 of the WG2 Report. However, each chapter would also address uncertainty explicitly in relation to the issues that it covers (e.g., in a box). It may be useful to identify and apply more detailed uncertainty analysis to a limited number of outputs in each chapter.

User perspectives. It is necessary to consider the perceptions and needs of different kinds of users when designing the standard uncertainty descriptors and when discussing risk in the Report. For example, it may be useful to test uncertainty descriptors on users prior to adopting them in the Report.

Special uncertainty reviewers. There is a need to study the option of asking some uncertainty experts to review the treatment of uncertainty in the Report and its consistency across different parts. An alternative would be to direct the regular expert reviewers to pay attention to uncertainty issues. In either case we need to clearly define what we would like the reviewers to do.

4.3 Working Group III perspective

Uncertainties in TAR. Although WGIII TAR authors addressed uncertainties in the WG3-TAR, they did not adopt the Moss and Schneider uncertainty guidelines. The treatment of uncertainty in the WG3-AR4 can be improved over what was done in the TAR.

Process. One thing that is needed for developing a more consistent treatment of uncertainties in the AR4 is a 2-page set of guidelines for authors on the treatment of uncertainty in the AR4. The preparation of these guidelines should start before the first LA meeting and involve the CLAs, in order that writing teams develop ownership of the document. It will also be necessary to designate specific experts to review uncertainty issues in the AR4. An additional possibility is to have another meeting on this issue with authors from all Working Groups in 2006.

Differentiated approach. Estimation of uncertainty in the WG3-AR4 is prominent in the outlines for chapters on framing issues (Chapter 2) and on long-term mitigation (Chapter 3), and will also be important to the sectoral and cross-sectoral chapters on short- and medium-term mitigation (Chapters 4–11). However, given what is known about mitigation on the long term versus the short and medium term, the authors of these chapters may need to use different tools to determine and describe uncertainty.

Tools for describing uncertainties. There are a variety of tools available for describing uncertainty. These include likelihood scales, traceable accounts (that describe the assumptions and specific circumstances that affected why the authors made particular uncertainty statements), documented expert judgment, and a qualitative matrix of consensus versus availability of information.

Challenges. The authors of the WG3-AR4 face several challenges in trying to apply the same approach as WG1 and WG2 authors to describing uncertainty. For example, it is very challenging for economists and social scientists to attempt use a likelihood scale based on experience in the natural sciences, and which is quite different from the way they usually treat uncertainty. Another challenge is to assign uncertainty estimates to issues like mitigation potentials and estimates of future emissions or drivers, as very little literature exits to support such estimates.

5 Conclusions

The next steps to follow on from the workshop would be:

- A special issue of Geosciences is to be published containing papers based on presentations at the workshop. This would be coordinated by Michel Petit. Papers should be submitted by July.

- Following the strong support at the workshop for preparation of guidance notes for incoming LAs, a draft would be prepared by the workshop committee and distributed for review by both past and present CLAs. Some key points that had been made for inclusion in these guidelines were:

    - Authors should consider how to deal with uncertainty early on in their planning.
    - Key issues requiring careful treatment of uncertainties should be identified as soon as possible.
    - Consistency across the report should be maintained by using techniques for communicating uncertainty from among a set of options summarized in the guidance notes.
    - Authors should consider both structural and statistical sources of uncertainty.
    - Authors should note the difference between likelihood and level of confidence and use the appropriate terminology.
    - Probability distributions should only be used where there is high confidence in the underlying science.
    - Traceable accounts should document the basis used for making expert judgments.

- It was agreed that the such guidelines should be available for the first LA meetings.

- Preparation of an Uncertainty Primer for readers of the report would be valuable. This could be produced as a stand alone report by suitably qualified experts, however, it was not clear whether such a primer could be incorporated as a formal part of the AR4.

- Further consideration should be given to innovative graphical ways of presenting uncertainty - first within Working Groups but comparisons between Working Groups could be valuable.

- Targeted expert reviewers, operating within the standard IPCC review process, should be used to provide comments to the author teams on how issues of uncertainty were being treated and the degree of consistency in approach and language across different parts of the report. Such expert reviewers should be selected by the Working Group Bureaux, taking advice from experts in communication and uncertainty.

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Annex 1:
Workshop Program

DAY 1: Tuesday, 11 May

08:30–09:00	**REGISTRATION**	

Introduction

09:00	*Seamus Smyth (NUI)*	Welcome on behalf of National University of Ireland
	Mary Kelly (Irish EPA)	Welcome on behalf or Irish Environmental Protection Agency
	S. Solomon	Welcome on behalf of IPCC

Plenary Session 1: Using information in an uncertain world

Chair: M. Petit

09:30–10:00	*M. Manning & M. Petit*	Purpose of the workshop
10:00–10:30	*G. McBean*	Overview: Evolution in the communication and use of scientific uncertainties
10:30–11:00	**BREAK**	
11:00–11:30	*R. Connell*	Helping UK decision-makers deal with climate risks and uncertainties: The UKCIP approach
11:30–12:00	*S. Smith*	A reinsurer's view of weather and climate
12:00–12:30	*A. Grinbaum & J.-P. Dupuy*	Living with uncertainty: From the precautionary principle to the methodology of ongoing normative assessment
12:30–13:30	**LUNCH**	
13:30–14:00	*G. Morgan*	An overview of some issues in uncertainty and climate change

Plenary Session 2: Approaches to uncertainty in IPCC assessments: Drivers of change, observations and diagnosis

14:00–14:30	*R. Swart*	Introduction to Breakout A: Uncertainty in socio-economic factors
14:30–15:00	*D. Parker*	Introduction to Breakout B: Approaches to observational uncertainty in the IPCC Third Assessment Report
15:00–15:30	**BREAK**	

Continued next page

DAY 1: Continued

15:30–17:30	**Breakout A: Determining and describing uncertainty in socio-economic factors** **Part I - Uncertainties in socio-economic driving forces - General.** *Chair: R. Swart; Rapporteur: H.-H. Rogner; Lead-in to discussions by:* *N. Nakicenovic:* Uncertainties associated with emissions scenarios and the role of technology *N. Adger:* Uncertainty in adaptive capacity	**Breakout B: Determining and describing uncertainty in observed climate change and its effects** **Part I - Approaches to uncertainty in observations of contemporary climate and paleoclimate, including extremes,** *Chair: M. Manning; Rapporteur: D. Easterling; Lead-in to discussions by:* *D. Easterling:* Issues related to uncertainty in the observed climate record *M. Schlesinger:* Climate sensitivity: Uncertainties and learning *W. Easterling:* Bridging uncertainty from climate models to simulation of impacts and adaptation: The case of crop yield modelling
19:30	**Conference Dinner hosted by Irish EPA** *Buses leave from south gate of Maynooth campus area for dinner at Barberstown Castle.*	

DAY 2: Wednesday, 12 May

09:00–10:00

Breakout A–continued

Part II - Uncertainties in emissions and impacts scenarios, costs and mitigative/adaptive capacity.

Chair: H. Rogner; Rapporteur: R. Swart; Lead-in to discussions by:

J. Reilly:
Describing scientific uncertainties in climate change to support analysis of risk and of options: Coupling models across disciplines

Breakout B–continued

Part II - Approaches to uncertainty in model validation, detection and attribution of change, observational constraints on near term climate change, ecosystem responses.

Chair: D. Easterling; Rapporteur: M. Manning; Lead-in to discussions by:

M. Allen:
Observational constraints on future climate: Distinguishing robust from model-dependent statements of uncertainty in climate forecasting

C. Parmesan:
Uncertainty in estimating biological impacts of climate change: Sources of error and methods of quantifying uncertainty

10:00–10:30 **BREAK**

Plenary Session 3: Approaches to uncertainty in IPCC assessments: Effective communication and projections of the future

10:30–11:00	*R. Moss*	Introduction to Breakout C: Approaches to uncertainty in IPCC assessments: Effective communication
11:00–11:15	*J. Mitchell*	Introduction to Breakout D: Uncertainty in predictions: Some thoughts
11:15–11:30	*G. Yohe*	Introduction to Breakout D: Assessing the scientific literature given the cascade of uncertainty

Plenary Session 4: Review of Breakouts A and B

11:30–12:00	*H-H. Rogner*	Summary of Breakout A and discussion *To summarize approaches and possible guidelines/options for communicating uncertainty in socio-economic factors, e.g. scenario assumptions and costing.*
12:00–12:30	*M. Manning*	Summary of Breakout B and discussion *To summarize approaches and possible guidelines/options for communicating uncertainties in observations and detection and attribution of change.*
12:30–13:30	**LUNCH**	

Continued next page

DAY 2: Continued

13:30–15:00	**Breakout C: Effective communication of uncertainty** **Communicating uncertainties in risks, projections, time scales, irreversibility, cost estimates, integrated scenarios.** *Chair: R. Moss; Rapporteur: M. Petit; Lead-in to discussions by:* *G. Morgan:* (13:30–14:30)	**Breakout D: Determining and describing uncertainties in projections of climate change and its effects** **Information from GCM comparisons, ensemble runs, probabilistic projections and 'not-implausible' futures, additional regional modelling issues, integrated assessments, propagation of uncertainty.** *Chair: J. Mitchell; Rapporteur: J. Murphy; Lead-in to discussions by:* *T. Palmer:* Representing model uncertainty in climate prediction *M. Collins:* Uncertainties in modelling climate change *L. Mearns:* Calculating probabilities of regional climate change using a Bayesian approach
15:00–15:30	**BREAK**	
15:30–17:30	**Breakout C–continued** **Approaches to effective use of language; standardized terminology; presentation techniques.** *Chair: M. Petit; Rapporteur: R. Moss; Lead-in to discussions by:* *R. Jones:* When do POETS become dangerous? *A. Patt:* Communicating probabilities with words: Potential pitfalls and biases	**Breakout D–continued** *Chair: M. Schlesinger; Rapporteur: G. Yohe; Lead-in to discussions by:* *R. Lempert:* New approaches for characterizing climate change uncertainties for decision-makers *G. Yohe:* Bringing long-term uncertainty to bear on the short-term

DAY 3: Thursday, 13 May

Plenary Session 5: Review of Breakouts C and D

09:00–09:30	*R. Moss*	Summary of Breakout C and discussion *To summarize approaches and possible guidelines/options for identifying areas of consensus in author teams; and use of standard terminology for levels of confidence.*
09:30–10:00	*J. Murphy & G. Yohe*	Summary of Breakout D and discussion *To summarize approaches and possible guidelines/options for use of model ensembles, pdfs, and dealing with propagation of errors.*
10:30–11:00	**BREAK**	

Working Group breakout session

WG Specific Sessions: To discuss/summarize issues that arose in the TAR and prospects for new / better approaches to uncertainties in the AR4.

10:30–12:30	**WG1** *Chair: S. Solomon*	**WG2** *Chair: J. Palutikof*	**WG3** *Chair: O. Davidson*
12:30–13:30	**LUNCH**		

Plenary Session 6: Review of outcomes and next steps

Summary of Working Group breakout sessions. To review approaches to uncertainty specific to each WG in turn: What has emerged, and what issues are to be referred to Lead Author meetings.

Chair: M. Manning

13:30–14:00	*M. Manning*	Review from the WG1 perspective
14:00–14:30	*J. Palutikof*	Review from the WG2 perspective
14:30–15:00	*L. Meyer*	Review from the WG3 perspective
15:00–15:30	*Steering Committee*	Closing remarks. Next steps: special issue of Geosciences, workshop report
15:30	**CLOSE**	

Annex 2:
Extended Abstracts

Uncertainty in Adaptive Capacity

W. Neil Adger

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Both the impacts of observed and future climate change and the capacity to adapt to these changes are unevenly distributed, spatially and socially. We can easily envisage that the capacity of an individual to deal with crisis or stress as a result of crossing critical climate thresholds changes over their life-course and is dependent on social status, wealth and knowledge. At a different scale, the determinants of adaptive capacity for a country are equally complex and equally interrelated. The challenge for the emerging insights into adaptation is how to characterize this adaptive capacity in a meaningful sense and to find generic determinants of adaptive capacity at various scales to build predictive models of its evolution into the future.

Adaptive capacity is a vector of resources and assets that represent the asset base from which adaptation actions and investments can be made. Within the IPCC TAR, it is recognized that this capacity may be latent and be important only when sectors or systems are exposed to the actual or expected climate stimuli. Vulnerability to climate change is therefore made up of a number of components including exposure to impacts, sensitivity, and the capacity to adapt. So adaptive capacity is, therefore, a component of vulnerability. Adaptive capacity has diverse elements encompassing the capacity to modify exposure to risks associated with climate change, absorb and recover from losses stemming from climate impacts, and exploit new opportunities that arise in the process of adaptation.

Adaptation decisions taken by individuals (e.g. to use insurance, relocation away from threats, or changing technologies) are all constrained by government and regulatory decisions. Government policies and individual adaptations are not independent of each other. Indeed all adaptation decisions and policies have socially differentiated impacts and equity implications.

Where Moss and Schneider (2000) show an explosion of uncertainty towards the ‘range of possible impacts’, those uncertainties relate to only to the ‘exposure’ elements of vulnerability. The uncertainties associated with adaptive capacity are those relating to uncertainty in the determinants of adaptive capacity as well as uncertainty in projecting those determinants into the future. There are generic features of adaptive capacity of societies to climate variability and change as well as to other types of stress. These are to do with the resources available to cope with exposure, the distribution of these resources across the landscape and between groups within a population, and the institutions which mediate both resources and coping with risk. If institutions fail to plan for changing environmental conditions and risks, adaptive capacity is constrained, and vulnerability increases.

Adaptive capacity in effect gives a picture of the adaptation space within which adaptation decisions are feasible. It is therefore more meaningful and tractable to develop scenarios of adaptive capacity than scenarios of adaptation per se. Predicting adaptation requires adopting a model that describes the processes of adaptation. This is difficult because adaptation comes through markets, civil society and government action and complex interactions between them. Work by Berkhout and colleagues (2004), for example, show empirically that it is not meaningful to describe a single adaptation path of a climate-sensitive sector of the economy. They demonstrate that in the house-building sector in the UK faced with expected changes in risk from flooding, a fragmented picture appears of niche markets and diverse strategies, the diversity of strategies being defined by the adaptation space and the capacity of the sector.

Developing scenarios of adaptive capacity at various scales highlight the nature of uncertainty in this area. Clearly adaptive capacity is dependent on a range of socio-economic variables for which there are specific uncertainties. Many of these relate to discussions on uncertainty in mitigation. Rates and patterns of demographic change, the development and diffusion of technologies for adaptation, and the distribution of economic well-being are all elements of adaptive capacity that are also driving emissions and the capacity to mitigate (Yohe, 2001).

The objective of much work in the area of adaptive capacity is to develop robust national-level indicators of vulnerability and capacity to adapt to climate risks. The national level is an appropriate scale for information utilised by central government in determination of policy. Comparing adaptive capacity across countries can identify leverage points in reducing vulnerable to climate variability and, by inference, to climate change, which is likely to be manifest through changes in the frequency and severity of existing hazards at least in the short- to medium-term. Identification of nations with low specific adaptive capacity can act as an entry point for both understanding and addressing the processes that cause and exacerbate vulnerability. A common critique of work at this scale is that the sub-national spatial and social differentiation of vulnerability, and local conditions mediate the capacity to adapt (Yohe and Tol, 2002). Published studies of national-level vulnerability have generally been based on assumptions about the factors and processes leading to vulnerability, informed by intuitive understandings of human-environment interaction.

The contextual nature of vulnerability, the difficulties of validating indicators, and considerations of timescale provide challenges to the development of robust indicators. Brooks and colleagues (2004) attempt to account for the hazard-specific and context-specific nature of vulnerability and adaptive capacity in developing national level indicators that explicitly addresses the issue of timescale. They find that on multi-year and decadal timescales, the capacity of a country to cope with and adapt to extreme events associated with climate variability is associated predominantly with health, governance and political rights, and literacy. Eleven key indicators exhibit a strong relationship with decadally-aggregated mortality associated with climate-related disasters. Validation of indicators using mortality outcome data goes some way towards addressing the issue of subjectivity in the choice of indicators. Expert judgment data, collected through a focus group exercise, identifies the most important indicators through consideration of processes and contexts. Perhaps not surprisingly, the role of governance is key: the Brooks et al. (2004) results indicate that the most vulnerable nations are those situated in sub-Saharan Africa and those that have recently experienced conflict.

Governance is an uncertain area. Not only is it difficult to project scenarios of governance into the future or to predict their change, but the very notion of governance indicators is problematic. Some theories suggest, for example, that the presence of civil society groups lobbying for interest groups is a drain on effective governance, while other theories suggest exactly the opposite – that membership of formal groups is an indicator of the vibrancy and effectiveness of government and themselves promote trust in government. These competing notions of governance and the role of social capital have been empirically tested to elicit the relationships between trust, civic action and economic performance (Knack, 2003; Knack and Keefer 1997) with mixed results. Clearly elements of governance such as trust are important in adaptive capacity but its determinants and its evolution in the future remain obscure.

Governance creates other dimensions of uncertainty in adaptive capacity. It may seem intuitively obvious what direction of change of key indicators enhances adaptive capacity at the national level (e.g. greater wealth represents enhanced capacity to adapt). But the objectives of government across different areas of adaptive capacity are not given. Rather they are a function of the underlying objectives of governance. There are inevitably discrepancies between governments whose aspirations are to maximize the welfare of its citizens, compared to those governments which seek to maintain control of their citizens, or those that seek to reduce the vulnerability of the most vulnerable groups. These different aspirations lead to different weightings of the elements of adaptive capacity – seeking to reduce vulnerability would likely lead to investment in short term hazardous impacts more than in coping with long term changes for example. Haddad (2004) has shown empirically that the ranking of adaptive capacity of nations is significantly altered when governmental aspirations are taken into account. But government aspirations change, often with revolutionary zeal.

In summary, there are pertinent and critical issues of uncertainty in determining adaptive capacity at many different scales, from that of individuals through to that of nations. But adaptive capacity shows highlights only the resources available for adaptation rather than the most likely or most desirable adaptation decisions to be taken. Adaptation, constrained by the capacity to adapt, involves a further set of uncertainties in decision-making processes.

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Annex 2: Extended Abstracts

Observational Constraints on Future Climate: Distinguishing Robust from Model-Dependent Statements of Uncertainty in Climate Forecasting

M. R. Allen[1], B. B. B. Booth[1,3], D. J. Frame[1], J. M. Gregory[2,3], J. A. Kettleborough[4], L. A. Smith[5], D. A. Stainforth[1] & P. A. Stott[3]

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Background

The IPCC Third Assessment Report (TAR) was strongly criticised for failing to present its headline projections of 21st century climate change in quantitative probabilistic terms[1]. Although it was argued[2] that this accurately represented the literature at the time, quoting ranges of uncertainty with no indication of the likelihood of the actual climate straying outside these ranges will not be acceptable in the Fourth Assessment Report (AR4). Quantitative probabilistic climate forecasting raises fundamental challenges, in particular regarding the treatment of system response uncertainty or model error[3,4].

Sources of uncertainty in climate forecasting

AR4 will need to distinguish clearly between

1. Uncertainty in anthropogenic forcing due to different emission paths ("scenario uncertainty")
2. Uncertainty due to natural variability, encompassing internal chaotic climate variability and externally driven (e.g. solar, volcanic) natural climate change ("natural variability")
3. Uncertainty in the climate system's response to external forcing due to incomplete knowledge of feedbacks and timescales in the system ("response uncertainty")

These different sources of uncertainty need to be distinguished because they have very different policy implications. Scenario uncertainty is a special case because it is, to some degree, under policy control. Some uncertainties due to natural variability may be reduced by detailed observations of the current trajectory of the climate system, but typically on timescales of a few years, thereafter representing an irreducible lower bound on forecast skill even given complete knowledge of climate system behaviour. All aspects of response uncertainty are reducible in principle by the acquisition of new information, but it helps to distinguish between

3a. Robust aspects (timescales, forecast variables) of response uncertainty that are unlikely to be revised substantially except on the timescale of climate change itself
3b. Subjective aspects of response uncertainty that could be revised substantially with a change in expert opinion, the acquisition of new data or implementation of new models.

We will argue that the system may be sufficiently linear on anthropogenic climate change timescales for a useful distinction to be made, at least in principle, between these sources of uncertainty even though there are obvious interactions. For example, more sensitive climates will typically display higher levels of natural variability, and estimates of response uncertainty will typically depend on the scenario considered, particularly if constrained by past observations[5,6].

Relative importance of sources of uncertainty and implications for presentation

Studies undertaken since the TAR[6] have demonstrated that response uncertainty dominates global temperature predictions over the first few decades of the 21st-century, while contributing about half the overall uncertainty in temperature projections to 2100, the remainder due primarily to scenario uncertainty. Natural variability is primarily important on decadal and sub-decadal timescales at the global mean level, but significantly more important at longer timescales on smaller spatial scales. The headline temperature projection figure (5d) in the TAR-SPM[7] showed an inner "plume" representing scenario uncertainty alone (a single model forced with the range of SRES scenarios) and an outer "plume" showing combined scenario and response uncertainty (several models forced with the range of SRES scenarios). Even with such small samples, uncertainties sum approximately in quadrature, so this presentation tends to exaggerate the role of scenario versus response uncertainty. The converse presentation showing response uncertainty as the inner plume (a single scenario forcing a range of models) suggests an almost negligible role for scenario uncertainty until the mid-21st-century, which is also potentially misleading. The use of an energy balance model suppresses the contribution of natural variability altogether. A more balanced presentation would be to show forecast plumes combining response uncertainty and natural variability for a (necessarily small) range of representative emissions scenarios, allowing the reader to visualise the impact of adopting different scenarios in the context of other sources of uncertainty in the forecast[6].

Confidence versus likelihood in the presentation of uncertainty

No consistent distinction was made in the TAR between statements of *confidence*, reflecting the degree of consensus across experts or modelling groups regarding the truth of a particular statement, and statements of *likelihood*, reflecting the assessed probability of a particular outcome or that a statement is true. This needs to be resolved in AR4, because we need to communicate the fact that we may have very different levels of confidence in various probabilistic statements. For example, we might wish to argue we have a much higher level of *confidence* in the statement

A: "anthropogenic warming is likely to lie in the range 0.1-0.2°C per decade over the next few decades under the IS92a scenario" (TAR SPM)

than in the statement

B: "it is likely that warming associated with increasing greenhouse gas concentrations will cause an increase in Asian summer monsoon precipitation variability" (ibid.)

even though both can only be qualified by the same "better than two in three chance" *likelihood*. The first statement is based on the analysis of observed anthropogenic warming, the constraint of energy conservation and the assertion that no strongly non-linear global climate changes are anticipated in the coming decades. It is unlikely to change through the introduction of higher-resolution models, additional physical processes or changes in expert opinion. Although relatively weak in itself ("likely"), this statement of odds is reliable in the sense that the level of uncertainty is unlikely to be revised other than downwards as more data are acquired. In contrast, the second statement represents the current consensus across climate models, and the uncertainty estimate could be revised either up or down as the next generation of models and additional physical processes are considered. Hence, although both statements refer to the same level of probability, they have very different policy implications: there is little point in postponing policy decisions in case the scientific community changes its mind on the first statement, because it is unlikely do so, whereas new modelling results are much more likely to impact on the second.

Robust, observationally constrained, STAID probabilistic forecasts

Probabilistic statements that rely on constraints provided by observations, making use of climate models simply to identify robust relationships between observable and forecast quantities, have a very different status to statements based on model inter-comparison studies or surveys of expert opinion. Underlying statement A above, both basic theory and a range of results from climate models suggest near-linear relationships, or transfer functions[5], between warming attributable to greenhouse gases over the 20th century, the idealised Transient Climate Response (TCR)[7] to a 1% increasing CO_2, and global mean warming over the 21st century under any sustained increase in forcing scenario (e.g. A1FI, A2, IS92a etc). A range of attribution studies estimate the 20th century attributable greenhouse warming trend to be in the range 0.6-1.3°C/century (5-95% range)[5,6,7], taking into account uncertainty in anthropogenic sulphate forcing and response, natural external forcing and internal variability (see figure). If these attribution studies and transfer functions are correct, then the 5-95% range of uncertainty in both TCR and forecasts of 21st century global mean warming under any one of these scenarios is only around a factor of two regardless of the models used or prior opinions of the forecasters[8]. This is almost certainly less than the corresponding range of uncertainty in climate sensitivity. We refer to such forecasts as STAID, or Stable Inference from Data[4].

STAID forecasts are not immutable, since new information might cause us to revise our estimates both of past attributable warming (or whatever the constraining observable quantity might be) and the transfer function linking observable to forecast variables (for example, a new class of ocean model might consistently assign a high likelihood to thermohaline collapse in the near future). But such revisions would represent conventional scientific progress, as the current paradigm (that near-term thermohaline collapse is very unlikely) is overturned. Expert judgement is still required to qualify a STAID forecast with an assessment of our confidence in the assumptions on which the forecast is based. Its role, however, is second-order: judgement does not impact directly on actual forecast likelihoods.

In contrast, if a probabilistic forecast is based simply on the spread of results from a range of climate models, even if these are weighted by some measure of similarity to observations, then the experts' decisions as to which models to include in the initial ensemble have a first-order impact on forecast likelihoods. For example, the figure shows the distribution of 20th century warming trends attributable to greenhouse gases based on a conventional attribution analysis that does not depend on the amplitude of any model's response to greenhouse or any other external forcing. The crosses show the corresponding warming trends inferred from the TCRs of models in the CMIP-2 model inter-comparison, with diamonds enclosing the models used in the headline uncertainty ranges of the TAR. The decision to exclude the highest-response model from the TAR forecast ranges implies a zero chance of an attributable 20th century greenhouse warming trend exceeding 1°C/century, even though the data allows a >30% chance of a past greenhouse warming of this magnitude. We will argue that probabilistic forecasts cannot be considered robust as long as they are so dependent on expert judgment, and the solution is to condition forecasts explicitly on observations, using models to identify useful relationships between observable and forecast variables rather than as an explicit input into the forecast likelihoods themselves.

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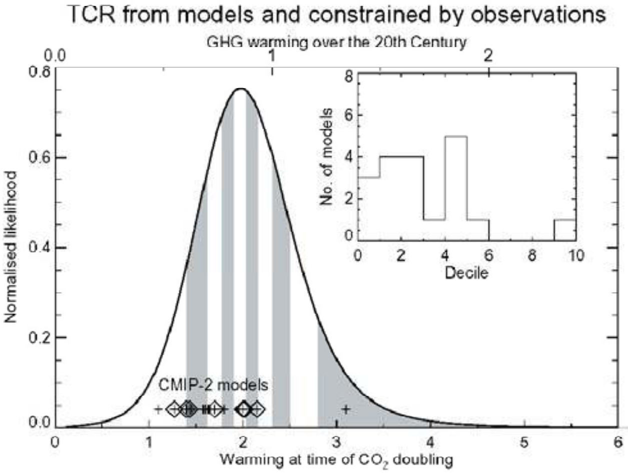

Figure. Comparison of the distribution of transient responses to increasing CO2 expressed as attributable warming over the 20th century (top axis) and Transient Climate Response, TCR (bottom axis). Crosses indicate members of the CMIP-2 model inter-comparison, while diamonds show models included in the summary figures of the 2001 IPCC Scientific Assessment. Inset panel shows the number of CMIP-2 models falling into each decile of the distribution inferred from the detection and attribution analysis: a representative ensemble would have equal numbers in each decile, whereas a forecast based on this ensemble, even if weighted by distance from observations, would substantially underestimate the likelihood of high TCRs. See ref. 4 for more details.

Annex 2: Extended Abstracts

Uncertainties in Modelling Climate Change

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1. The Hadley Centre Contribution to Quantifying Uncertainties

Following the recommendations of the TAR, The Hadley Centre has undertaken a programme of research which aspires to quantify uncertainties that arise from modelling assumptions and to produce probabilistic predictions of climate change. The programme is based around ensembles of experiments with version 3 of the Hadley Centre model in which uncertain model parameters are varied.

A number of key developments have been made to date (Murphy et al., 2004):

1. A 53 member ensemble has been performed using the atmosphere model coupled to a slab ocean (HadSM3). Modelling experts identified 29 poorly-constrained model parameters and in each case gave estimates of their range of uncertainty. In each ensemble member, a single parameter was perturbed with respect to the standard model version to the maximum or the minimum of the range and a calibration, control and 2xCO_2 experiment was performed. This experimental setup is useful in identifying the key uncertainties in atmospheric feedbacks which control the magnitude of global and large-scale regional[1] climate change.
2. A technique has been developed whereby each ensemble member can be assigned a relative weight based on the skill of that member in simulating present day climate. The technique computes a simple normalised root mean squared (RMS) error between the time-averaged model climate variable and time-averaged observed climate variable. RMS errors are summed over a large number of dynamical and physical variables to produce a Climate Prediction Index (CPI). This provides a more objective alternative to "expert" assessment of the skill of a climate model.
3. A linear statistical approach has been used to produce a probability density function (PDF) from the 53 ensemble members expressing the uncertainty in equilibrium global climate sensitivity. The PDF has been further refined using the CPI to up-weight more skilful models and down-weight less skilful models. This leads to an estimate of the 5-95% range of sensitivity of 2.5-5.6°C for a doubling of CO_2.
4. The ensemble has been used to investigate a common method of generating probabilistic predictions of large-scale regional climate change in which the patterns of climate change from one model are simply scaled by the global mean changes from other models. It is found that this method is likely to underestimate the true uncertainty in large-scale regional climate change predictions.

In addition to this study the following project has been initiated (Stainforth et al., 2004):

5. A subset of 6 of the parameters have been used perform a multi-thousand member ensemble of HadSM3 using idle time on home and office personal computers (the climate*prediction*.net project). Multi-parameter perturbations were made, exploring all possible combinations of minimum, intermediate and maximum values of six parameters affecting cloud, convection and precipitation. Model versions are found with implied climate sensitivities ranging from less than 2ºC to more than 11ºC.

Work that is currently underway and that will be made available to the AR4:

6. A 128 member multiple-parameter perturbation ensemble of HadSM3 is under production using again the simple control and 2xCO_2 scenario. In this ensemble, the 29 uncertain parameters are perturbed together. The parameter combinations were chosen using a linear statistical modelling approach and are those which are most likely to produce skilful simulations of present day climate (based on the CPI), while sampling the model parameter space and the range of possible climate sensitivities as efficiently as possible. This ensemble (combined with the climate*prediction*.net ensemble) will provide a basis for the identification of non-linear interactions between processes.
7. A 16 member multiple-parameter perturbation ensemble of HadCM3 (i.e. the Hadley Centre atmosphere model coupled to a dynamical ocean model) is also under production. For each member

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[1] Here we use the term "large-scale regional" to distinguish the scales of regional climate which are reliably taken from a global model from those produced using dynamical or statistical downscaling techniques.

the following simulations are planned; a multi-century pre-industrial control phase, a phase forced with historical natural and anthropogenic factors from 1860-2000; a high SRES scenario (probably A2) from 2000-2100 and a low SRES scenario (probably B1), also from 2000-2100. Perturbing model parameters leads to imbalances in the model's radiation components hence flux adjustments are employed.

8. The 16 member HadCM3 ensemble will be combined with scaled results from the 128 member HadSM3 ensemble to provide time dependent estimates of the uncertainties in large-scale regional climate change implied by the combined effects of parameter perturbations and natural variability.
9. Boundary conditions from members of the transient HadCM3 ensemble will be used to drive high-resolution regional model (HadRM3) simulations of climate change over Europe in order to provide more detailed regional predictions, including changes in extreme events.
10. In related work, the perturbed parameter HadCM3 ensemble members will be used in studies of seasonal-decadal climate prediction in which the model is initialised from observed climate states using data assimilation.

We believe these studies provide the first systematic attempt to quantify uncertainties in a complex climate model at both global and regional scales. There are many assumptions and caveats. It will provide a basis for probabilistic predictions conditional on the range of modelling uncertainties considered. Future work will seek to explore a wider range of uncertainties by considering other Earth System modules and by including alternative parameterisations from other GCMs.

2. General Comments on Ensemble Climate Prediction and Quantifying Uncertainties for AR4

As pointed out in the concept paper for this meeting, uncertainty arises because of lack of predictability (or natural variability), uncertainty in modelling and uncertainty in scenarios. The following points are most relevant for the first two types of uncertainty:

1. While "simple" models have been used to produce probabilistic assessments and predictions of global climate change (see e.g. Forest et al., 2002), complex coupled global circulation models (GCMs) represent the only real hope of producing the regional and multi-variable probabilistic predictions required for adaptation and mitigation strategies. Ensembles of GCM projections are therefore essential to provide a realistic basis for quantitative assessments of climate-related risk.
2. No group is in a position to produce an ensemble which samples all modelling uncertainties for AR4. All PDFs will therefore have assumptions and caveats associated with them.
3. Because of the impossibility of probabilistic forecast verification on century time scales, the only way to have confidence in the prediction PDF is that it is "stable" and does not widen when new information (e.g. models with increased resolution) is introduced (Allen et al. 2003).
4. The weighting of ensemble members by their relative skill is crucial in order to constrain the upper and lower limits of possible climate change. Methods for weighting ensembles are in their infancy and consensus is unlikely to be reached during the production of AR4.

3. A Scenario for the Representation of GCM Uncertainty in AR4

There are many barriers to quantifying uncertainties and producing probabilistic predictions with GCMs. The science is in its infancy, yet it is crucial for both the impacts and the policy communities and for the long-term health of the science of climate change, that we make a concerted effort in AR4 to be quantitative about uncertainties. For example, the following strategy could be feasible:

1. Data from control and scenario experiments from the world's modelling groups could be uploaded to the DDC/PCMDI as soon as they become available.
2. Simple but objective skill-score measures could be developed to produce weighted probabilistic predictions with assumptions and caveats clearly stated. Different modelling centres could take the lead in constructing predictions for different variables/regions.

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Annex 2: Extended Abstracts

Helping UK Decision-Makers Deal with Climate Risk and Uncertainty: The UKCIP Approach

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Introduction

Since it was established in 1997, the UK Climate Impacts Programme (UKCIP)[1] has worked with a wide range of regional and sectoral decision-makers in the public and private sectors on climate impacts and adaptation. Based on interactions with these stakeholders, this paper:

1. Describes how, from UKCIP's experience, decision-makers are currently addressing climate change impacts and adaptation uncertainties;
2. Outlines some of the main features of a new decision-centred tool for managing climate risks and uncertainties, developed by UKCIP and the UK Environment Agency; and
3. Concludes with some suggestions of ways in which scientists involved in the IPCC AR4 could provide more decision-centred information.

1. How are UK decision-makers currently addressing climate change uncertainties?

Stakeholder-led impacts and adaptation studies under the UKCIP umbrella have used the UKCIP98 or UKCIP02 climate change scenarios (Hulme and Jenkins, 1998; Hulme *et al*, 2002). These studies have, under the guidance of UKCIP, identified the possible impacts of a number of scenarios – most commonly, low and high (emissions) climate change scenarios. In several cases, study findings are now referred to in key regional planning documents. However, while we now have strategic planning documents that include some qualitative information about climate impacts, to date, this information has seldom been used to make 'real' adaptation decisions on the ground. Most UK decision-makers have not yet identified which decisions should include adaptation, or worked out *how much* adaptation to undertake, or *which climate change scenarios (if any)* to base their adaptation decisions on, etc. Notable exceptions are to be found in flood management and water resource planning.

UK flood management takes account of climate change, by making allowances for changes on the coast and through a sensitivity test for increased river flows (MAFF, 1999 & 2001; Defra, 2003). Details of the 'climate change allowance' for these two areas are

Table 1. Allowances for climate change in UK flood management (MAFF, 1999 & 2001; Defra, 2003)

Decision area & parameter	Allowance for climate change	Reason for decision on allowance
Coastal flood management:		
Mean and extreme sea levels	4.5mm p.a. for next 40-50 years + adjustments for local land movements. 'In view of … high degree of uncertainty, it is not possible at present to give guidance on whether allowances for changes in storm surge due to climate change should be used.' (MAFF, 2001). 'Extreme levels should be reviewed if higher extreme values, especially around the Thames Estuary, are supported by future modelling' (Defra, 2003).	Allowance of 4.5mm p.a. adopted following IPCC (1990). Reviewed after publication of UKCIP02 climate change scenarios: no change made for mean sea levels, but advice for extreme levels revised as per Defra (2003) quote.
High and extreme wind speeds	Test sensitivity to 10% increase in offshore wind speeds and wave heights by 2080s and 5% increase in wave periods. Needs to be considered in relation to depth limited conditions inshore' (Defra, 2003).	New recommendation after publication of UKCIP02 scenarios.
River flood management:		
High and extreme rainfall and river flow	'Sensitivity analysis of river flood alleviation schemes should take account of potential increases of up to 20% in peak flows over the next 50 years' (MAFF, 2001).	Adopted following analysis of flood flows on Thames and Severn rivers, using HadCM2 (Reynard *et al*, 2001). Reviewed after publication of UKCIP02 scenarios: no change made, though further research currently in progress.

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[1] UKCIP is based at the University of Oxford and funded by the Department for Environment, Food and Rural Affairs

Box 1: Including climate impacts in water resource planning

i. A recent report to the water industry (UKWIR, 2003) provides regional change factors for the 2020s, for mean monthly rainfall, temperature and potential evapotranspiration (PE), as well as runoff, based on the UKCIP02 low, medium(a) and high emissions climate change scenarios.

ii. These factors are used in water resource models to calculate 'Deployable Output (D.O.) with climate change' – the annual average quantity of water that can be supplied in the most severe drought in the perturbed time series, thus:
    - The rainfall and PE factors are used to perturb observed 80-year time series of rainfall and PE, which are then input to aquifer/recharge models, to simulate base flow.
    - Surface flow is derived from catchment models perturbed using the runoff factors.

iii. The 'D.O. with climate change' values then feed in to a Monte Carlo model as three discrete values, along with probability distributions of other uncertainties, to produce an overall 'Headroom' uncertainty. A 2% increase in water demand due to climate change by the 2020s (Downing *et al*, 2003) is included at this stage.

iv. The company takes a view on the level of risk that is acceptable to itself and the regulators to select a value of 'Headroom' from this distribution, which is used in the supply demand balance equation:

Demand + Headroom =
Deployable Output – Outage (losses)

Note (a): The medium scenario has two 'subsets', medium low and medium high, but these are identical for the 2020s (see Table 7, Hulme et al, 2002)

provided in Table 1. Analysis of the quotes in the table indicates that allowances for climate change are not currently included for risk factors where there is gross uncertainty, such as for changes in extreme sea levels. Most of the allowances that are included could best be described as reasonably precautionary.

For water resources, the water companies have to include information on climate impacts in their Water Resources Plans to the Environment Agency. The most recent plans cover the period up to 2030. The approach taken varies from company to company. That adopted by Thames Water Utilities (see Box 1) is described as 'reasonably pessimistic, but not too pessimistic' (Thames Water Utilities, 2004).

In summary, many UK decision-makers have yet to make decisions about how much climate adaptation to undertake. Those who have made adaptation decisions tend to have adapted to what they understand to be a 'medium' expected amount of climate change, and to the changes they understand are most likely. Sensitivity tests are being used to investigate the significance of changes where the evidence from the climate science community is less well established.

2. A decision-centred tool for managing climate risks

UKCIP and the Environment Agency have recently published a report that presents a decision-making framework for taking account of climate risks and uncertainties (Willows and Connell, 2003). The framework (see Figure 1) describes a process for the appraisal and management of risks and uncertainties. Importantly it is similar to many others used routinely for corporate risk management. It is therefore recognisable to decision-makers and their technical advisers. Training workshops have demonstrated issues that are key to its successful application (Box 2). Climate change may rarely be the sole material risk factor or source of uncertainty for the outcome of most decisions. Hence we believe that climate risks are best addressed by 'mainstreaming' them within existing, routine or strategic risk management processes. The UKCIP framework is now being incorporated into guidance published by other organisations[2]. Most recently, we have developed a guidance note on how to include climate risks under the forthcoming European Union Strategic Environment Assessment (SEA) Directive, which applies to spatial planning. We are currently working with a group of institutional investors with interest in good corporate governance and risk management, to further develop the framework for application in the investment community.

3. Suggestions for providing more decision-centred information in AR4

We consider that all sources of uncertainty of relevance to the decision should be identified and given appropriate attention in any decision-making process. Within the climate change community at present, there is a strong emphasis on emissions uncertainty, but much less consideration of climate impact (system) model

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[2] For instance, the UK Office of the Deputy Prime Minister; UK Department for International Development; European Environment Agency; UNFCCC.

Box 2: Key issues for application of decision-making framework (Willow and Connell, 2003)

Decision-makers should take a balanced approach to managing climate risks, alongside the other risks they face. To do this, it is important to understand the significance of climate risks to the decision problem being considered. Where climate risks are of primary importance, this is described as a *climate adaptation decision* – for instance, the flood management case presented above. *Climate-influenced decisions* include climate risks as one of a number of important risk factors. Climate risks are insignificant for *climate independent decisions*.

Decision-makers need to establish their own decision-making criteria (framework stage 2), against which they will appraise their options (stage 5). These criteria should take account of defined thresholds, which represent the boundary between tolerable and intolerable levels of climate risk. Notably, this approach does not rely on the decision-maker 'choosing' which climate scenario to adapt to. The criteria chosen will also depend on the decision-maker's attitude to climate risks. Adaptation itself is not risk free: there are risks of over- and under-adapting to climate. A risk-averse approach to climate change uncertainty should lead to a better level of 'protection', but may mean that resources were 'wasted' on unnecessary adaptation.

Decision-makers should aim to identify important climate risk factors, which will be their priorities for adaptation, and to describe the uncertainties associated with these. Tools that help to capture, categorise and communicate information about uncertainties are very useful in this respect (Janssen *et al*, 2003, Walker *et al*, 2003). The policymaker's view of uncertainty focuses on the valuation of outcomes, conflicting objectives, priorities and interests. The modeller's viewpoint emphasises cumulative uncertainties associated with model results and the robustness of conclusions. Climate modellers draw boundaries at the input to the impact model, though the uncertainty within the impact model may be of equal or greater significance.

We recommend that decision-makers should aim to keep open or increase options that will allow climate adaptation to be implemented in the future, when the need for climate adaptation and the performance of different adaptation measures is less uncertain. The circular, iterative nature of our risk framework promotes adaptive management, which is being increasingly recognised as a useful technique for dealing with climate and other uncertainties (Harremoes, 2003). An important aspect of adaptive management is to avoid implementing adaptation constraining decisions. These are decisions that will make it more difficult to cope with future climate risks – such as inappropriate development in a flood risk area (termed 'mal-adaptations' in IPCC TAR).

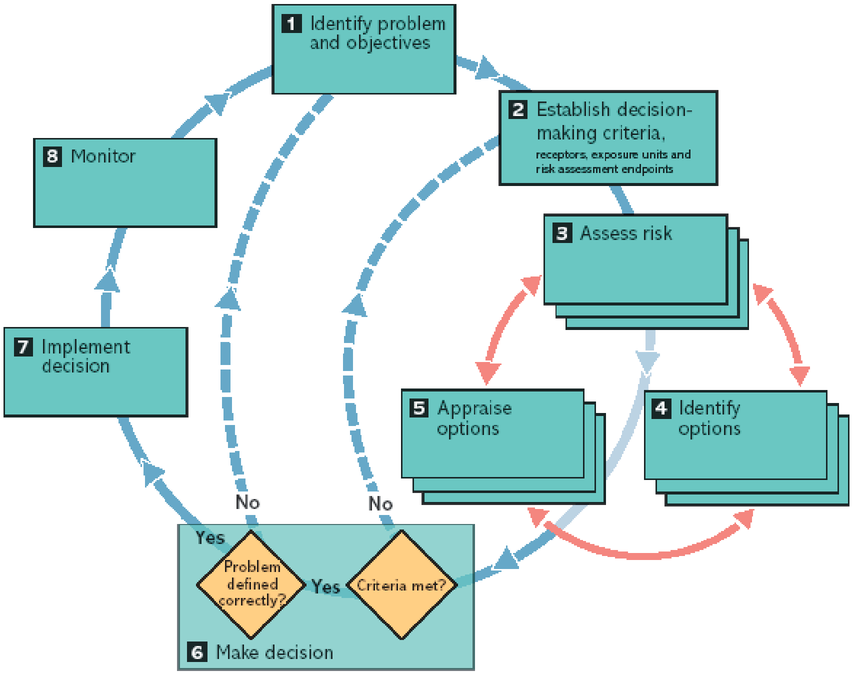

Figure 1. A framework to support good decision-making in the face of climate risks

uncertainties and of other (non-climate) risks. It would be useful if the AR4 could begin to redress this balance, and highlight the need for decision-makers to better understand the relationship of their system to climate. We consider that a thresholds-based approach to climate risks is useful for decision-makers, and again, this is something on which the AR4 could give guidance.

Busy decision-makers are addressing climate as one of a large number of risks. Where scenarios are presented, they would find it most useful to have a central 'best guess' with 'high' and 'low' bounds (at least until *ca*. 2030, when emissions scenario uncertainties have not started to expand). Increasingly, however, more sophisticated users of climate information, such as the water companies, are calling for probabilistic climate information. For these users, the following approaches would be most helpful:

i. A single forecast from the present day until *ca*. 2030, incorporating natural climate variability, emissions and modelling uncertainties within one probability density function (PDF) for each climate variable (and with scenarios for emissions uncertainty for forecasts beyond 2030); or
ii. Identifying scenarios that represent the most significant uncertainties over the next 20-30 years, and providing information (as PDFs) for climate variables that are contingent on each scenario and the uncertainties underlying it; and
iii. Possibly providing other scenarios for rapid non-linear changes that are considered possible within the time frame of most planning decisions.

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Living with Uncertainty: From the Precautionary Principle to the Methodology of Ongoing Normative Assessment

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We have become capable of tampering with, and triggering off, *complex* phenomena. As a consequence we have to confront a new kind of uncertainty. The key issue is to develop new concepts of prudence that are suited to this situation. A long time ago Aristotle's *phronesis* was dislodged from its prominent place and replaced with the modern tools of the probability calculus, decision theory, the theory of expected utility, etc. More qualitative methods, such as futures studies, "Prospective", the scenario method were then developed to assist decision-making. More recently, the precautionary principle emerged on the international scene with an ambition to rule those cases in which uncertainty is mainly due to the insufficient state of our scientific and technological knowledge. We believe that none of these tools is appropriate for tackling the situation that we are facing now.

What is needed is a novel approach to the future, neither scenario nor forecast. We submit that a methodology we introduce under the label *ongoing normative assessment* is a step in that direction.

We first show that the conceptual underpinnings of the notion of precaution are extremely fragile. One of the major deficiencies which hamstrings this notion is that it does not properly gauge the type of uncertainty with which we are confronted at present. Our situation with respect to new threats, in particular abrupt climatic change, exhibits novel features that must be seriously taken into account. Although uncertainty is objective, we are not dealing with a random occurrence either. This is because each of the catastrophes that hover threateningly over our future must be treated as a *singular event*. Neither random, nor uncertain in the usual sense, the type of "future risk" that we are confronting is a monster from the standpoint of classical distinctions

We review and discuss a series of dimensions that make the kind of uncertainty we are confronting objective, and not merely epistemic: deterministic chaos and sensitiveness to initial conditions; existence of tipping points and other complex behaviour; incompressibility of information.

However, we put the emphasis on yet another source of uncertainty due to the fact that society is a participant. It is a gross simplification to treat the climate and the global ecosystem as if they were a physical dynamical system. Human actions influence the climate, and global warming is partly a result of human activity. If many scientists and experts ponder over the determinants of climate change, it is not only out of a love for science and knowledge; rather, it is because they wish to exert an influence on the actions that will be taken by the politicians and, beyond, the peoples themselves. The experts see themselves as capable of changing, if not directly the climate, at least the climate of opinion.

When these observations are taken seriously, it is usually in the manner of control theory: human decision is treated as a parameter, an independent or exogenous variable, and not as an endogenous variable. Then, a crucial causal link is missing – the motivational link. Human decisions that will be made will depend, at least in part, on the kind of anticipation of the future of the system, this anticipation being made public. And this future will depend, in turn, on the decisions that will be made. A causal loop appears here, that prohibits us from treating human action as an independent variable.

We distinguish three ways of anticipating the future of a human system, whether purely social or a hybrid of society and the physical world. The *foresight* method treats the system as if it were a purely physical system; the *Prospective* method, and its incarnation in the scenario approach, treats the human agent as intervening on the system from the outside; and the method we advocate puts centre stage the causal loop described above. We show that the linear, "occurring" time familiar to all decision makers must be replaced with a different conception of temporality, which we dub *projected time*: it takes the form of a loop, in which past and future reciprocally determine each other.

If the future depends on the way it is anticipated and this anticipation being made public, every determination of the future must take into account the causal consequences of the language that is being used to describe the future and how this language is being received by the general public, how it contributes to shaping public opinion, and how it influences the decision-makers. In other terms, the very description of the future is part and parcel of the determinants of the future. This self-referential loop between two distinct levels, the epistemic and the ontological, is the signature of human affairs. This condition provides us with a criterion for determining which kinds of description are acceptable and which are not: the future *under that description* must be a fixed point of the self-referential loop that characterizes projected time.

Any inquiry into the kind of uncertainty proper to the future states of the co-evolution between climate and society must therefore include a study of the linguistic and cognitive channels through which descriptions of the future are made, transmitted, conveyed, received, and made sense of. This is a huge task, and we limit ourselves here to three dimensions that seem to us of special relevance for the study of climate change: the certainty effect, the aversion to not knowing, and the impossibility to believe. These effects give rise to cognitive barriers, e.g. that if an agent does not have information or experience, he or she does not take action; a situation that for an outsider appears as paralysis in decision-making. An immediate concern, then, is to offer a way of functioning which is capable to bringing the agents back to operational mode from the dead end of cognitive paralysis.

We conclude our study with a description of the methodology of *ongoing normative assessment*. Such a methodology is a balanced solution between waiting until it is too late, if the effects are dangerous, and acting when it is yet too early. This may be presented as a prescription to *live with* a possible catastrophe in order for the catastrophe not to occur.

Issues Related to Uncertainty in the Observed Climate Record

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This paper examines some issues that result in uncertainty in results of climate studies using observations from various observing systems. The main focus here is on data completeness, and data homogeneity issues that can contribute to uncertainty in scientific results.

The primary evidence for observed changes in the climate has come from observing networks that were established mainly in support of weather forecasting. These networks provide observations that are well suited to the needs of the forecasting and aviation community, however, they are often not well suited to the detection of climate change. Changes in observing practice, instrumentation, station location and incomplete data often result in non-climatic changes in time series that can mask the more subtle climate change signals present in the data. These non-climatic changes, most commonly referred to as *inhomogeneities* or *time-dependent biases*, increase our uncertainty regarding any conclusions drawn from these data. Following are some examples of these problems.

Missing Data

Data used to develop baseline climate data sets such as the Global Historical Climatology Network (Peterson and Vose 1997) come from a variety of sources including individual country data sets, and data received on the Global Telecommunications System. For a number of reasons the period of record for most stations contains missing data. Observations may be made hourly or daily, and these data are then used to create averages for longer periods (e.g. monthly, seasonal, or annual), which eventually are used to create a product like the global annual temperature time series. If an observing station has incomplete data, then the longer period averages will contain some kind of bias depending on the weather characteristics of the missing period.

Discontinuities

Discontinuities in time series that are non-climatic in origin occur due to a change at an observing station, or due to a change in some statistical method for creating longer period averages. Observing station changes may be a station relocation, change in instrumentation or change in observing practice such as changing observing time. This change commonly results in an abrupt step change in the time series resulting in either colder or warmer readings. Changes may be very small (e.g. <<1degC) or larger, but will increase uncertainty in scientific results. The U.S. Cooperative Observing Network (COOP) uses an observing system that records both the highest (maximum), and lowest (minimum) temperature in the previous 24h period, then these values are recorded by the observer at a set time each day (e.g. 7 am or 5 pm), and the thermometers are reset. Figure 1 shows the bias introduced into March temperatures by a change in the observing time from late afternoon to

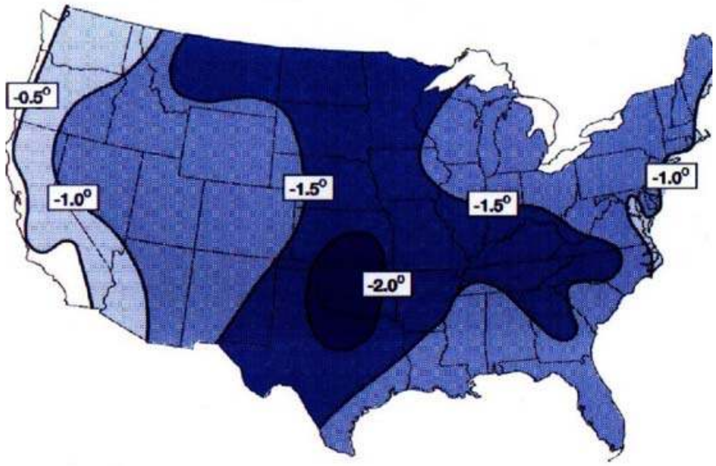

Figure 1. Change in the average March temperatures (°C) resulting from changing the time of observation from 5 P.M. to 7 A.M. local time in the U.S. Cooperative Observing Network (from Karl et al. 1986).

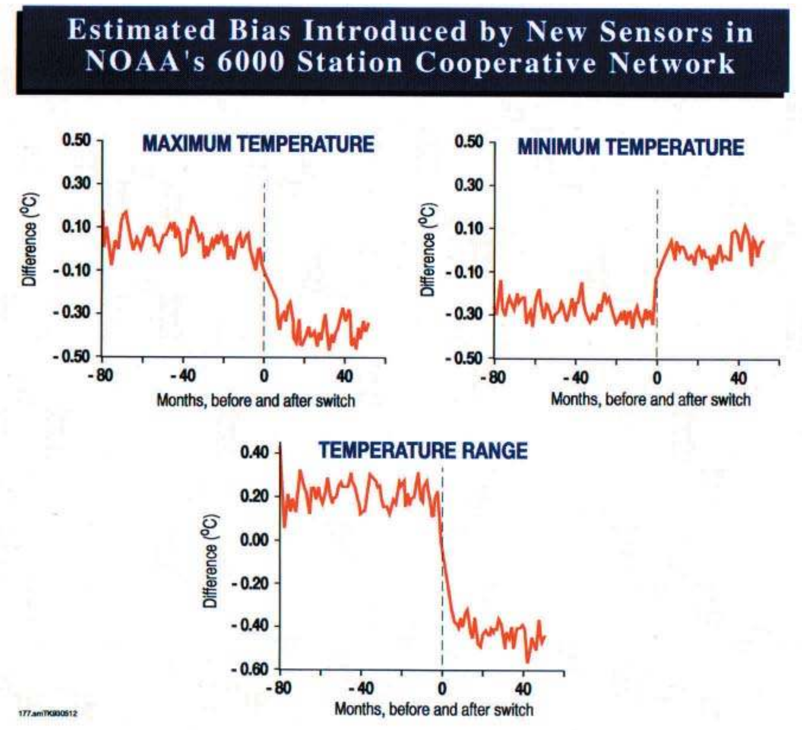

Figure 2. Estimated bias introduced into observations of maximum temperature, minimum temperature and the diurnal temperature range due to a change from liquid-in-glass to electronic thermometers in the U.S. Cooperative Observing Network. (from Quayle et al. 1991).

morning, which has been the trend in the COOP network over the past 20 years. This change has resulted in an artificial cooling in the time series due to a step change to cooler monthly averaged temperatures. Figure 2 shows what can happen when there is an instrument change in an observing network. In the mid-1980s the U.S. National Weather Service began changing temperature observing instruments in the COOP network from liquid-in-glass thermometers to the Maximum-Minimum Temperature System (MMTS) which is an electronic thermistor-based system. At stations that received the MMTS the average bias introduced by the change was a cooling of the maximum temperature, warming of the minimum temperature and narrowing of the diurnal temperature range (DTR=maximum temperature minus minimum temperature).

Landuse/Landscape Changes

Changes in landuse/landscape around an observing site also causes non-climatic changes in climate data. Urbanization is one clear example of this effect and one that has caused much concern and uncertainty in climate trends, particularly temperature trends. Figure 3 shows the differences in observed temperature and the diurnal temperature range for large urban areas (metropolis), smaller urban areas, and rural areas in China and Japan. In both countries, the large urban areas are warmer than the smaller urban and rural areas. Similarly, the DTR in large urban areas is smallest, compared to the smaller urban areas and rural areas. A number of studies have examined the impact of urbanization in the climate record and arrived at similar conclusions: that approximately 0.1degC of the observed 0.6degC warming since the late 1800s in the global temperature time series is due to urban warming (Jones et al. 1990, Easterling et al. 1997).

Data Adjustment Methods

A number of methods have been developed to adjust station data for discontinuities (e.g. Easterling and Peterson 1995), and Karl et al. (1986) developed a methodology to adjust data from the COOP network for changes in observing time. Karl et al. (1988) developed a population-based method to adjust temperature data for increasing urbanization effects. Finally, Easterling et al. (1996) have shown that differences between results from adjusted and non-adjusted data get smaller as the area of averaging gets larger (e.g. from a small region to the globe), however these kinds of data problems clearly have implications for uncertainty in regional estimates of climate change.

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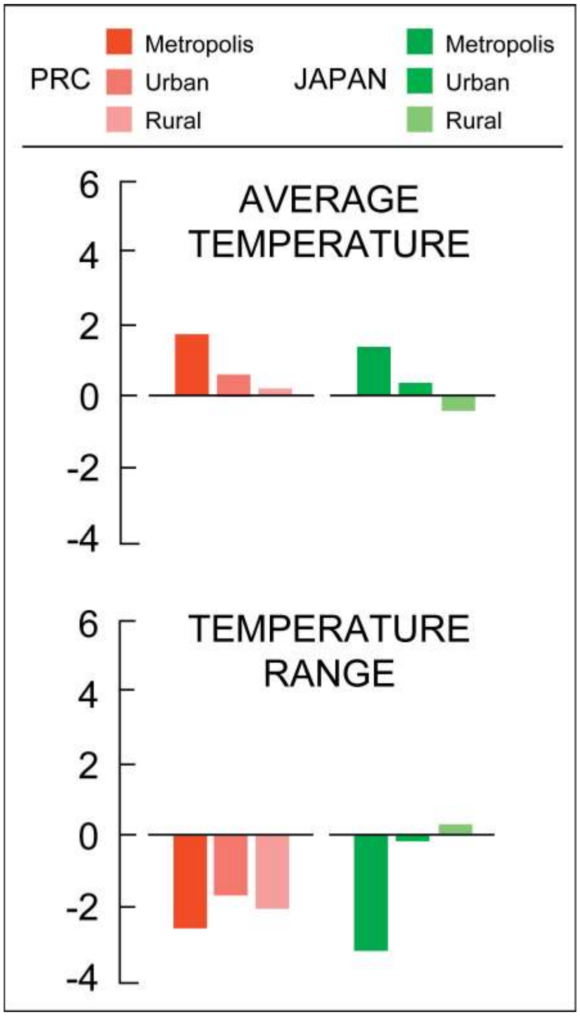

Figure 3. differences in average temperature and the diurnal temperature range in large urban areas, smaller urban areas, and rural areas in China and Japan.

Bridging Uncertainty from Climate Models to Simulation of Impacts and Adaptation: The Case of Crop Yield Modeling

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Estimates of the impacts of climate change and the likelihood of successful adaptation are often considered to be the most uncertain links in the chain of information flow beginning with the measured and predicted sensitivity of the climate system to increased radiative forcing and ending with the predicted vulnerabilities of ecosystems and society to climate changes. State-of-the-science impact assessment modeling integrates climate change effects on biophysical and socioeconomic systems, and accounts for adaptation and mitigation (Figure 1). Not only does the uncertainty of climate change scenarios propagate through impact assessments, but new uncertainty is introduced with each additional component of the impact assessment. The challenge of impact assessment is to convey a strong sense to the stakeholders/decision makers of the likelihood of a given impact occurring or the successful avoidance of impacts by adaptation (NRC, 2003). The purpose of this paper is to review important sources of uncertainty in impact modeling, using crop simulation models as a case in point, and to propose some simple question to serve as a checklist to AR4 WG II authors for building a stronger case for expressing uncertainty than occurred in the TAR.

The largest single source of uncertainty in the results of impact modeling derives of the climate change scenarios that are used to force the impact models. There is a tendency to think of impact estimates as being no more reliable than the sum of uncertainties of the climate change scenarios that drive them. The features of climate change scenarios that are most problematic for impact models are the estimated magnitude, rate, variability (in time and space), and scale (temporal and spatial) of climate change. While all of those introduce uncertainty for crop modeling, variability and scale are particularly challenging. Crop yields vary much more with changes in interannual climate variability than changes in climate means. The change in occurrence of extreme events has a much larger impact on Kansas wheat yields, for example, than a simple change in mean climate with no change in variability (Mearns et al. 1996). An example of the effect of manipulating the variance of climate change on the distribution of maize yields across the Southeastern U.S. is shown in Figure 2. The scale resolution of physiological crop models is usually no more than a hectare while the scale resolution of GCMs is hundreds to thousands of kilometers. This scale mismatch introduces large uncertainty in simulated crop yield response to climate change across regions. Spatial scale uncertainty can be quantified by comparing crop yield simulations forced by low resolution GCMs

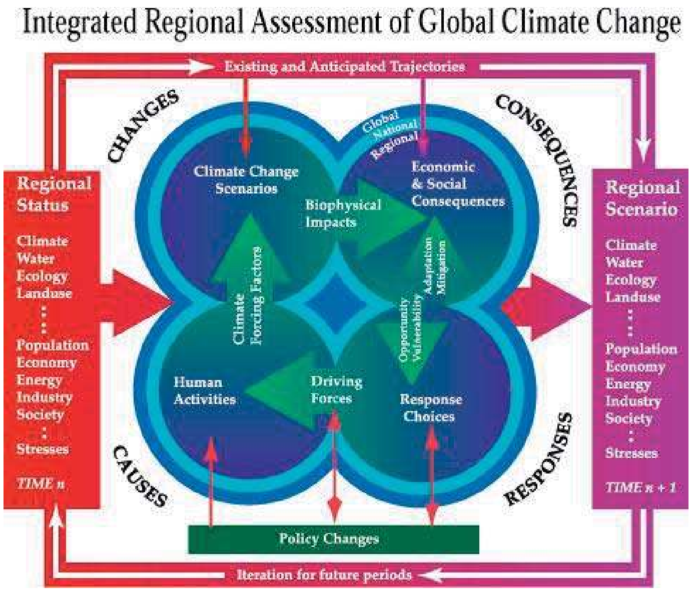
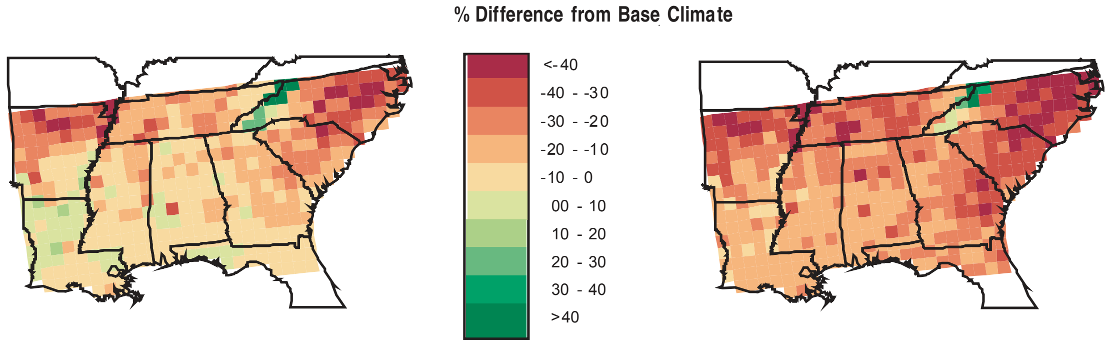


Figure 1. Components of Regional Integrated Impact Assessment Modeling (Source: Penn State Center for Integrated Regional Analysis)



2 x CO2 , current variance

2 x CO2 , 2 x current variance

Figure 2. EPIC simulations of maize yield response to different variances of RegCM 2xCO2 climate change (1960-95 baseline).

with those forced by high resolution nested regional climate models (Figure 3). A particular dimension of climate variability that is difficult to evaluate in impact models is the chaotic and/or unpredictable nature of the time-evolving climate change. Periods of highly contrasting modes of climate variability will elicit widely divergent impacts and adaptation challenges from those of more consistent modes. Currently, there is little information on that form of uncertainty in the impact assessment literature.

Climate uncertainty apart, other sources of uncertainty in impact assessment identified by Katz (2002) include model structure and scaling/aggregation assumptions. Incomplete or inaccurate model structures are common in impact research. This often leads to important differences in those structures between models that designed to predict similar quantities. For example, most crop models rely on the concept of optimum photosynthetic temperature for the estimation of temperature stress on plants. Yet, significantly different optima for the same crop are used among different models. The difference in optimum photosynthetic temperature between EPIC-maize and CERES-maize models is approximately 1°C, which introduces a built-in bias (Figure 4). Other deficiencies in crop model structures that introduce uncertainty include crude specification of the direct effects of atmospheric carbon dioxide on photosynthetic and water use efficiencies, the effects of pests and pathogens, and extreme meteorological events (e.g., hail, high wind, flooding).

Scaling/aggregation assumptions introduce another significant form of uncertainty to impact models. Physiological crop models are, for all practical purposes, point-specific. Yet their predictions are often treated as representative of regions. Scaling is typically done by weighted averaging of model outputs over areas of homogeneous inputs such as soils or cropping system. Often the model outputs are derived of non-linear variable-process relationships, which makes scaling-up tricky. Averaging (making linear) of such non-linear relationships over space creates significant aggregation errors illustrated in Figure 5. The more non-linear the functional relationship, the greater the aggregation error introduced by averaging.

There are many more sources of uncertainty in impact assessments than have been mentioned here,

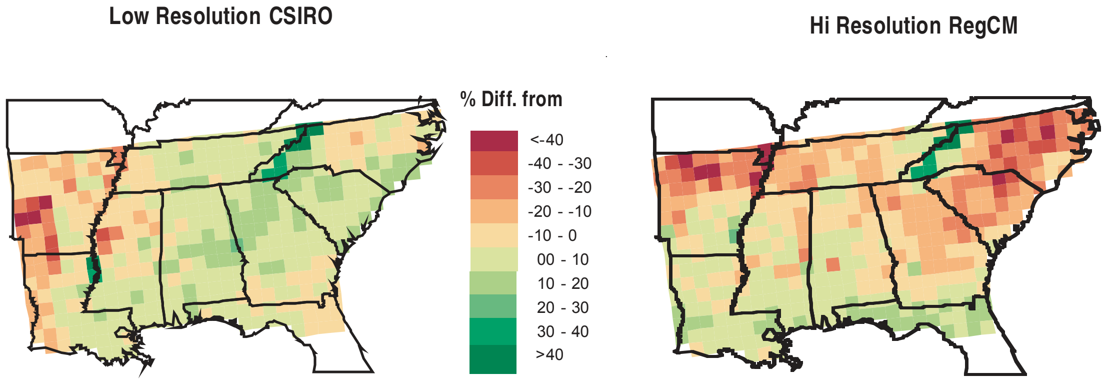


Figure 3. EPIC simulations of maize yield response to low resolution 2xCO2 climate change and to high resolution 2xCO2 climate change.

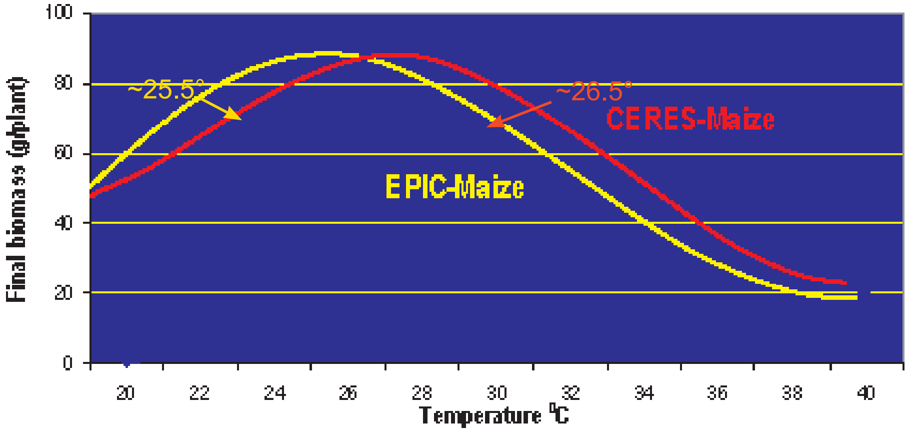


Figure 4. Photosynthetic temperature curves for the EPIC-Maize and CERES-Maize models.

but the above are among the more widely recognized ones. In the IPCC-TAR WGII report, considerable effort was given to characterizing uncertainty, with much of this being done after the review had been completed. Uncertainties were retro-fitted into important statements. This brought praise and criticism at the same time (Reilly et al., 2001). For the AR4, it is crucial that treatment of uncertainty be conceptualized and incorporated into the initial stages of the assessment. It is important to remember that the IPCC is hostage to the requirement that research to be included in the assessment has appeared in approved literatures. Only a fraction of the relevant important impact and adaptation research to be reported in the AR4 will be based on use of SRES climate change scenarios. Hence, it will be difficult to adhere purely to the suggestion by Manning and Petit (2003) that WG II focus on conditional uncertainty in the effects for a given climate change scenario and that overall uncertainties be treated at the synthesis report level. In preparation for treatment of uncertainty in the WGII AR4, the following questions might serve as guidelines for establishing internal consistency of individual research findings that are being compared across regions, time periods, climate change and socioeconomic scenarios, sectors, and so on. They include:

- How similar/different are the climate change scenarios being used to examine impacts similar in terms of transient vs. equilibrium, assumed variability, spatial and temporal resolution, and so on?

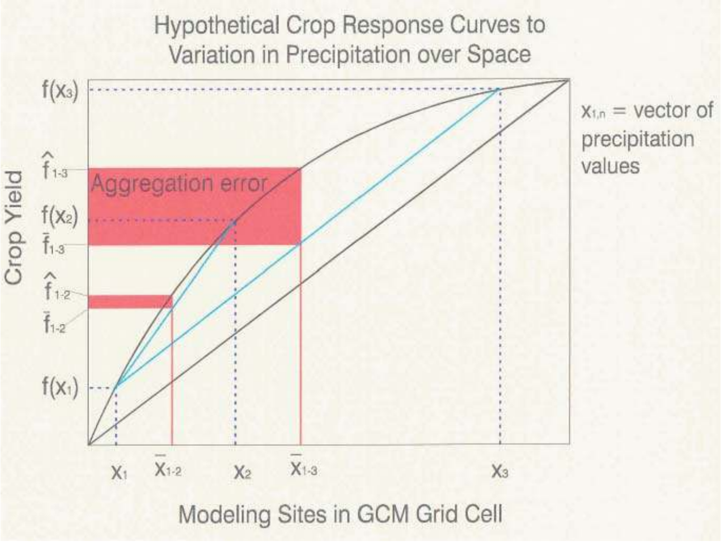


Figure 5. Aggregation error resulting from averaging values predicted by a non-linear variable-process relationship—the difference between the linear locus of points described by averaging and that described by the true non-linear functional relationship is the aggregation error.

- Are model assumptions (e.g., rate of increase in atmospheric CO2 direct effects, types of adaptation deployed) similar between studies?
- How similar/different are the model structures between studies?
- Is there a basis for creating a range of climate change impact outcomes across ensembles of climate change scenarios for certain quantities (e.g., crop yields, runoff, sea level rise damages, species changes)?

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Annex 2: Extended Abstracts

When Do POETS Become Dangerous?

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POETS represent the Probability Of Exceeding Thresholds, and are an essential part of assessing the risk of climate change.

Understanding and responding to the enhanced greenhouse effect is all about risk assessment and management. Greenhouse science would largely be a quaint scientific curiosity if it were not for the consequences of climate change (climate-related risks) and the consequences of managing those consequences (policy-related risks).

The construction of risk can broadly be expressed as likelihood × consequence. Risk itself contains the major components of hazard and outcome. However, beneath that broad framework, are many subsidiary structures that are context specific. Context is provided by scale, time, agency, types of hazard, feedback, location and the list goes on. Climate change-related risk is messy, not least because of uncertainty, and it is not easy to package those risks neatly. If both risk and uncertainty are to be managed, we need to define which elements of risk are over-arching and which are context specific. The image may be of a common superstructure populated by a lot of rooms. We need to be aware of both the overall structure and what is in each of the rooms, without losing one for the other.

Risk assessment is not bound by the image of traditional science: value-free investigations carried out in a dispassionate environment with the results being presented as "facts" handed down from on high. While it is possible to investigate climate hazards within a fairly rational scientific framework, the value-based consequences cannot be assessed in this way. If we are going to assess climate change using formalised methods of risk assessment combining hazards and consequences, different disciplines and approaches need to be integrated from Day One. The intertwining of science and values in assessing risk means that large assessments, such as those conducted by the IPCC, must begin with synthesis conceptualised, and not try to build synthesis from the sum of the parts.

One of the over-arching elements required for risk assessment is the measurement of different levels of consequence. The types of consequence arising out of climate change will be many, ranging from monetary loss and loss of life to various changes in system outputs, system character or to changes in systems themselves. The global criterion set by the United Nations Framework Convention on Climate Change is dangerous anthropogenic climate change. Local criteria have not been set by the Convention, nor is it made clear how they can be aggregated to assess risk at the global scale.

Three levels of risk need to be assessed: the need to manage risk, testing the efficacy of risk management options and estimating residual risk (that which remains after all management options have been exhausted). This is where researchers need to consult POETS, or the Probability of Exceeding Thresholds, to examine risk in each context. Thresholds are used very liberally in this context. They refer to a non-linear change either in an impact (e.g. coral bleaching), or in the response to a given level of impact (e.g. government support for rural communities under prescribed drought conditions). The threshold also has to be constructed in such a way that key climate variables can be linked to a value-based outcome (linking hazard and consequence).

The use of thresholds here is much broader than used in complex system science or in ecology where it refers to structural change in system behaviour (i.e. change in system state). Thresholds can range from being objective to highly normative. For example, in exceeding a given level of harm, the critical threshold is indicating that for this particularly activity (to which the threshold pertains), this level is dangerous. Thresholds can be physical, biological, legislative or regulatory. They can be universal (e.g. global health standards) or derived by stakeholders for a specific context. Stakeholder-derived thresholds can be used to communicate a consensus, or different groups may have different thresholds that measure criticality in quite different contexts – what may be good for one group may be injurious to another.

When do POETS become dangerous? This can be estimated by linking key climate variables to critical thresholds by using common factors such as mean global warming and sea level rise. For critical thresholds, the scale of criticality is linked to scale of impact. It may be linked to a catchment where water supply becomes too low to meet basic demand, a political region where numbers of people at risk is measured, an ecosystem such as area of coral reef at risk of mortality from thermal bleaching, or global from the risk of ice-sheet collapse. The first level of risk is reached when the POET is deemed significant enough to require risk management, i.e. it may become dangerous if nothing is done.

Adaptation to climate change will raise a threshold by expanding the ability of activity to cope, thus reducing its probability of being exceeded. The mitigation of greenhouse gases will reduce the probability of exceeding a threshold by reducing its contributing climate hazards.

For adaptation, probabilities will be high for activities where critical thresholds are likely to be exceeded with low levels of global warming or sea level rise. Mitigation will reduce the likelihood of warming and sea level rise from the upper end of the potential range, thus reducing the likelihood of exceedance of many smaller scale thresholds and fewer larger scale thresholds. Presumably, the latter are the more serious, although this assumptions needs to be tested more fully. Dangerous climate change is a conceptualised threshold that is reached where a sufficient level of criticality is accumulated.

It is apparent from the wording of the UNFCCC that dangerous can be associated with a level of criticality, rather than probability, thus attaching danger solely to the consequences of risk. Or more pointedly, the requirement within Article 2 to stabilise greenhouse gases in order to **prevent** dangerous anthropogenic climate change, by using the word prevent, implies that the probability of such an outcome should be zero.

This interpretation is highly problematic for several reasons:

1. It is not possible to estimate dangerous climate change *a priori*. Bayesian reasoning may be used to assess what dangerous might mean *a posteriori* (by induction) but it is not possible to guarantee a zero probability of exceeding a consequence that can be imagined but not located within a range of change, and where that range of change itself is uncertain.
2. Dangerous will be aggregated across different sectors, locations and scales, each of which will need to be assessed using an appropriate method of risk assessment.
3. People interpret danger using both likelihood and consequence, so the consideration of what is dangerous for each separate activity will be interpreted by the likelihood of exceeding an activity-specific critical threshold. Large consequences will be interpreted as dangerous if they have a small probability of occurring; localised consequences will not be of wide concern (except to those affected) unless aggregated, they have a high probability of occurring.
4. Policymakers will weigh up the risks of policy decisions along with climate-related risks being assessed by the IPCC. We have already seen how the economic risks associated with reducing greenhouse gases have been given priority over the economic risks associated with potential damages of climate change because of different levels of certainty and time preference.

When do POETS become dangerous? This can be attempted for some of the smaller, provincial POETS and those that can be closely linked to global warming and sea level rise, where criticality can be established. This implies that in many instances, we have enough information to move forward with risk management with a high level of confidence that well-framed options will produce positive results (and reduce the likelihood of dangerous climate change). And what about the global POET – when does it become dangerous? This continues to present a problem, but if we assess all POETS within a largely common framework, while allowing for the context-specific aspects of risk, it will be possible to develop a fuller picture of risk at the global scale. However, it is unlikely that dangerous climate change within the context of the UNFCCC can be considered independently of probability. Within current knowledge limits we can at best limit the probability of exceeding dangerous climate change rather than preventing it. To manage dangerous POETS we need to understand them first.

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Annex 2: Extended Abstracts

Characterizing Climate-Change Uncertainties for Decisionmakers

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Attempts to characterize climate-change uncertainties often envision a *predict-then-act* approach to decisionmaking (Lempert, Nakicenovic, Sarewitz, and Schlesinger, 2004). That is, experts first provide information sufficient to predict the likelihood of alternative future states of the world so that decisionmakers can then choose the optimum response. This approach proves exceedingly powerful in situations where uncertainties are well-characterized. However, when uncertainties are deep *predict-then-act* can encourage analysts and decisionmakers to overconfidence in their estimates of uncertainty in order to make predictions more tractable; can make it more difficult for parties with different expectations and values to agree on actions, since the method requires them first to agree on predictions; and can lead to strategies vulnerable to surprises which might have been countered had the available information been used differently. An alternative robust decisionmaking (RDM) approach (Lempert, Popper, and Bankes, 2003) envisions a process where scientific and other information is used to: i) identify robust strategies whose satisfactory performance is largely independent of the resolution of most "unknowns" and ii) characterize the residual deep uncertainties via their impact on the choice among strategies. RDM can reduce problems of overconfidence by challenging analysts and decisionmakers to explore a wide range of plausible futures and is designed to facilitate agreement by providing an analytic framework where parties can agree on near-term actions robust across many expectations and values. This talk will describe the RDM approach and suggest some of the benefits and challenges of using this framework to organize discussions of uncertainty within the IPCC.

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Annex 2: Extended Abstracts

Overview: Evolution in the Communication and Use of Scientific Uncertainties

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This paper will provide an overview of how communicating uncertainty and risk has evolved over the past 15 years. From the First to Third Assessment Reports the approach and the audience have changed. The IPCC reports now a read and used as basis for decisions by a wide variety of users: political and industrial leaders, media, the broad population and each will view the information from their perspective of needs and decisions. There is also the scientific community, which will scrutinize the results and their presentation. These audiences and uses of the information provide both challenges and opportunities to the scientific community in the way of presenting uncertainty.

Much of the thinking on uncertainty has been framed in the context of its use to improve risk assessments. However, different communities do risk analysis in different ways. Industry and some governments take a formal approach while the general public deals more in perceptions and analysis in terms of personal understanding and experience. For many, there is a major asymmetry in the decision process and outcome, being wrong in one direction is different than being wrong in the other. In addition, not all uncertainty is the same: there are important catastrophic events, thresholds, etc., that are to be avoided because of their implications. The communication of uncertainty for these types of events will need to be carefully examined.

In some cases, there will be pressure to give simple answers, (i.e., yes or no) and in some of those it will be appropriate to say: we do not know. How will IPCC address these issues? Should IPCC have a process to come to consensus and be able to respond to questions that arise out of the assessment after it is completed (but were not considered in the assessment). Since there will be increasing need to assess uncertainty across the domains of the three IPCC WGs, it is important to have consistency in approach while allowing for some flexibility.

Quantifying Uncertainties in Projections of Regional Climate Change: A Bayesian Approach

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[2] *University of North Carolina*

We present a Bayesian statistical model that combines information from a multi-model ensemble of AOGCMs and observations to determine probability distributions of future temperature and precipitation change on a large regional scale. The posterior distributions derived from the statistical assumptions incorporate the criteria of bias and convergence in the relative weights implicitly assigned to the ensemble members. Our approach is an extension and elaboration of the Reliability Ensemble Averaging (REA) method developed by Giorgi and Mearns (2002). To illustrate the method we consider the output of mean seasonal temperature and precipitation from 9 AOGCMs run under the A2 SRES scenario for Boreal winter and summer over 22 large regional land areas. The shapes of the final probability density functions for temperature and precipitation vary widely from unimodal where model results agree or where outlying projections are discounted due to large biases to multimodal where models that cannot be discounted on the basis of bias give diverging projections. We also pose some alternative models that include correlations between present and future temperature signals and test alternative forms of the probability distributions assumed for the model error terms. We also present an example of how the probabilistic information for future climate could be used in a hydrologic impacts context. We suggest that a probabilistic approach, particularly a Bayesian model, is a useful platform from which to synthesize the information from an ensemble of climate model simulations at regional scales. Moreover, the Bayesian model can serve as an interdisciplinary tool through which climate modelers, climatologists, and statisticians can work more closely.

Approaches to Uncertainty in IPCC Assessments: Effective Communication

Richard H. Moss

Climate Change Science Program Office

The IPCC has the responsibility to communicate effectively with the users of its reports. This is usually conceived of as a matter of "outreach" from the science community that prepares the reports to decision makers and the informed lay public who use them. Professional, cultural, linguistic, political, and national perspectives can impede the flow of information and make communication more challenging. In addition, conclusions often involve interpretation of necessarily uncertain projections about future climate change and its consequences. Conclusions that may appear to be clear in process or model studies are difficult to interpret in the real world, where simplifying assumptions and conditions do not necessarily apply, and all other things are not held constant.

Past assessments have used a number of terms for describing the subjective level of confidence that can be attached to different conclusions. Evaluations of past assessments have repeatedly shown that without definition, a statement such as "x may happen" or "x is likely to happen" mean very different things to different people. Terms such as "virtually certain," "probable," "likely," "possible," "unlikely," and many others have been used in the past without qualitative or quantitative calibration, leading to unnecessary confusion and disputes over interpretations of the conclusions of assessments by decision makers, the general public, and the media.

Uncertainty guidance for the AR4 must address these issues and develop common standards and approaches that apply, at a minimum, to cross-cutting conclusions likely to be addressed in summaries for policy makers (SPMs) or the synthesis report—in short for any conclusions significant enough that they are candidates for inclusion in a document summarizing the "top 20" findings of the AR4.

These are not the only communications challenges that confront the IPCC, however. Preparation of IPCC reports also requires effective communication among the scientists and other experts involved in preparing them. Climate change research actually involves application of parts of many different disciplines, each with its own specialized terminology. Findings are evolving rapidly and there are often multiple lines of evidence within or across fields that are related to a particular question or issue and that do not point to the same conclusions. Scientists use "objective" instruments to seek "factual" accounts of the world around them, but in practice they must often negotiate and agree on what the different lines of evidence mean and how they should be interpreted. This requires effective technical communication across disciplinary, linguistic, cultural, and other barriers.

Thus the uncertainty guidance to authors should not only address the public communication aspects of uncertainty, it should also raise awareness of psychological, group, and other dynamics that can lead to imprecision, inconclusive statements, and over confidence in statements that interpret the available scientific evidence.

This paper will briefly review the uncertainty guidance prepared for authors of the Third Assessment Report (TAR) and suggest issues that need to be addressed in uncertainty guidance for the AR4. These include: (1) agreeing on a process to produce a common set of confidence terms for use by all Working Groups; (2) improvements needed in the existing guidance based on the mixed experiences of the TAR; (3) the potential for increased use of decision analytic surveys in the AR4; and (4) level of support and approaches for implementation of the guidelines.

Conclusion

If the AR4 is to represent a further advance over the TAR and other recent assessments, guidance on the assessment and communication of uncertainty will need to be further developed and applied across all three Working Groups. The rationale for this is stated extremely clearly in the cross-cutting paper prepared as background for this workshop:

> "Clarity in describing uncertainty requires very careful attention to choices of the ideas being expressed and the language used to do so. Distinctions between the probability of events and the confidence in such probability estimates, between subjective and objective assessments of uncertainty, and between uncertainty applying to more observationally based and more model based results, all require careful and consistent use of language."

Nothing less than the utility of the assessment for decision makers and the informed lay public is at stake.

Annex 2: Extended Abstracts

Uncertainties Associated with Emissions Scenarios and the Role of Technology

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The role of technology in anthropogenic climate change is unique. Technology is one of the main driving forces of greenhouse gas (GHG) emissions and thus global warming. It also ranks high as a solution, both in mitigating global warming through reductions of GHG emissions and in helping adapt to its impacts. For example, the Intergovernmental Panel on Climate Change (IPCC) finds that technology is at least as important a driving force of GHG emissions as population and economic growth (Nakicenovic *et al*., 2000). Another IPCC finding is that innovative technology is an important driving force for a broad range of GHG atmospheric stabilization levels over the next 100 years or more (Morita and Robinson *et al*., 2001). More specifically, the emissions scenarios of IPCC indicate an increase in the mean global temperature of 1.4 to 5.8 degrees Celsius by 2100 (Cubasch and Meehl *et al.*, 2001). Roughly half of this uncertainty range is due to the fact that it is not known how sensitive climate will be to increasing concentrations of GHGs and the other half is due to the uncertainty of the future emissions paths themselves, which to a large extent will be determined by technology choices.

The relative contributions of different driving forces to the overall uncertainty of emissions can be decomposed according to the so-called Kaya identity. This type of identity was originally used to assess different impacts. The underlying method of analysis is called IPAT: Impact = Population × Affluence × Technology (IPAT). The IPAT identity states that environmental impacts (e.g., emissions) are the product of the level of population, affluence (income per capita), and the level of technology deployed (emissions per unit of income). Accordingly, Kaya identity represents the main emissions driving forces as multiplicative factors (Yamaji *et al.*, 1991):

$CO_2 = (CO_2/E) \times (E/GWP) \times (GWP/P) \times P$,

where CO_2 are carbon dioxide emissions, E (primary) energy consumption, GWP the gross world product, and P population. Changes in CO_2 emissions can be described by changes in these four factors or driving forces. Since the onset of the Industrial Revolution, global CO_2 emissions increased on average by 1.7 percent year and can be expressed as the product of global population growth of about 1.2 percent per year, per capita GWP (measured at exchange rates) growth rate of about 1.7 percent per year, decline of energy intensity, E/GWP, of about 0.9 percent per year and decline of carbon intensity of energy, CO_2/E, at about 0.3 percent per year. E increased on average at about 2 percent per year and GWP at about 2.9 percent per year. During the last century, these growth rates correspond to a 5.4-fold increase of CO_2, 7.3-fold of E, 17.5-fold of GWP, and 3.4-fold increase of P.

A similar assessment of factor increases can be obtained for scenarios in the literature. Taking 2100 as a future reference point, the identity gives following ranges compared to their current levels (based on the 5^{th} to 95^{th} percentile of scenario distributions): form a 3-fold decline to a 6-fold increase of CO_2, from a slight increase to almost an 8-fold increase of E, from almost a 5-fold to more than a 15-fold increase of GWP, and from no increase to a 3-fold increase of P. This indicates that, as in the past, the largest factor increase is anticipated for GWP in scenarios. Like in the past, improvements in energy and carbon intensities offset some of these increases resulting in lower ranges of CO_2 emissions growth. At a face value, this also indicates that the joint ranges of energy intensity and decarbonization (as joint proxies for technology) are comparable to those of population and per capita economic activities, respectively. Thus, it is expected that technology would continue to be among the most important driving forces of future emissions.

It should be noted, however, that Kaya identity does not imply any causality. Further analyses shows that these driving forces in the identity are not independent of each other, but rather depend in a very structured manner on each other and are correlated. An oversimplified "stylized fact", both historically and in scenarios, is that lower population growth rates are associated with higher levels (and/or growth rates) of affluence (per capita GWP) and lower energy intensities (higher rates of intensity improvements). The evolution of carbon intensities (decarbonization) is more complex and can go both ways – intensification and desintensification. In the first approximation, this means that technological change can take different directions even for scenarios that are otherwise close to each other in other driving forces. For example, the scenarios with lowest population and highest levels of economic development among the IPCC set, span about 90 percent of the range of future emissions in the literature, from half the current levels to more than a six-fold increase. Virtually all of the difference comes from evolution of energy technologies behind the various variants of the basic IPCC A1 scenario family (Nakicenovic, *et al.*, 2000).

The key to reducing this uncertainty about future anthropogenic climate change are measures and policies to achieve stabilization of future GHG concentrations in the atmosphere in accordance with the Article 2 of the United Nations Framework Convention on Climate Change. This further amplifies the importance of technology as it plays a crucial role in reducing future emissions (as in the case of IPCC A1 scenario family given above). One generic finding about the required reductions to achieve atmospheric stabilization is that global carbon dioxide emissions can increase somewhat for a while, but must peak during the next decades and decline well below current levels, say down to a quarter or at most a third of current levels by the end of the century or soon thereafter. In the very long run, beyond the time horizon of this century, net emissions must slowly cease and approach zero. In other words, achieving total decarbonization of the global energy system is a must, if the concentrations are to be stabilized. This is independent of the stabilization level chosen, be it high or low! In the very long term, the global energy system must change in such a way that all GHG emissions cease. For higher stabilization levels we have a bit more time before the peak is reached: 2065 to 2090 for 1000 ppmv (parts per million volume) on one end of the scale, but as soon as 2005 to 2015 to achieve stabilization at 450 ppmv. Even for 550 ppmv, emissions must peak between 2020 and 2030.

This indicates that the emission path we choose to embark on will make an enormous difference. For obvious reasons, the mitigation task is more humble and more likely to take place if the reference emissions are lower, if there is a transition toward “leaner” patterns of energy use and toward decarbonization of the energy system for other reasons than climate change. This not only makes the resulting climate change much less threatening, but also makes the task of reducing emissions to a given stabilization level easier to reach and much less costly. Often, the development paths that achieve stabilization describe a more sustainable future with relatively low energy demand and a transition toward less carbon intensive and zero-carbon energy technologies.

The main energy-related technology measures for reducing GHG emissions are efficiency improvements, decarbonization of fossil energy, carbon capture and storage (over hundreds if not thousands of years), a shift toward less carbon intensive and zero-carbon energy sources, and afforestration. The introduction and market deployment of these new and advanced technologies for reducing emissions will take a long time. For example, the replacement of older by new energy systems and sources is a slow process; it might take on the order of more than 20 to 50 years to replace 80 percent of (global) energy capital stock. Thus, it is necessary to introduce new and advanced energy technologies as soon as possible in order to achieve cost reductions and other technology improvements through learning and positive returns to scale by the time substantial emissions reductions need to take place. Most of the new and advanced technologies for reducing GHG emissions are currently costlier than their conventional counterparts in use today. Generally, cost reductions and improvements will be required to assure timely replacement of fossil intensive systems by those with lower or zero emissions. This is a global process that cannot be limited to just some parts of the world, even though the specific measures and policies need to be local.

Deep uncertainties surround all driving forces of future emissions: the rates and directions of technological change are perhaps among the most uncertain ones. One of the large sources of uncertainty is that technology improvements through learning and positive returns to scale are themselves highly uncertain. Investments in new and advanced technology will only achieve improvements and cost reductions in some cases. However, the corollary is also true, without such uncertain investments there surely will be no improvements. Thus, experimentation and accumulation of experience are indispensable to achieve technological change and the replacement of old by new systems. For scenarios, this means that large ensembles of runs are required that share some of the assumptions about main drivers and investigate variations of others so as to explore different sources of uncertainty in main driving forces and emissions in a consistent manner while maintaining scenario integrity and logic. Technology needs special attention and in particular the cumulative nature of learning. Given that mitigation measures and policies to achieve concentrations stabilization imply less uncertainty about future emissions also means that they constrain the range of future technology change toward the higher level. In other words, stabilization scenarios induce higher rates of technological change. It is interesting to note that they do not appear to have the same effect on the uncertainties of other underlying driving forces, e.g. population and economic development. These are some of the salient challenges to be overcome in the characterization of uncertainties associated with stabilization scenarios.

Annex 2: Extended Abstracts

Paleoclimate: Estimating the Uncertainties

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Paleoclimate data provide observations of climate system behavior that extend instrumental and satellite perspectives back centuries to millennia. Quantitative records of both *climate forcing* (e.g., orbital, solar, volcanic, trace gas, land use, and aerosol) and *response* (e.g., temperature, precipitation, ocean circulation, extremes, etc.) can be reconstructed from a wide range of proxies. As such, networks of paleoclimate data add the longer temporal perspectives needed to: 1) define the full range of natural variability; 2) separate natural from anthropogenic change, and in doing so determine the extent to which 20th century warming and other climate changes are unprecedented; 3) constrain how climate variability is affected by large changes in forcing, such as those that occurred repeatedly in the past, and that are likely in the future; 4) understand the patterns and causes of abrupt climate change (e.g., abrupt changes in ocean circulation, megadrought, and sea level rise); 5) evaluate the extent to which state-of-the-art climate models can simulate realistic responses to climate forcing; 6) constrain the sensitivity of the earth system to doubled atmospheric CO_2 concentrations.

Given the unique perspectives afforded by paleoclimatic data, as well as the rapidly expanding interdisciplinary use of paleoclimatic data, it is important to work out the best ways to convey uncertainty in the myriad types of paleoclimatic data. A goal of the IPCC AR4 WG1 Chapter 6 ("Paleoclimate") will be to present a transparent and accurate assessment of the uncertainty associated with paleoclimate data and the implications of these data for the climate change community.

Chronostratigraphic (time) control is a central aspect of all paleoclimatic data. Whereas the methods of dendrochronology assure tree-ring age models that are accurate to the year, most other data – even those characterized by annual layers or bands – are somewhat less accurate. Fortunately, recent advances in chronostratigraphic methods have made it possible to both estimate age errors, and also to reduce them. For example, use of annually-laminated sediments now usually involves multiple sediment cores. Ice core age models based on annual layers use multiple tracers (e.g., isotopic, visual, elemental) to define annual deposition. Radiometric-based age models (e.g., ^{14}C or U-series) now benefit from more accurate methods and more availability. Hence, such age models are now routinely based on many more dates than a decade ago, and age model uncertainties are correspondingly smaller. Radiocarbon-based age models now benefit from a much improved understanding of secular ^{14}C change through time, and also from the development of a ^{14}C-calendar age calibration capability back to the earliest parts of the radiocarbon time scale (e.g., back to 40,000 years before present).

Issues regarding the uncertainty associated with the climate signal traced by different paleoclimatic proxies (e.g., those based on tree ring, sediment, ice core and other sources) are as varied as the proxies themselves, and a goal of Chapter 6 will be to articulate these in detail. Usually, it is possible to assess the extent to which methodological assumptions are met, as well as the degree to which the proxy reconstructions calibrate and verify (visually and statistically) against instrumental data. Calibration in both the time (e.g., for tree ring, and other annually-resolved data) and space (e.g., for fossil pollen or macrofossil data) domains are now based on a rich history of method development. In many paleoclimatic applications, increased confidence is also gained via multi-proxy and multi-site approaches. Although statistical confidence intervals increasingly common for paleoclimatic reconstructions, they are not always easy or feasible. Even in these cases, however, paleoclimatic results can still provide uniquely useful insights into how the climate system works.

Representing Model Uncertainty in Climate Prediction

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Prediction is the life-blood of science, but without corresponding estimates of uncertainty, predictions are in principle unscientific, and in practice useless. Uncertainties in climate-change predictions arise from three basic sources: uncertainty in the future composition of the atmosphere, uncertainty in the forecast initial state, and uncertainty in the computational representation of the equations of motion of climate. With adequate understanding of such sources, these uncertainties can be represented in ensemble forecast systems; the dispersion of the ensemble being an estimate of the corresponding uncertainty in the climate-change prediction. In this presentation, emphasis is focussed on the representation of the most important but least-well understood of these sources: model uncertainty.

The standard global climate model comprises a projection of the well-known partial differential equations of climate on some suitable Galerkin basis (eg spherical harmonics, grid points, finite elements and so on), together with a set of parametrisations to represent unresolved processes such as small-scale topography and convection. The development of such parametrisations was motivated by the macroscale representation of microscale molecular processes in statistical mechanics; correspondingly it is presumed that within any grid box (actual or equivalent) there exists an incoherent ensemble of such processes in secular equilibrium with the resolved-scale flow. The parametrised tendency represents the average effect of this statistical ensemble of small-scale processes on the grid-box mean flow. Hence, for example, parametrisations of small-scale orography apply a drag to the large-scale flow associated with a field of incoherent sub-grid gravity waves, and convective parametrisations apply a warming associated with the dominance of subsiding air between a sub-grid field of incoherent convective plumes.

Within this framework, there are three ways of representing model uncertainty in ensemble forecast systems:

- The multi-model ensemble which comprising complete quasi-independent models (Palmer and Räisänen, 2002: Palmer et al, 2004);
- The multi-parametrisation ensemble comprising different parametrisations of a given sub-grid process within a single-model framework (Houtekamer, 1996)
- The multi-parameter ensemble comprising different values of parameters within a single-model and single-parametrisation framework (Murphy et al, 2004: Allen and Stainforth, 2002)

There is no doubt that ensemble forecast system with these types of representation lead to more reliable forecast systems. Fig 1 (from Hagedorn et al, 2004)

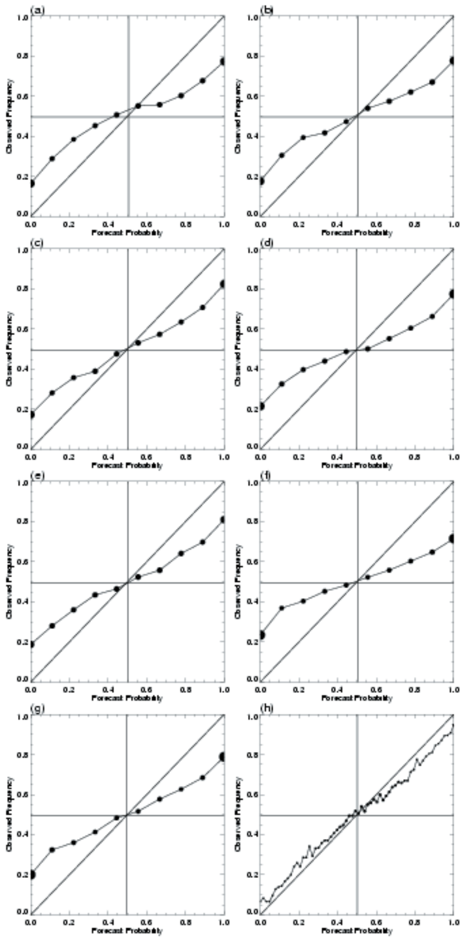

Figure 1. Reliability diagrams for probabilistic seasonal forecasts that 2m temperature is above normal, for grid points in the tropics. Perfect reliability requires the reliability curve to lie on the diagonal. a)- g) individual-model ensembles within the DEMETER project. h) the DEMETER multi-model ensemble. See Hagedorn et al (2004) for details.

shows that probabilistic seasonal forecasts of tropical temperature are intrinsically more reliable using the DEMETER multi-model ensemble system, than are ensemble forecasts from any of the corresponding single-models. On the other hand, the DEMETER multi-model forecast system is much less reliable when applied to forecasts of extreme precipitation over Europe (not shown). In this sense, one cannot have as much confidence in probabilistic multi-model climate-change forecasts of the changing risk of flooding over Europe (Palmer and Räisänen, 2002, see Fig 2), as one would have with corresponding forecasts of temperature change.

One can therefore ask whether the conventional framework described above is adequate to account for all model uncertainty. The answer is clearly no. The fundamental problem is that in the real climate, there is no scale separation between the "microscale" and "macroscale" . Hence, the notion that the sub-gridscales can be represented by bulk-formula parametrisations is unjustified. For example, no matter what model, parametrisation or parameter is used in the conventional framework, each element of any the sample of sub-grid topographic momentum tendencies will slow the large-scale flow. By contrast, Fig 3 shows how coherent sub-grid topography can actually accelerate the flow within a grid box. Similar considerations apply to convective tendencies, where heat and momentum tendencies associated with individual organised mesoscale convective complexes need not imply local warming, or a down-gradient transfer of momentum.

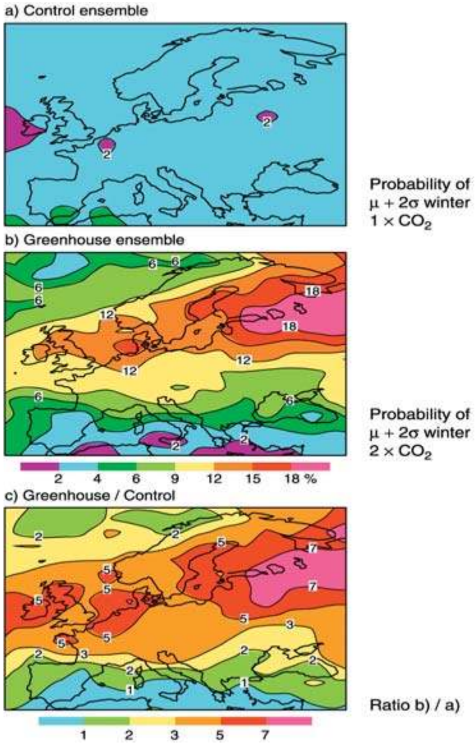

Figure 2. The changing probability of extreme seasonal precipitation for Europe in boreal winter. a) the probability (in %) of a "very wet" winter defined from the control CMIP2 multi-model ensemble with 20thC levels of CO2 and based on the event E: total boreal winter precipitation greater than the mean plus two standard deviations. b) The probability of E but using data from the CMIP multi-model ensemble with transient increase in CO2 and calculated around the time of CO2 doubling (years 61-80 from present). c) The ratio of values in b to those in a, giving the change in the risk of a "very wet" winter arising from human impact on climate.

To overcome these deficiencies, a different paradigm is needed to represent sub-grid scales in global climate models. As suggested in Palmer (1997, 2001) a possible framework is one in which the sub-gridscales are represented by simplified stochastic-dynamic models, coupled to the explicitly-resolved scales in the climate models over a range of scales. This implies a fundamental paradigmatic shift in the notion of the sub-grid tendency. In the conventional framework, the sub-grid tendency represents the mean of an ensemble of sub-grid processes; in this new paradigm, the sub-grid tendency represents a single possible realisation of a sub-grid process. The ensemble of sub-grid processes is therefore built up through the corresponding ensemble integrations of the climate model.

As found by Wilks (2004), this new paradigm is inherently unsuited to deterministic forecasting. However, it is well suited to ensemble forecasts, and gives improved forecast performance (Buizza, 1999; Wilks, 2004). It can also reduce model systematic error (Palmer, 2001; Lin and Neelin, 2003, Williams et al, 2004). It can also increase internal model variability on different timescales, which may have important ramifications on the climate change detection/attribution process.

A more specific framework for an implementation of this notion of representing sub-grid scales by simplified stochastic-dynamic models is through stochastic cellular automata (see Palmer, 1997, 2001; Khouider et al, 2003). The cellular automaton concept is used to represent phenomena like mesoscale organisation, or blocking by unresolved topographic obstacles. At ECMWF, a so-called Cellular Automaton Stochastic Backscatter Scheme (CASBS) is under development (Shutts and Palmer, 2004). The stochastic backscatter idea is based on the idea that a fraction of the implied dissipation associated with conventional parametrisation is scattered back to the resolved flow; the fields onto which energy is backscattered are determined by the rules of the cellular automaton.

For IPCC AR4, the representation of model uncertainty in climate-change projections will be based on multi-model, multi-parametrisation and multi-parameter concepts. In the EU FP6 project ENSEMBLES, a strict comparison of multi-model, multi-parameter and CASBS approaches will be performed. In future IPCC assessments, it is likely that a more complete and more rigorous approach to representing model uncertainty in climate change projections will be possible.

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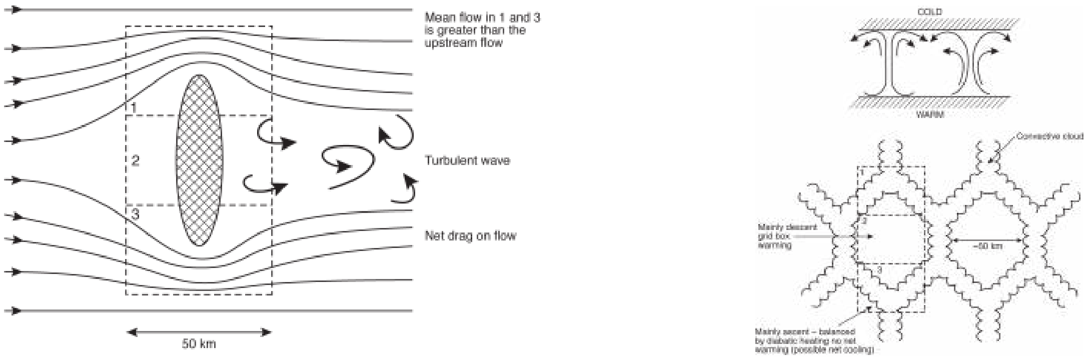

Figure 3. Schematic illustrations of the fact that for scales which are only somewhat smaller than the smallest resolved scales, the conventional notion of parametrisation breaks down, eg local sub-grid topography need not imply a drag on the flow, and local convective activity need not imply (subsidence) warming or downgradient momentum transport.

Annex 2: Extended Abstracts

Approaches to Observational Uncertainty in the IPCC 3rd Assessment Report

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We begin by describing the background to the treatment of uncertainty in the IPCC 3rd Assessment Report (TAR), using the guidelines developed by Moss and Schneider *in* IPCC Cross-Cutting issues Guidance Papers (2000). We then review the approaches to uncertainty in Chapter 2: Observed Climate Variability and Change. These were varied and included:

- Statistical estimation of uncertainty in global and regional anomalies: mainly covariance-based techniques.
- Restricted Maximum Likelihood and other techniques for estimating uncertainty in linear trends.
- Physical consistency.
- Consensus.

The authors of Chapter 2 did not explicitly consider the structural uncertainty arising from choice of analysis techniques, so this subject is reviewed and its importance stressed. Cited bibliography is listed in the TAR.

1. Statistical estimation of uncertainty in global and regional anomalies

- Folland et al (2001): Gridbox uncertainties based on sample sizes and coherence (Jones et al., 1997); local then global optimal averaging accounting for gaps; uncertainties in the bias-corrections based on careful interpretation of the literature. Figs 2.1b, 2.7, 2.8 of TAR.
- Mann et al (1999, 2000): Uncertainties based on power spectrum of calibration residuals in eigenvector-based reconstructions. Figs 2.20, 2.21, 2.28 of TAR.
- Levitus et al (2000b): Uncertainties based on optimal averaging / interpolation. Fig 2.11 of TAR.
- Pollack et al (1998): Standard error of stacked borehole temperature reconstructions. Fig 2.19 of TAR.

2. Linear trend estimation using Restricted Maximum Likelihood (REML) and other techniques

- REML: Account is taken of (Tables 2.1, 2.2 of TAR):
- Uncertainties in the individual terms of the time-series owing to data-gaps and biases (urbanization, bucket-corrections)
- Serial correlation
- Finite sample size
- REML estimates the Gaussian probability distribution function of the trend, given the data. Input uncertainties are assumed to be Gaussian.
- For precipitation trends (Fig 2.25 of TAR) REML was not used. Significance was established by the concurrence of a t-test and a non-parametric test.
- For extremes (Figs 2.33 and 2.34 of TAR) significance of differences between 2 periods was assessed with a t-test; trends were estimated by weighted (by number of stations) linear regression.

3. Physical Consistency

- Cloud vs. diurnal temperature range: Fig 2.3 of TAR
- SST vs. night marine air temperature: Fig 2.5 of TAR
- Marine vs. land temperature: Figs 2.6, 2.9, 2.10 of TAR
- Snow vs. land temperature: Fig 2.13b of TAR
- Worldwide glacial retreat: Fig 2.18 of TAR
- Palaeoclimatic series: Fig 2.24 of TAR

4. Consensus (Fig. 2.39 of TAR)

- *** Virtually certain (probability >99%)
- ** Very likely (probability at least 90% but not more than 99%)
- * Likely (probability >66% but < 90%)
- ? Medium likelihood (probability >33% but not more than 66%)

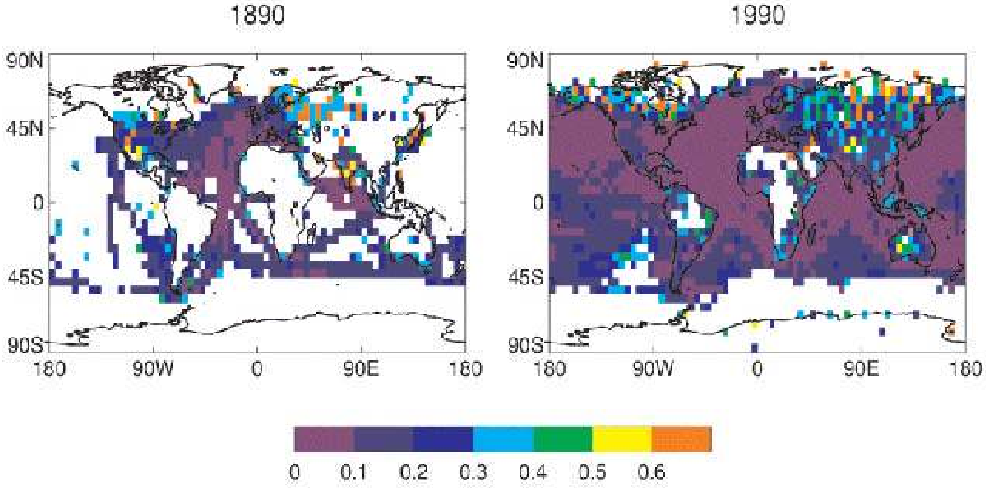

Figure 1. 5° annual average grid box data error (°C). From Folland et al. (2001)

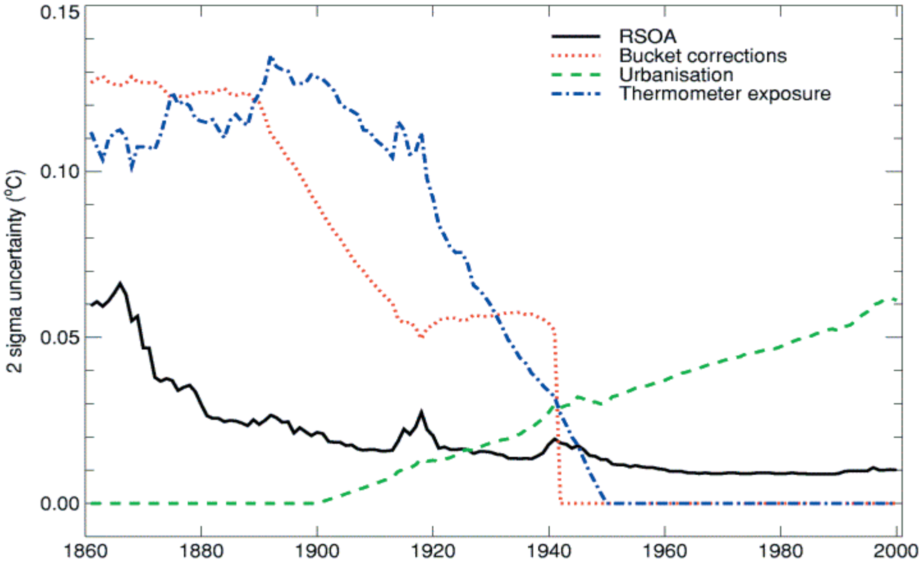

Figure 2. Two sigma uncertainties (°C): Land air temperature (SST) uncertainties multiplied by fraction of data area which is land (ocean) based. From Folland et al. (2001).

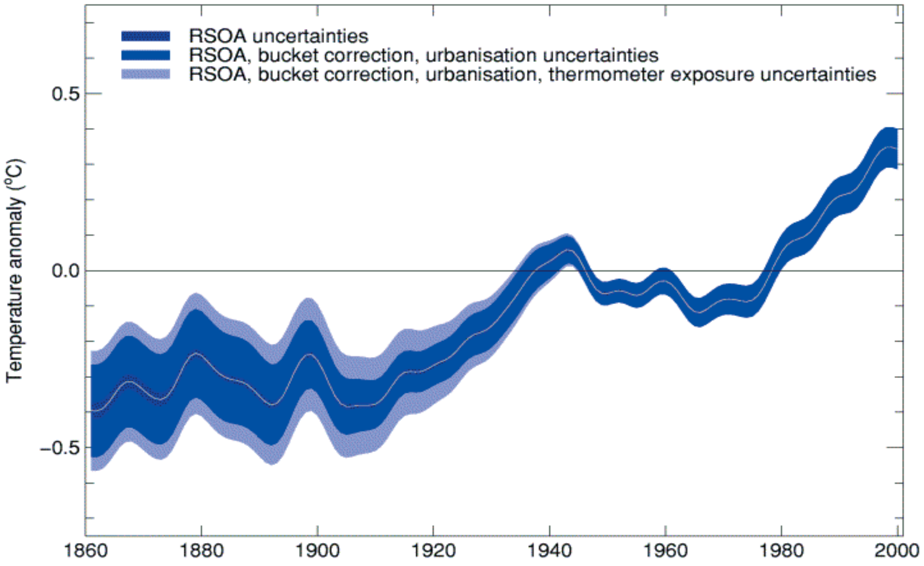

Figure 3. Decadal Global Average Surface Temperature Anomaly (°C), 1861–2000. From Folland et al. (2001).

Table 1. Surface temperature trends & 2 sigma uncertainties, as in IPCC 2001 (all uncertainties included)

Period	Globe	N. Hemisphere	S. Hemisphere
1861–2000	0.61±0.16	0.64±0.26	0.51±0.14
1901–2000	0.57±0.17	0.64±0.22	0.48±0.15

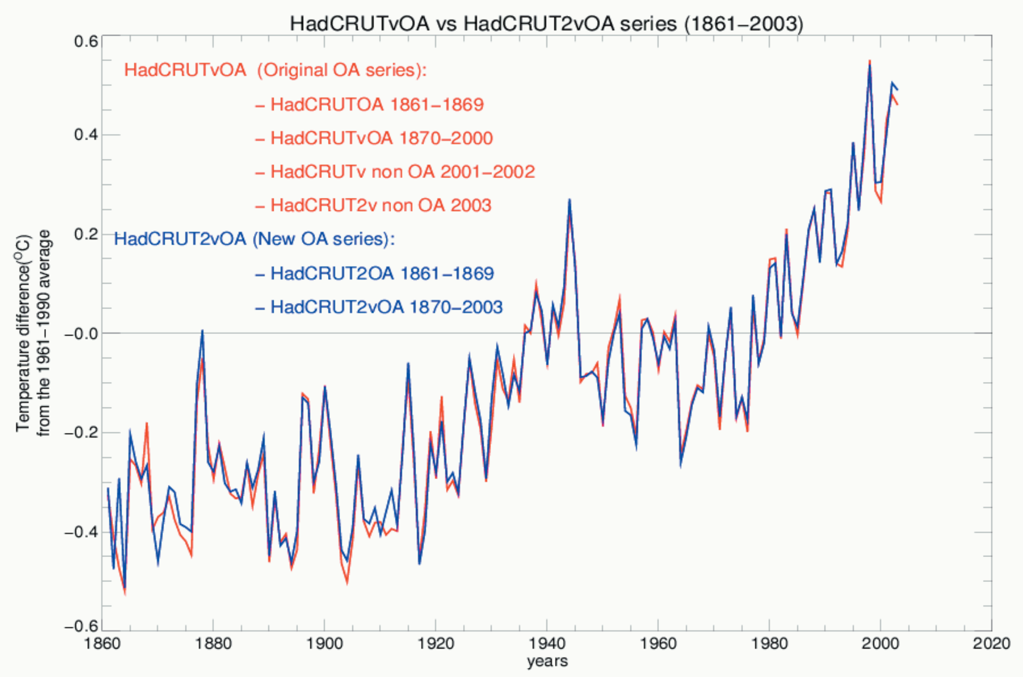

Figure 4. Upgrading of global temperature series

Structural Uncertainty

- Example: Forming a homogeneous series from several different satellites' Microwave Sounding Units
- Corrections are required for:
  - Orbit decay -- satellite gets closer to Earth
    - Only needed for LT retrieval; entails very small uncertainty.
  - Diurnal drift -- satellites drift aliasing in the diurnal cycle
  - Instrument temperature.
    - Conversion into brightness temperature has non-linear dependence on the satellite temperature.
  - Other intra-satellite bias.
    - Any remaining biases removed.
  - Inter-satellite biases
- Two sources:
  - Residual uncertainty
    - Uncertainty inherent in the method in the presence of finite data. This is what is normally published.
  - Structural uncertainty
    - Uncertainty introduced by the method chosen to go from raw radiances to a "homogeneous dataset"

Are the MSU datasets consistent?

- The respective published estimates with 2 sigma (residual only) uncertainty estimates are:
  - i) 0.02 +/-0.05 K / decade
  - ii) 0.10 +/-0.02 K / decade
  - iii) 0.24 +/-0.02 K / decade
- Implies either:
  1. some (all?) are physically implausible methods or
  2. that structural uncertainty is the major source of uncertainty (error!) and that this implicitly needs to be taken into account

Structural uncertainty is a serious and widespread problem

- Estimates of trends fundamentally affect our understanding of climate change.
- MSU and other series differ too greatly to allow safe detection and attribution of climatic changes.
- We need multivariate analysis and, for the future, at least 3-point calibration and validation.

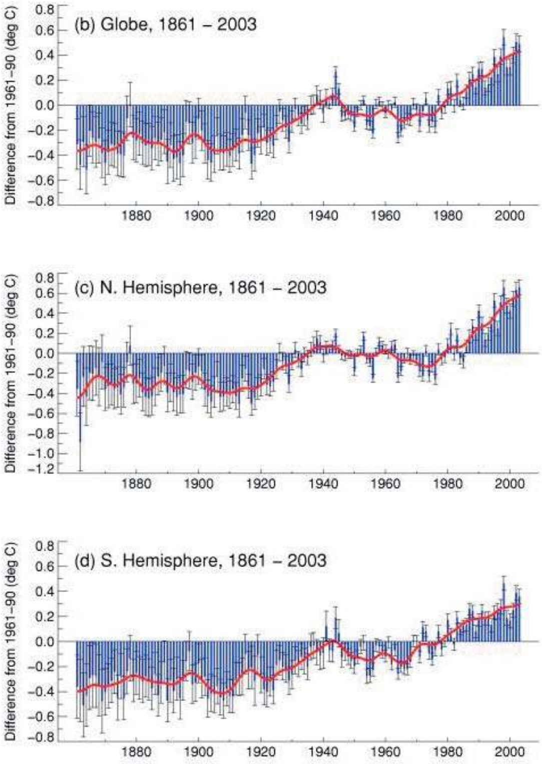

Figure 5. New global and hemispheric temperature series

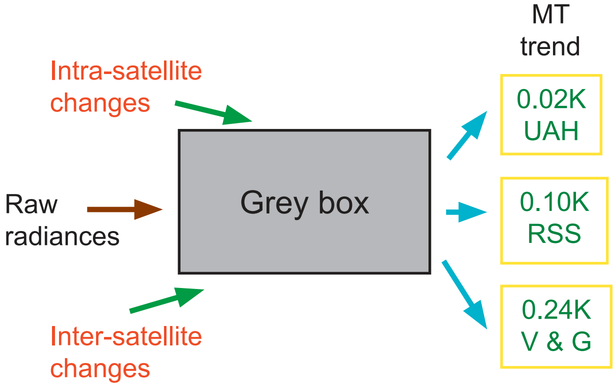

Figure 6. Three MSU datasets: Decisions made will always involve a degree of subjectivity in absence of agreed transfer standards

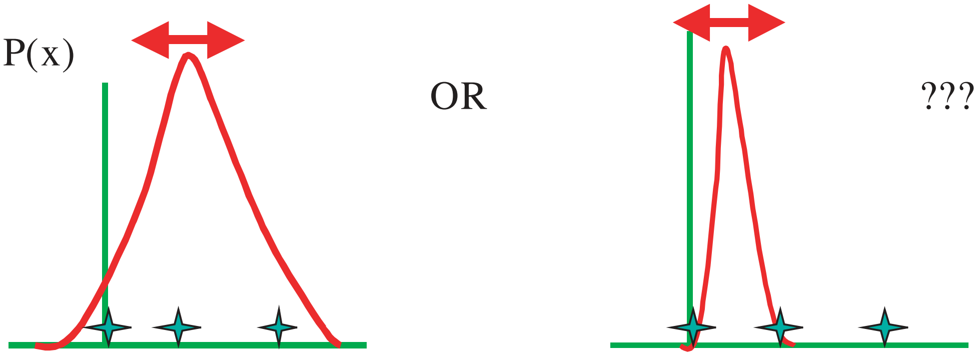

Figure 7. What is the true structural uncertainty? Red is the PDF of best-guess global-mean trends for an infinite number of physically realistic treatments. Green stars are published estimates. Which (left or right) is correct is important!

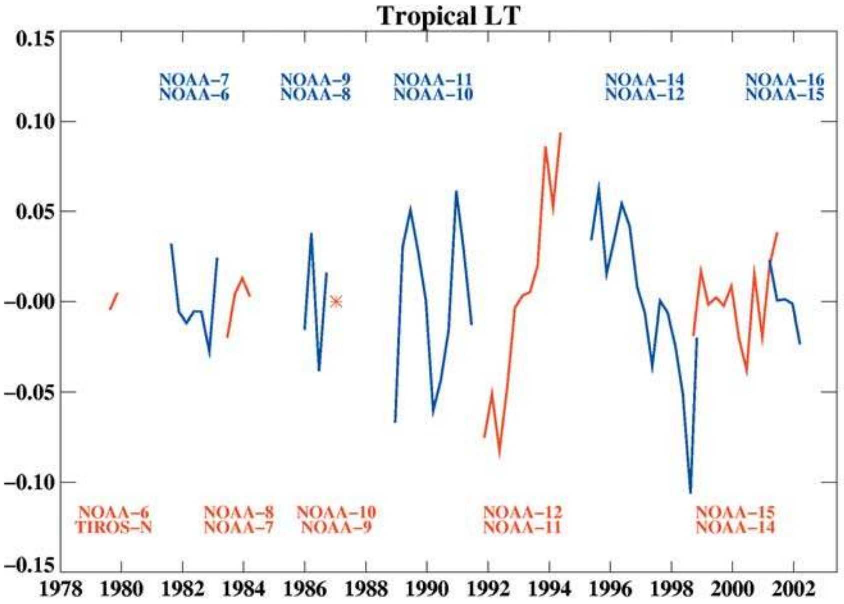

Figure 8. Lower Tropospheric Inter-Satellite temperature differences

Uncertainty in Estimating Biological Impacts of Climate Change: Sources of Error and Methods of Quantifying Uncertainty

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There are multiple sources of uncertainty in assessing current impacts of climate change on natural biological systems and in making projections about future impacts (see extended discussions in Parmesan 2002, Parmesan in press, and Parmesan and Galbraith in press). These will be discussed using the following framework of uncertainties in:

- *Data & analysis:* Are changes real? Issues of quantity, quality and appropriate analyses
- *Attribution:* Given changes are real, how can causation (climate change) be inferred from correlation?
- *Prediction (projection):* Given changes are real and rigorously linked with climate change, how sure can we be of specific predictions of future biological impacts?

Data and Analysis

Biological data has large variation in the quality and quantity of information across species, geographic regions and through time. Paleological data extends several thousands of years into the past, but is limited to a few appropriate taxa (e.g. trees, mammals and beetles) and suffers from poor spatial resolution (appropriate sampling points are geographically rare). More modern records of species' distributions and behaviors (timing of breeding, etc.) that could be used to assess climate sensitivity are scarce for most regions and for most species. Northern Europe and parts of Asia (Japan) are exceptions, with some detailed records for key species going back to the mid-1700s. Biological recording blossomed in the 1970s, allowing for rigorous analyses of changes over the past 20-30 years, but much lowered sampling intensity and data gaps make analyses of longer time periods problematic.

Sampling and recording methodologies have changed through time, which can create artifacts. Some large databases (e.g. the US Breeding Bird Survey) rely on amateur recorders, which can introduce bias. Statistical analyses presented in peer-reviewed literature are not always appropriate given the auto-correlated nature of species' characteristics through time and given potential sources of data bias. This can be remedied by re-analysis of published data, or by use of meta-analyses that synthesize data from many studies. Relatively new bayesian methods can incorporate particular sources of error and quantify the uncertainty in estimates of many biological characters, such as changes in abundance, distribution, or phenology (timing) (Wikle 2003a,b, Dose & Menzel 2004).

Attribution

Even with excellent time series data, linking biological trends to climate trends is inherently correlational. Difficulties lie in attribution due to many confounding factors which may be simultaneously driving the population, species or ecosystem in the same direction as expected by climate change. Identification of unique biological fingerprints of climate change impacts can provide attribution for systems with appropriate data (Table 1, Parmesan and Yohe 2003).

Once these problems have been tackled, final attribution is bolstered by supporting evidence of climate sensitivity from either empirical or modeling studies. These would include basic experimental work documenting physiological or behavioral climate tolerances and field transplant experiments placing individuals into different climate habitats.

For more than 30 years, theoretical ecologists have used comparisons in the explanatory power among multiple models which vary key parameters and assumptions to help identify the underlying driving process. Such process-based models can be used to identify and test alternate hypotheses. For example, with respect to the failure of cod to recover from recent collapse, with published competing models, one can test an ocean temperature model against a life-history/foraging model as alternative explanations of the recovery failure (deRoos & Persson 2002). Because this often requires considerable modeling skill, studies of climate change impacts, which are usually conducted by field biologists, have rarely incorporated this method of direct comparison of competing models in order to discern attribution.

Finally, positive publishing bias creates difficulties with general conclusions from individual studies, but can partially be accounted for by synthesizing results from multi-species studies where non-response is documented alongside climate change response (Table 2, Parmesan and Yohe 2003).

Prediction (Projection)

Formulating projections of future biological impacts under various climate change scenarios holds perhaps the largest uncertainty. There are continuing debates on the fundamental nature of biological impacts—particularly on the relative importance of ecological vs. evolutionary response. This is further complicated by a large difference in scale: evolutionary models tend to be derived from population genetics models (single populations, local change), whereas ecological models tend to be derived from biogeographic models (whole species, regional to continental change).

Biogeographically-based models begin with the assumption that climate is the main driver of species' distributions. There is general agreement that this holds for the coarse (regional to continental) scale, but not for the local scale (see discussion in Pearson & Dawson 2003). Thus, uncertainty has a strong link with scale. Further, these models all assume that current distributions correctly define a species' climate tolerances. This is a particular problem in predicting responses to non-analog climates. Process-based models are based on fundamental physiological tolerances or other primary traits that have been documented through experimentation. It has been argued that these are better able to accurately predict response to future climate scenarios than are bioclimate-based models, but this is rarely explicitly tested. Within the class of bioclimate models, there are different models being used by different labs, which apparently yield very different results – e.g. different levels of over-prediction. Differences among bioclimate models is currently being

Table 1. Biological fingerprint of climate change impacts: differential sign-switching patterns diagnostic of climate change as underlying driver.

Sign-switching Pattern	% of species showing Diagnostic pattern
Community Abundance changes have gone in opposite directions for cold-adapted vs. warm-adapted species. Usually local, but many species in each category. Diverse taxa, *n*=282[1]	80%
Temporal Advancement of timing or northward expansion in warm decades ('30s/40s & '80s/'90s); delay of timing or southward contraction in cool decades ('50s/'60s) 30-132 yrs per species. Diverse taxa, *n*=44[1]	100%
Spatial Exhibited different responses at extremes of range boundary during particular climate phase. Data from substantial parts of both northern and southern range boundaries for each species. All species are northern hemisphere butterflies, *n*=8	100%

Note:

[1] Numbers of species represent minimum estimates, as not all species were described in sufficient detail in each study to classify. A few species showed two types of sign-switching, and so are included in more than one cell. Data are from references in text and from raw data from L. Kaila, J. Kullberg, J. J. Lennon, N. Ryrholm, C. D. Thomas, J. A. Thomas & M .Warren.

Table 2. Summary statistics and synthetic analyses derived from literature in Table 1 of Parmesan & Yohe (2003).

Type of change	Changed as predicted	Changed opposite to prediction	*P*-value
Phenological			
N = 484/(678)	87% (n=423)	13% (n=61)	$<0.1 \times 10^{-12}$
Distributional changes			
At poleward/upper range boundaries	81%	19%	
At equatorial/lower range boundaries	75%	25%	
Community (abundance) changes			
Cold-adapted species	74%	26%	
Warm-adapted species	91%	9%	
N = 460/(920)	81% (*n*=372)	19% (*n*=88)	$< 0.1 \times 10^{-12}$
Meta-analyses			
Range-boundaries (*N* = 99)	6.1 km-m/decade northward/upward shift[1]		0.013
Phenologies (*N*=172)	2.3 days/decade advancement[1]		< 0.05

Notes

Data points represent species, functional groups or biogeographic groups. Total #species > 1700, total #distinct units = 1540 (because of grouping of species in some studies). N = number of statistically or biologically significant changes / (total number species/functional groups with data reported for boundary, timing, or abundance processes). The "no prediction" category is not included here.

[1] Bootstrap 95% confidence limits for mean range boundary change are (1.26, 10.87); for mean phenological shift are (-1.74, -3.23).

quantified with standardized datasets by an NCEAS working group (National Center for Ecological Analysis and Synthesis, U.California Santa Barbara). Unless this debate progresses in the next 2 years, a prudent treatment of predictive models used in the AR4 would present multiple outputs from different classes of models and from competing models of the same class.

Conclusion

I propose that it is “well-established” (sensu Moss & Schneider 2000) that 20th c. climate change has caused substantial biological changes at the global scale. The causality link relies on scientific inference derived from multiple research approaches, including mechanistic understanding from both ‘natural’ and manipulative experiments, and diagnostic fingerprints of climate impacts, as well as on long-term correlational data. However, I propose that projections of future responses are less certain, falling into the realm of ‘competing explanations’. There are multiple reasons for greater uncertainty in future as compared to past estimates of biological impacts. These include:

- Uncertainty in whether response in any given instance will be largely ecological (e.g. species geographic range shift) or evolutionary (e.g. changes in physiological tolerance).
- Uncertainty in climate projections which then become incorporated into biological models (often implicitly rather than explicitly).
- Uncertainty as to which broad type of biological model to use (*e.g.* biome models vs. individual species models – either bioclimate envelope models or process based models)
- Large differences in outcomes even within one 'type' of biological model. For example, multiple bioclimate models can be substantially different in their ability to map current species' distributions as well as in their estimated future distributions (see Table 1 of Thomas *et al.* 2004, and in presentation).

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Annex 2: Extended Abstracts

Communicating Probabilities with Words: Potential Pitfalls and Biases

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Difficulties interpreting probabilities

Scientists face the two challenges of divining and communicating the probabilities of events associated with climate change. For both tasks, climate change represents a case where a frequentist view of probability is inadequate, and instead there exists some confidence or likelihood that an event will happen. A great deal of psychological and economic empirical research has shown that individuals, including many of those with scientific or technical training, have a difficult time using probabilistic information consistently, especially when it is of the non-frequentist form that climate change offers. The literature has shown particular and predictable biases in how people respond to probabilities, such as extremely high risk-averse behavior in the face of very low probability events, combined with risk-taking behavior in the face of high probability events. The literature has also shown that people typically over- or under-respond to new information in the task of updating their prior probability estimates for particular events, and that in responding to probability estimates, often bring additional values into play. All of these, of course, create challenges for the assessment of these probabilities, so that the readers of the assessment – policy-makers, the media, and the lay public – can best understand and use the information. The literature offers many lessons for how better to communicate probabilities, most of which revolve around establishing a participatory approach where users can gain practice working with this type of information.

Approach of the TAR, Working Group I

The approach taken by the IPCC Working Group I in its Third Assessment Report represents a significant step forward in the conduct of scientific assessment. Based on targeted background papers, the working group settled on a communication style that avoided discussing the probabilities of climate change events in numerical terms, but rather with words. For most readers, these words probably come closer to their intuition, namely that scientists have a degree of confidence that particular future events will in fact take place. Thus, in the non-frequentist framework, the use of these words makes more sense to more people than actual numbers. Since these are events for which it is typically very difficult to arrive at specific numerical probability estimates, and have confidence in them, the use of words to communicate them probably involves no loss of precision.

There are, however, two potential problems that could arise out of the use of words, instead of numbers. The first stems from the fact that such words have intuitive meanings for people, given that they are part of people's day-to-day language. Thus, while the IPCC authors may have intended for people to interpret words such as "unlikely" to mean a particular confidence or probability range, people may understand the word to imply a different range. The TAR authors attempted to address this problem by precisely defining the ranges of probabilities that each of the seven terms they used meant, but it is possible that readers will not return to those definitions every time they hear the words. The second problem stems from this precise definition of probability ranges for each of the terms, which may not represent people's intuitive use of the words. Since people interpret probabilities differently for different types of event, such as events of different magnitudes, it is possible that their interpretation of the words used will be biased according to the type of event being described. In this case, using fixed ranges of probabilities for the events could be *counter-intuitive* to many readers, leading to poor understanding, or even biased interpretation.

Empirical evaluation of the TAR approach

To examine the extent and magnitude of either of these two potential problems, two controlled surveys have been conducted. The surveys asked respondents to match the words used in the IPCC report to ranges of probabilities. In each administration of the survey, there were four versions distributed, mixed randomly among the participants. Two of the versions asked participants to match numerical estimates with a particular verbal phrase used to describe probability, much as policy-makers might be expected to do when reading an IPCC report. The other two versions asked participants to match words to a particular assessed numerical probability, much as the authors of the IPCC reports need to do. For each of these, one version described an event of high magnitude, while the other version described an event of low magnitude.

The first survey took place in May 2001, and used students at Boston University, in the United States, as the experimental group. The results have been reported in a paper published in 2003 in *Climatic Change*, but are worth repeating here, since they reveal a potential bias. The group asked to pick a numerical range to describe a given verbal phrase tended to pick larger numbers for the smaller magnitude event. The group asked to pick a verbal phrase to describe a given numerical range picked a more serious sounding phrase to describe the higher magnitude event. As the analysis in the paper describes, these two biases could cancel each other out, leading to accurate communication. However, if one of the groups is forced to describe numerical ranges with particular words and phrases, and their audience does not pay attention to this fact, then bias will result: the audience will take smaller magnitude events more seriously than they deserve, and larger magnitude events less seriously than they deserve. In the aggregate, this could lead to an under-response to the risks of climate change.

The second survey took place in December 2003, and used participants at the COP 9 meeting in Milan as the experimental group. The results have not been previously been reported. In this case, using people who are experts in climate change, the bias observed in the first survey did not appear. These experts, apparently, are able to separate out the magnitude of the events from their interpretation of its probability. However, the variance in responses among this experimental group was almost the same as that among the first experimental group. That indicates that this group, as much as the Boston University students, interprets the words according to intuitive meanings, and does not rely on their expert knowledge in matching words with numbers. In this second administration of the survey, we also asked participants whether they had read the IPCC TAR Working Group I report, or the associated Summary for Policy-Makers, in which the probability ranges were defined. We found that the variance in the answers was almost identical among those who reported having read the report and those who reported not having read the report. Thus, the fact the TAR defined the meaning of words used to describe probabilities did not appear to influence how people then interpreted those words.

Recommendations

The empirical study reveals that the approach taken in the TAR, while a definite step forward, still carries with it some potential problems. The extent of these problems varies, to some extent, on the degree of expertise of the readers or users of the information. Among more technically trained users, the IPCC authors should expect people to continue to interpret the probability words fairly intuitively. Among less well-trained users, there is the potential for a biased response, in the direction of under-response to the net impacts of climate change, as a result of the fixed scale of words. While some of these problems may simply be inevitable when dealing with difficult probabilistic concepts, there are some possible ways to improve the communication.

First, it may be valuable to include in the report itself, at the time of defining the words used to describe probabilities, some of the difficulties and biases that people often have using such words. This would put people on notice, and indeed might cause them to catch themselves before interpreting the words later on in a purely intuitive manner. In essence, the report would be alerting them that their intuition could prove wrong, and introduce bias.

Second, it may be valuable to go through the exercise, frequently in the report, and perhaps also in the Summary for Policymakers, of *using* the words and estimates of probabilities. This was a recommendation of the background papers for the TAR, and is what often occurs when probabilities are described in a public participation or stakeholder dialogue setting. This could involve presenting hypothetical or real policy problems, in which the probabilities of climate change impacts play a role in the analysis. In these examples, the readers would be led through the task of translating the probabilistic words into numerical probabilities, and vice-versa. It would be valuable to do this for events of very different magnitudes, and very different assessed likelihoods.

Third, the results highlight the importance, in as much detail as space allows, of describing the sources of uncertainty for each of the events being assessed. In describing these sources, the readers would be guided through the process of either computing or estimating likelihoods from the numerous compounding sources, and translating these likelihoods into both words and ranges of numbers. Of course, such an understanding of the sources of uncertainty already occurs, and is often the most valuable part of the discussion; the assistance it offers people in understanding the words, phrases, and numbers used to describe uncertain events is simply an additional justification.

Annex 2: Extended Abstracts

Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options: Coupling Models Across Disciplines

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Future emissions of greenhouse gases, their climatic effects, and the resulting environmental and economic consequences are subject to large uncertainties. The task facing the public and their policymakers is to devise strategies of risk reduction, and they need a clear representation of key uncertainties to inform these choices. The attempt by the IPCC in the Third Assessment Report to quantitatively address uncertainty was an important and positive step forward but more progress is needed. Given guidelines of the IPCC that limit it to reporting results from peer-reviewed literature, the assessment report is, however, necessarily limited in what it can do absent such published literature. Even when restricted to reporting on studies that have appeared in the literature, the task of accurately discussing results that relate to uncertainty/error in estimates is not always as straightforward as it would seem. This workshop to address how the next IPCC assessment can improve its description of uncertainty is thus a critical step forward, and may encourage scientists to conduct and publish analysis that then can be cited by the IPCC. For some further discussion, see Reilly et al., 2002.

The goal of the IPCC to describe science results in a way that is relevant and useful to national governments and the broader public who must decide what the risks of climate change relevant to them are and how to respond. It is likely no accident that the workshop has a somewhat cumbersome and lengthy title. Any veteran of the process of international negotiation will guess that each of the word choices reflect some conscious effort to stay within bounds of the specific described scope of the IPCC. The IPCC is seeking to 'describe' (not estimate) 'scientific uncertainties' (as opposed to legal or policy uncertainties?) to 'support analysis of risk and of options' (the actual analysis of what to do in response to uncertainties is left for others). Importantly, even with all that careful wording the title of the workshop recognizes that the reason for describing uncertainty relates to decisions; i.e. the choice among options in the face of possible risks.

As scientists we often conduct analysis of error or uncertainty in the context of hypothesis testing, where we establish a relatively stringent requirement for rejecting a null hypothesis. Is there something significant in the data or is an apparent difference merely an artifact of sampling or measurement error? 'Has climate changed?' is such a question. The null hypothesis in this case is that any measured trend is not significantly different in the sense that, given natural variability, repeated plays of the last century would produce a mean of no change, albeit any one play could produce a climate that drifted toward either warmer or cooler over the period. We often choose something like a 95% confidence limit before rejecting the null of no change, wanting to be quite sure that the measured trend is unlikely to be consistent with natural variability. Of course, in this case we have more than simply this statistical relationship that would lead us to believe that the climate has changed—we can identify substances that we know with a high degree of confidence affect the radiative balance of the atmosphere, and we expect them to have some effect on some aspect of the climate. In fact, we know that different substances act in different directions, and so we might find little trend in something like global average temperature but believe that opposing powerful effects mostly offset one another. In these cases, we are interested in estimating not whether there is something statistically different from a null, but the magnitude of the effect, and the uncertainty in that magnitude.

For decision-making purposes, it is usually not enough to simply know that there is an effect but rather we need to know (1) the magnitude, (2) the cause(s) (and what mitigation options will reliably reduce the effect) (3) and the economic and broader impacts. (e.g. Reilly and Schimmelpfennig, 1999, 2000). For additional related perspectives see, Webster, 2003. As uncertainty cascades through the system from uncertainty in multiple driving causes, to uncertainty in physical responses, we end up with uncertainty in the social and economic impacts.

While there are more complex ways in which uncertainty can affect decisions, to the first order, we are interested in the expected value of a change. Simplified as a discrete (and exhaustive) set of events, the expected value is the probability of each event times the cost/value of that event occurring, summed over the exhaustive list of events. In the normal course of hypothesis testing, acceptance regions of 5%, or 2.5%, or 1% are the norm. But, for decisionmaking purposes, if there are very large consequences of events with even much smaller likelihood—1 in a 1000 or 1 in 100,000,000—accuracy in the tail of our distribution is critical. Suppose we imagined a climate catastrophe involving 100 trillion dollars and 100,000,000 deaths. The expected value of the catastrophe is 100 billion dollars and 100,000 deaths if the chance is 1 in 1000 but 10, 000 dollars and 1 death if the chance is 1 in 100,000,000. If all we know is that the event is in the 1% tail (99% certain it won't happen, 1% chance it will) and use the .01 as an estimate of likelihood then we would estimate the expected value as 1 trillion dollars and 10,000 deaths. The point: we cannot easily dismiss an extreme event because the chance of it occurring is very small, if we are not precise about what we mean by 'very small.' Nor does it necessarily follow that just because we can imagine a catastrophic event that it should weigh heavily in decisions unless we are more precise about the likelihood of occurrence.

So far, much work has simplified measures of climate change, particularly when computing likelihoods, to a change in global-mean surface temperature. Impacts have been summarized in relation to this statistic: 1or 2 degree C change may be less harmful, 3 or 4 degree C change may be more harmful. While the work recognizes that this is not strictly the case, the community would like to believe, or argues as if, the global-mean surface temperature change could be an approximately sufficient statistic to gauge the magnitude of social and economic impact. Abrupt change, changes in variability or the pattern of precipitation with little or no change in the global-mean surface temperature could be equally or much more disruptive than a several degree change over the course of 100 years. So any work that attempts to understand uncertainty in climate change as it might affect society and the economy must deal with the likelihood of changes (and extreme even if highly they are highly unlikely) in these other statistics of climate. (e.g. Reilly et al., 2001, 2002, 2003).

A final general issue is on the nature of 'cascading uncertainties.' As we know from studies of humans' cognitive abilities, even experts have biases in dealing with uncertainty. One of those biases seems to be the notion that as one adds more uncertain variables, the cascade of these through the system means ever-widening uncertainty in a final projection that depends on all of these variables. That is mostly not the case. Unless the new variable is one that is really uncertain, and to which the final projection is really sensitive, adding more uncertain variables may not increase uncertainty in the final outcome much at all. The newly uncertain variable may take on a high value, but the effect it has on the projection is limited because it may be offset by chance low values in other variables. There is an almost inevitable tendency for individuals to take multiple ranges and put together all the highest and all the lowest ends to come up with a range. For example, some would use the highest emissions scenario with the highest sensitivity climate model and lowest emissions scenario with the lowest sensitivity climate model to create a temperature range. But unless one believes there is perfect correlation (and in this case the right assumption would seem to be that there should be no correlation) this can lead to a very wide range that is much less probable than either of the two underlying uncertainties. Unfortunately the standard method of science is to divide the problem down into manageable bits, and to estimate very specific relationships (and uncertainty in them) through very careful procedures where other conditions can be precisely controlled. To be relevant to decision-making, however, one needs to add these manageable bits back together again, and understand what each of these relationships (and the uncertainty in them) mean for the outcomes of interest.

All of the above issues are a case for quantitatively assessing uncertainty with coupled models. They are also a case for developing within these models the ability to represent the processes that might lead to extreme responses (with possible extreme forcing from other models) even if these are not very likely to occur.

Our group in the MIT Joint Program on the Science and Policy of Global Change has coupled relatively complex models (Prinn et al., 1999) to allow us to conduct analyses that can begin to estimate how the likelihoods of different outcomes of interest depend on uncertain variables, and to some extent uncertainty in model structure (Webster et al., 2003). Some further and very preliminary work has sought to understand how different mitigation options (very broadly speaking) could reduce the odds of different climate outcomes. While we have sought to use the best available information to quantify uncertainty in inputs, and 'realistic' models of various systems (Forest et. al., 2000, 2002; Webster et al., 2002), compared to the task at hand the effort is only a rudimentary start along the required path.

Key tasks for the science community involve developing within complex models the ability to represent uncertainty in parameters, processes, and feedbacks. (1) Continue developing the capacity to couple models and to efficiently simulate these coupled systems. (2) Work on representing processes that may be unlikely but possible under some conditions. (3) Increase the flexibility of models so that the behavior is not structurally determined—if climate sensitivity is uncertain, a models should be able to represent this uncertainty through change in parameters or perhaps plug-in changes in codes for subsystems. (4) Carefully document and report uncertainties in the literature. These tasks will require the community to continue development of models of varying complexity. Practically, simulating thousands of scenarios (large ensembles) is not possible with the most detailed earth system models. In addition, useful insights into complex behavior of earth systems can be investigated, at least initially, in simpler models.

Key tasks for the IPCC: (1) Summarize the literature accurately, and focus particularly on the state of the science literature with respect to its ability to describe the uncertainty. (2) Identify outcomes of relevance to decision-making and describe efforts to quantify uncertainty in these rather than report quantification of uncertainty in all variables that have been treated in the literature. (3) Describe the limits of the existing estimates, what is needed for research to progress, and how our understanding would change depending on the results of further research.

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Annex 2: Extended Abstracts

Climate Sensitivity: Uncertainty and Learning[1]

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1. Introduction

The importance of human-induced climate change depends critically on the temperature sensitivity of the climate system, measured by the change in global-mean temperature ($\overline{T}$) resulting from a doubling of the pre-industrial carbon dioxide (CO_2) concentration, denoted by ΔT_{2x}. If ΔT_{2x} is small, then the problem of human-induced climate change may not be acute. If ΔT_{2x} is large, then human-induced climate change may be one of the most severe problems of the 21st century.

The earliest estimate of ΔT_{2x} was made by *Arrhenius* [1896] using an energy-balance model [*Schlesinger et al.,* 1997], which yielded ΔT_{2x}=5.4°C. Subsequent estimates by such models, radiative-convective models and general circulation models [*Schlesinger et al.,* 1997] gave estimates respectively of 0.24°C [*Newell and Dopplick,* 1979] to 9.6°C [*Möller,* 1963], 0.48°C [*Somerville and Remer,* 1984] to 4.2°C [*Wang and Stone,* 1980], and 1.3°C [*Washington and Meehl,* 1983] to 5.2°C [*Wilson and Mitchell,* 1987]. Based on studies with general circulation models, a U.S. National Research Council (NRC) study chaired by J. Charney wrote: "We estimate the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of ±1.5°C" [*Board,* 1979]. A subsequent NRC study chaired by J. Smagorinsky concluded that: "no substantial revision of this {Charney report} conclusion is warranted at this time" [*Board,* 1982]. The Intergovernmental Panel on Climate Change (IPCC) interpreted the findings of the Charney report to mean that $1.5°C \leq \Delta T_{2x} \leq 4.5°C$ [*Houghton et al.,* 1990, 1996, 2001][2] Estimates of ΔT_{2x} based on paleoclimatic and instrumental temperature data range respectively from 1.3°C [*Hoffert and Covey,* 1992] to 6°C [*Barron,* 1994] and from 0.7 to 10.0°C [*Schlesinger and Ramankutty,* 1992]. None of these estimates provided probability density functions (pdf's) for ΔT_{2x}. An expert elicitation [Morgan and Keith, 1995] did provide subjective pdf's for 16 experts whose 90% confidence intervals ranged from 0.1–0.5°C to 0.1–8°C. More recently, subjective estimates of the ΔT_{2x} pdf were obtained from the instrumental temperature record using Bayesian updating [*Tol and Vos,* 1998], with the result that the posterior pdf depended strongly on the assumed prior (initial) pdf. The most recent studies based on the instrumental temperature record have found that there is a significant likelihood that ΔT_{2x} lies outside the $1.5°C \leq \Delta T_{2x} \leq 4.5°C$ range (Figure 1) [*Andronova and Schlesinger,* 2001 (AS), *Forest et al.,* 2002; *Gregory et al.,* 2002].

2. ΔT_{2x} Uncertainty Due to Radiative Forcing

Figure 2 illustrates the uncertainty in the optimal estimate of ΔT_{2x} due to uncertainty in radiative forcing (RF). For GT, the RF is due greenhouse gases and tropospheric ozone, and ΔT_{2x}=1.14°C. This value is very close to the value obtained when there is no net feedback, $\Delta T_{2x,0}=G_0 \Delta F_{2x}$, where $G_0=\overline{T}/(1-\alpha)S_0$ is the gain of the climate system with zero feedback [*Schlesinger* 1985, 1988, 1989].[4] Taking $\overline{T}$=288 K, planetary albedo α=0.3, and solar irradiance S_0=1367 Wm^{-2} yields G_0=0.3°C/Wm^{-2}. For ΔF_{2x}=3.71 Wm^{-2}, $\Delta T_{2x,0}$=1.12°C.

For GTA, negative sulfate aerosol RF is added to the positive GT forcing and ΔF_{ASA} (1990) is determined by the optimum estimation together with ΔT_{2x}. For GTA, ΔT_{2x}=4.8°C. This fourfold increase in ΔT_{2x} is required such that the observed $\overline{T}$ can be reproduced by the simple climate model (SCM) for the smaller net RF that results from the partial cancellation of the positive GT forcing by the negative sulfate forcing. In this light, the result for GT may be interpreted as the case for which the positive RF by carbonaceous aerosol balances the negative GT forcing by the sulfate aerosol forcing.

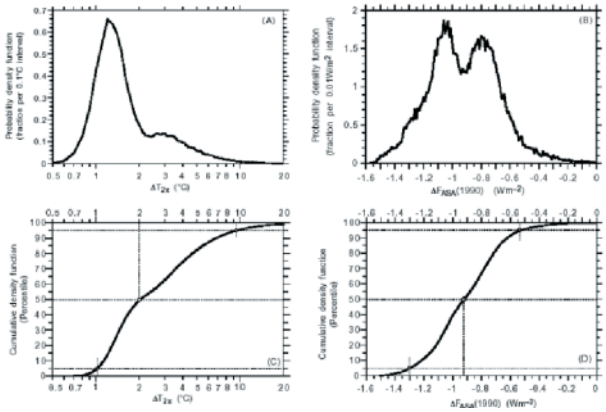

Figure 1. Probability density function (pdf, a and c) and cumulative density function (cdf, b and d) for ΔT_{2x} (left) and ΔF_{ASA} (1990)[3] (right) from AS.

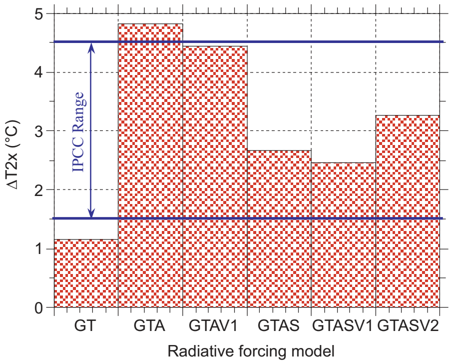

Figure 2. Dependence of ΔT_{2x} on RF model. G = GHGs, T = tropospheric ozone, A = sulfate aerosol, S = sun, V1 and V2 = different volcano radiative forcings.

Including the RF calculated by *Andronova et al.* [1999] for the volcanic optical depths of *Sato et al.* [1993], GTAV1 in Fig. 2, reduces ΔT_{2x} by about 8%. Including the solar-irradiance RF of *Lean et al.* [1998], GTAS in Fig 2, reduces ΔT_{2x} from its value for GTA by about 40%. A similar reduction is also obtained for the solar forcing of *Hoyt and Schatten* [1993] (ΔT_{2x} not shown). Because the solar-irradiance forcing constructed by both *Lean et al.* and *Hoyt and Schatten* increases over the period of instrumental temperature observations, the solar-irradiance forcing is positive. Adding it to the GTA forcing increases the net positive forcing. Accordingly, to reproduce the observed temperatures by the SCM requires the reduction of ΔT_{2x}. It is extremely important to learn whether or not the sun's irradiance varied as has been constructed. If it did not and changed only by the 0.1% observed by satellite since 1978 over a little more than two 11-year solar-activity cycles, then ΔT_{2x} is twice as large (GTA) as it would be if the sun did vary as constructed (GTAS).

Including volcanoes with GTAS decreases ΔT_{2x} by about 8%, as before. We have recently calculated the RF for the volcanic optical depths compiled by *Robertson et al.* [2001] and estimated their effect on ΔT_{2x} [*Andronova et al.,* 2004]. These optical depths differ from those of *Sato et al.* [1993] in both their chronology and intensity. When their RF is included with GTAS as shown by GTASV2 in Fig.2, ΔT_{2x} is increased by about 22%. This is in contrast to the 8% decrease in ΔT_{2x} when the *Sato et al.* [1993] volcanoes were included with GTA. Because volcanoes occur in only one hemisphere or the other, their RF is not the same in both hemispheres. Thus volcanoes influence not only $\overline{T}$ but also the interhemispheric temperature difference. Accordingly, volcanoes can either decrease or increase ΔT_{2x}.

From these results it is clear that reduction of the uncertainty in the estimation of ΔT_{2x} requires reduction of the uncertainty in the RF by aerosols, the sun and volcanoes.

3. Learning ΔT_{2x} Over Time

The uncertainty in ΔT_{2x} due to the natural variability of the hemispheric temperatures can be diminished in the future as additional observations become available. We illustrate this learning in Figure 3 where estimates of ΔT_{2x} for the GTA RF are shown in the form of box plots at 10-year intervals from 1940 to 2000, each with the observed temperatures starting in 1856. It is seen that the 5% confidence value for ΔT_{2x}, shown by the bottom of the box, changes very little with time, from about 1.2°C to 2.0°C. There is a larger variation of the 50% confidence value for ΔT_{2x}, shown by the solid line within the box, from about 6°C in 1950 to 3°C in 2000. The 95% confidence value for ΔT_{2x}, shown by the top of the box, in general decreases, from almost 27°C in 1940 to 12.5°C in 2000. Superposed on this downward trend in the 95% confidence level is an oscillation, apparently as a result of a temperature oscillation over the North Atlantic Ocean [*Schlesinger and Ramankutty,* 1994].

4. Conclusion

Progress in reducing the uncertainty in the value of ΔT_{2x} will require reducing the uncertainty in the RF, not only by aerosols, but also by the Sun and volcanoes. The uncertainty in ΔT_{2x} due to climate noise can be reduced by learning over time by performing future estimations using longer observational records. Thus, it is quite likely that the formulation and negotiation of policies to abate human-induced climate change will, for the foreseeable future, continue to be made against a backdrop of deep uncertainty. Such policy formulation and negotiation under uncertainty can be facilitated by robust adaptive decision strategy [*Lempert et al.,* 1996, 2003; *Lempert and Schlesinger,* 2000; 2002].

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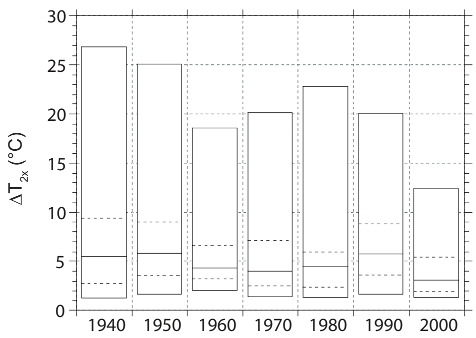

Figure 3. Box plots of ΔT_{2x} estimation of over time.

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Notes

[1] Based on Schlesinger, M. E. and N. G. Andronova, Climate Sensitivity: Uncertainty and Learning. Proceedings of the World Climate Conference, Moscow, 29 September to 3 October (in press).

[2] Strictly speaking, this interpretation is not correct. According to Webster's Revised Unabridged Dictionary "probable error (of an observation, or of the mean of a number), that within which, taken positively and negatively, there is an even chance that the real error shall lie. Thus, if 3{sec} is the probable error in a given case, the chances that the real error is greater than 3{sec} are equal to the chances that it is less. The probable error is computed from the observations made, and is used to express their degree of accuracy" [*Porter,* 1998]. Thus 3.0±1.5°C means that there is a 50% probability that $1.5°C \leq \Delta T_{2x} \leq 4.5°C$, and there is a 50% probability that ΔT_{2x} lies outside this range.

[3] Anthropogenic sulfate aerosol (ASA) radiative forcing in reference year 1990.

[4] Correctly speaking, the climate sensitivity is the gain of the climate system with feedback, $G_f=G_0/(1-f)$, where f is the feedback (op cit.).

A Reinsurer's View of Weather and Climate

Steve Smith

Director, Research and Development, ACE Tempest Reinsurance USA, Inc.

Reinsurers provide insurance for insurance companies. As such, reinsurers are often referred to as the financial risk taker of last resort. Reinsurance is a fragmented industry, with many different types of reinsurance available. Reinsurers may assume many different types of risk from life assurance risks to financial and credit risks. Property catastrophe reinsurers deal in weather and climate risk, particularly extreme weather and climate.

The need for reinsurance is very real. In the event of, say, a severe hurricane an insurance company may be liable for several billions of dollars, payable on the insurance it has written to homeowners. The insurance company in all likelihood will not have enough capital to pay all these claims (it is usually inefficient from a tax and investment point of view to for an insurer to hold very large pools of capital). The insurance company will use its own capital to pay for the lowest levels of claims and will then use its reinsurance to pay for the remainder.

Property catastrophe reinsurance is primarily concerned with catastrophic events which are high severity but low frequency. For example, a Category 5 hurricane has a very high severity but a very low probability of striking any one particular location. Property catastrophe insurance is priced with the two concerns of severity and frequency in mind.

Reinsurers make wide use of models of catastrophic events. The models, statistical in nature, generate stochastic events with defined probabilities. These virtual catastrophes will be applied to a series of locations, which make up the exposures of a given reinsurance contract, such that for each event a loss to the contract can be calculated. To actually price a reinsurance contract, a number of measures are employed but all the measures share a common thread – the event losses are convolved with the event probabilities.

We see therefore, that in the context of global climate change, reinsurers have two distinct but complementary questions:

1. How will the frequency of extreme events change?
2. How will the severity of extreme events change?

An increase in either, or both, would most likely lead to increases in reinsurance rates which would trickle down to consumers as increases in insurance premiums.

Annex 2: Extended Abstracts

Introduction to Session A: Determining and Describing Uncertainty in Socio-Economic Factors

Rob Swart

National Institute for Public Health and the Environment (RIVM), The Netherlands

Sources of Uncertainties (out of may possible typologies)

- **Measuring and monitoring:** how accurate are data, statistics?
- **Modelling dynamics:** how adequate do models describe reality (structure, parameters)?
- **Indicator selection:** how representative are the selected (input and output) indicators?
- **Expert judgement**
  - Future assumptions: how will the future evolve?
  - Human choice: how is it influenced by human choices?

Aspects of uncertainties

- Level of uncertainty: statistical, scenario (“what-if”), recognized ignorance
- Nature of uncertainty: knowledge-related, variability-related
- Knowledge base: level of agreement, amount of supporting evidence
- Value-ladenness: small or large

Issues covered by session A

- Part 1
  - Demographics
  - Affluence/income
  - Technological change
- Part 2
  - Scenarios (emissions, impacts & adaptation)
  - Costs (mitigation, damage, adaptation)
  - Mitigative and adaptive capacity

Demographics

- **Measuring and monitoring:** how accurate/reliable are population data and statistics?
- **Modelling dynamics:** how adequate do models describe demographic dynamics; how reliable are population projections?
- **Indicator selection:** what we want to know: number of people? number of households? age composition?
- **Expert judgement:** how are population characteristics influenced by other future developments, including policies?

Affluence/income

- **Measuring and monitoring:** how accurate/reliable are economic/income data/statistics?
- **Modelling dynamics:** how adequate do models describe economic dynamics, at micro, macro, international level? how does aggregation affect uncertainty?
- **Indicator selection:** is size or composition relevant? what is the most adequate indicator: GDP? PPP? HDI? other?
- **Expert judgement:** how is economic development influenced by other developments, including human choices/policies?

Technological change

- **Measuring and monitoring:** how accurate/reliable are technology data and statistics, e.g.technology penetration, emissions factors?
- **Modelling dynamics:** how adequate do models describe technological change; how is it linked to other variables like economic growth?
- **Indicator selection:** what we want to know: aggregate indicators like energy/carbon intensity? deployment of individual technologies?
- **Expert judgement:** how is technological change influenced by human choices, including market issues, policies? what about technologies that do not yet exist?

GHG emissions and impacts/vulnerability scenarios

- **General:** how do uncertainties in components add up? can probabilities meaningfully be addressed?
- **Measuring and monitoring:** how accurate/reliable are emissions data and statistics (e.g. CO2 vs. non-CO2, energy vs. non-energy)?
- **Modelling dynamics:** how do models combine demographic/economic/technological dynamics?
- **Indicator selection:** how well are all emissions/sources captured: CO2, 6 Kyoto gases, ozone, aerosols?
- **Expert judgement:** e.g. how are uncertainties with respect to policies separated from other socioeconomic uncertainties?

Mitigation, adaptation, damage costs

- **General:** how do uncertainties in components add up? can probabilities meaningfully be addressed?
- **Measuring and monitoring:** how accurate/ reliable is costing information? how can costs be defined?
- **Modelling dynamics:** how adequate do models describe costs; what are uncertainties related to different costing methods (e.g., top-down vs. bottomup)
- **Indicator selection:** what is actually covered by cost definitions? costs for whom?
- **Expert judgement:** how are costs estimates affected by baseline assumptions (socio-economic and fiscal issues, trade, exchange rates)? by policy choices?

Mitigative/adaptive capacity

- **General:** how do uncertainties in components add up? can probabilities meaningfully be addressed?
- **Measuring and monitoring:** how can adaptive/ mitigative capacity be measured?
- **Modelling dynamics:** how adequate do models capture adaptive/mitigative capacity? how does aggregation affect uncertainty?
- **Indicator selection:** are the factors which really determine adaptive/mitigative capacity understood?
- **Future assumptions/human choice:** how is future adaptive/mitigative capacity at different spatial scales influenced by human choices, including policies?

Introduction to Session D: Determining and Describing Uncertainties in Projections of Climate Change and Its Effects

Gary Yohe

Wesleyan University

Given the cascade of uncertainty in our understanding of a climate system, the fundamental task of an assessment is to evaluate the degree to which the cascade is accommodated and to describe the degree of confidence that can be attributed to a set of conclusions.

This talk will offer an example of how current research can examine of the implications of new and expanding distributions on climate sensitivity on near-term policy. The example casts a revised version of Nordhaus's DICE model through a reduced-form climate model calibrated across a cumulative probability distribution that shows at least 7% of the likelihood above 9 degrees. It then explores near-term hedging strategies for alternative concentration and temperature targets (given the assumption that uncertainty about the climate sensitivity and the ultimate target will be resolved in 2035) to conclude that modest near-term intervention are warranted. The conclusion is robust across alternative policy targets and climate sensitivities (in terms of economic criteria) when compared to adopting a do-nothing approach over the next 30 years.

The IPCC cannot be policy prescriptive, but it can assess policy recommendations of this sort when they appear in the literature with respect to uncertainty and confidence. The specific recommendations presented in the example can be asserted with only medium confidence, because the analysis falls into an "exogeneity trap" and therefore underestimates uncertainty over the next 30 years. Uncertainty in the areas considered will not be resolved by 2035. Many other economic futures are possible. Global mitigation will not be achievable in 2005, when the near-term policies are modeled to begin. Social, economic and political structures may change radically between now and 2035. And so on. The point is that prediction, projection, contextual, and implementation uncertainties are essentially ignored in the analysis; and calibration uncertainty is accommodated only in the climate model. Still, the qualitative result that near-term intervention is warranted on the basis of a risk assessment could be claimed with high confidence because an assessment could observe that the uncertainty that is included in the analysis generates the value for near-term hedging and that increasing uncertainty by accommodating other sources would only amplify that effect.

Annex 3:

A Concept Paper for the AR4 Cross Cutting Theme: Uncertainties and Risk

Martin Manning and Michel Petit

5 September 2003

Overview

An assessment of climate change science requires careful consideration of the level of scientific understanding that applies to all of the key issues covered. Uncertainties affecting currently available scientific results need to be explained clearly and in ways that avoid confusion and assist policymakers and non-specialists when considering decisions and risk management.

The AR4 should build on previous treatments of uncertainty in IPCC reports and assess relevant new literature in this respect. It will be important to further enhance the development of a consistent but unrestrictive style of describing the source and character of uncertainties during the assessment process. Authors should be encouraged to: explain the nature of underlying hypotheses and simplifying assumptions; identify scarcity or quality issues with data; and recognise the limitations of models which do not simulate all processes perfectly.

Wherever possible uncertainties should be quantified using well defined procedures based on relevant literature. Projections into the future should show ranges in which the effects of lack of predictability (chaos), uncertainty in modelling, and scenario assumptions are separately identified. The treatment of uncertainties in the AR4 should improve the value of key findings by providing a more precise context for decision making and for structured approaches to risk management.

1 Introduction

This concept paper is intended to elaborate ways in which uncertainty might be dealt with in the preparation of the IPCC Fourth Assessment Report (AR4). A basic premise adopted here is that a useful focus for treating uncertainty will be to consider how it affects risk assessment and risk analysis, hence the title of the theme deliberately links the two concepts. However, the scope of this theme is not intended to extend into the area of risk analysis itself. Rather the focus is on dealing with uncertainty, itself a highly complex topic, and how that may be treated in ways that are useful for risk analysis.

One purpose of linking uncertainty to risk is to improve communication between climate scientists and potential users of the information they can provide. Several initiatives to improve the use of climate change science and deal with uncertainty in the policy process over recent years have identified risk analysis as a useful focal point (e.g. Willows and Connell, 2003). Such developments deserve attention from the authors of the AR4 as they are likely to provide useful guidance on how uncertainty can be characterized in a constructive manner. Recognition of existing attempts to develop a dialogue between science and policy over issues of uncertainty could make the AR4 part of that development.

This paper is not intended to directly influence the structure of any of the Working Group reports. We believe that the issues raised here will inevitably permeate those reports quite broadly. In addition there have been significant advances since the TAR in specific areas of uncertainty analysis which will require coverage in the AR4. Such advances should be covered naturally in relation to the underlying material being assessed.

In the remainder of this concept paper we provide a summary of:

- the relationship between uncertainty and risk assessment;
- the treatment of uncertainty in the IPCC Third Assessment Report (TAR);
- some general issues that arise when describing uncertainty;
- some suggested areas in which uncertainty and risk may need specific consideration;
- a suggested process for reviewing the treatment of uncertainty during the AR4 drafting process.

This paper is not intended to provide a comprehensive review of all the topics covered but should identify a representative cross-section of them so as to guide further decisions on how the theme might be implemented in the AR4.

2 The nature of uncertainties and their relation to risk assessment

IPCC Assessment Reports play a key role in the dialogue between scientists and non-specialists (decision makers, citizens, consumers) regarding the risks of anthropogenic climate change. The role of scientists is to understand the meaning of available observations and to develop rational projections of the future. On the other hand, a wide range of people have to make their own decisions, irrespective of their scientific background. A fundamental premise of the IPCC's existence is that they can benefit from scientific and technical information on the possible consequences of their decisions. This requires that the IPCC process be used to translate scientific understanding into terms which can help every one in making up their own minds.

The goal of making scientific understanding of climate change widely accessible raises particular challenges when it comes to dealing with uncertainty. Uncertainties are usually more difficult to quantify than the factors to which they apply; their treatment is more complex both conceptually and operationally; and the normal use of language to describe uncertainty is often ambiguous. In order to deal with uncertainty in a way that is coherent across the AR4 and useful for decision making it is recommended that descriptions of uncertainty be designed in ways that will improve risk assessment. This approach recognizes that climate change will modify existing risks and in doing so introduce additional sources of uncertainty into risk assessment (e.g. Willows and Connell, 2003).

Although the concept of "risk" is used in several different ways (e.g. German Advisory Council on Global Change, 2000) it is defined quantitatively in a broad range of formal risk analysis techniques as the product of two factors: the likelihood that some event will occur or its expected frequency of occurrence, and the magnitude of the consequences of that event. This usage of the term “risk” has been adopted in previous IPCC activities (e.g. IPCC, 1998),

however, given the potential for ambiguous usage or interpretation of the term, it will need prominent definition in the AR4.

There is strong evidence that people treat consequences in a highly non-linear fashion, discounting small effects and emphasising large effects (e.g. Patt and Schrag, 2003). Systems normally survive because they are well adapted to the more frequent forms of low consequence events, whereas high consequence events can overwhelm the ability of any system to recover. This non-linear perception of consequences applies to the risk value, with low risk events normally being discounted and high risk events emphasised.

Probabilistic approaches can be applied to risk analysis when strict numeric probabilities can be defined, e.g. when long term statistics are available for stationary phenomena. Because of this, risk analysis is most easily linked to probabilistic approaches to uncertainty. However, risk analysis techniques are frequently adapted to deal with circumstances in which strict numeric probabilities can not be defined. In either case, uncertainty analysis plays a key role in risk assessment.

In order to assist risk assessment, descriptions of uncertainty should be focussed on aspects that are relevant to the strategies that might be applied to the issue being considered. For example, a tolerable pathways strategy, that aims to avoid impacts above some threshold, requires a focus on uncertainties in relevant critical thresholds and in the amount of climate change that would lead to crossing those. Risk assessment strategies that aim to identify unpredictable regimes[1] require information on how the reliability of estimates for likelihood and consequence decrease as a function of the magnitude or rate of change.

The above very brief summary of how an understanding of uncertainty may interact with risk assessment is intended to demonstrate that the best choices for describing uncertainty will depend both on the level of understanding of the relevant science, the nature of associated risk factors, and on the types of decisions that a corresponding risk assessment might influence.

3 The treatment of uncertainty in the TAR

Uncertainty was recognized as a cross-cutting issue early in the process of preparing the TAR. Moss and Schneider (2000) prepared a guidance document which was subject to two rounds of review. A series of recommendations was made regarding: careful characterization of the sources of uncertainty, coverage of ranges given in the literature, and consistent use of confidence descriptors. The latter recommendation introduced five levels of confidence to characterize collective expert judgements in terms of probabilistic ranges. In addition, an alternative means of

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[1] This is a common risk management strategy in the face of uncertainty, e.g. many insurance companies recently withdrew from the event insurance market in response to the outbreak of SARS because they felt unable to assess the risks being covered.

quantifying confidence, was proposed in which authors would refer to a level of understanding based on both the amount of evidence available and the degree of consensus among experts.

The Moss and Schneider approach recognizes the need to obtain semi-quantitative assessments of uncertainties based on subjective judgments of confidence and that these can be more robust when pooled across several experts (e.g. Morgan and Keith, 1995). It also required that such judgments be mapped into a five-level confidence scale using the terms:

very high (95% or greater), *high* (67–95%), *medium* (33–67%), *low* (5–33%), and *very low* (5% or less). The WG II TAR used these terms as defined in the guidance document and in many cases followed an informal process within expert teams for deciding which term should apply to the collective judgment.

The WG I TAR adopted a different seven-level scale to characterize confidence as follows: *virtually certain* was used to describe a greater than 99% chance that the result was true, *very likely* a 90–99% chance, *likely* a 66–90% chance, *unlikely* a 10–33% chance, *very unlikely* a 1–10% chance, and *exceptionally unlikely* less than a 1% chance. The mid-range option, 33–66%, was not used.

In retrospect it appears that use of specific language (words such as *likely* or *low confidence*) to describe probability ranges can be misleading or confusing and this aspect of describing uncertainty needs to be reviewed. For example, writing that the judgmental estimates of confidence expressed by low is 5–33%, suggests that experts are able to agree that an estimate of 32 % is better than an estimate of 34 %. Actually, they don’t agree on a probability value, but on a range of probability which can be defined at best on a 5 five points scale (as sometimes used in weather forecasts), anything significantly more precise being unjustified. If the AR4 is to use similar 5 or 7 point scales of confidence then at least the definitions used need to recognize fuzzy boundaries as done in the US National Assessment (USGCRP, 2000).

Similar choices occur between use of numeric ranges or semi-quantitative language to describe results. For example, in the SPM of the WG II TAR the expression “2 to 3 degrees” was replaced with “a few degrees”. Such a change has implications for the degree of certainty being expressed in the underlying message and also raises potential problems with differing interpretations when translated to other languages. In general, numeric estimates of ranges and of probabilities provide more accurate ways of communicating results.

A more qualitative characterization of “level of scientific understanding” was used for cases where the authors were unable to express uncertainties in probabilistic terms. The TAR WG II SPM followed the Moss and Schneider (2000) recommendation using four categories: *well established, established-but-incomplete, competing explanations,* and *speculative*. The WG I TAR also used the concept of level of scientific understanding to qualify estimated ranges for some key parameters. However, that usage did not employ the two-dimensional separation into extent of information and degree of consensus suggested by Moss and Schneider.

The use of similar words in different contexts may lead to confusion. For example the TAR WGII SPM states:

> Economic modeling assessments indicate that impacts of climate change on agricultural production and price are estimated to result in small percentage changes in global income (low confidence) with larger increases in most developed regions and smaller increase or declines in developing regions.

The intent here is to say that, although analyses generally indicate small changes in agricultural income at a global scale, we have low confidence in the tools available. That implies a significant probability that actual changes might be large, but such an interpretation of the statement is not immediately obvious. Thus describing uncertainty well requires careful use of language and it would be useful to review the TAR, particularly the SPMs, in order to provide guidance to authors of the AR4.

Authors of the WG III SPM felt it necessary to describe uncertainties in estimating costs and benefits of mitigation measures in explicit terms depending on the context. E.g.

> These two approaches (bottom-up and top-down) lead to differences in the estimates of costs and benefits, which have been narrowed since the SAR. Even if these differences were resolved, other uncertainties would remain. The potential impact of these uncertainties can be usefully assessed by examining the effect of a change in any given assumption on the aggregate cost results, provided any correlation between variables is adequately dealt with.

Such a statement might be judged as disappointing for a policy maker who would like to use those cost estimates, but it conveys precisely what are the present scientific uncertainties. In such situations, where sensitivity analyses are used to describe the limits of our understanding, graphical presentations of results are often the most effective form of communication.

While the language used to describe uncertainty was not strictly uniform across the TAR, the approaches adopted by different groups of authors were similar in many cases and some advances were achieved over the Second Assessment. The focus on careful treatment of uncertainty alerted authors to some forms of ambiguity that had appeared in earlier reports. For example, the use doubly caveated statements of the form “we have *medium confidence* that phenomenon X *might* occur” was largely avoided. By highlighting the subjective nature of confidence levels, the guidance document stimulated greater discussion of confidence within the author teams. Also the use of an arbitrary collection of words such as “possible”, “doubtful”, etc was avoided, improving comparability of confidence assessments from one part of the report to another.

It should be noted that IPCC assessments incorporate a conservative treatment of uncertainty at a structural level. The general approach of identifying consensus among a group of climate scientists means that areas where there remains considerable uncertainty tend to be automatically de-emphasized or simply omitted. Comparison with the peer reviewed literature shows that in many cases individual experts tend to use more definitive language than that agreed as the consensus among a team of authors. The role of the author teams can thus be to drive towards the lowest common denominator view which may offset an apparent tendency for individuals to be overconfident in their own assessments (e.g. Kahneman and Lovallo, 1993).

Another structural way in which uncertainty is embedded in the IPCC assessments is through the use of scenarios for future change in underlying factors such as socio-economic change. The IPCC Special Report on Emission Scenarios (SRES) had a strong influence on the projections and timescales used in the TAR which may have obscured some longer term issues but did create a focus on a wide range of emission scenarios. Scenario analysis is widely used as a way of characterizing uncertainty for less predictable aspects of future projections.

This leads to the question as to whether some form of likelihood can be ascribed to individual scenarios – e.g. in the form of a time varying cumulative probability distribution for specific parameters such as CO_2 emissions. This issue has been strongly debated among experts and there is as yet no consensus on the issue (e.g. Wigley and Raper, 2001; Reilly et al, 2001; Allen et al, 2001; Schneider, 2001; Lempert and Schlesinger, 2001; Pittock et al, 2001)

4 General issues that arise in describing uncertainty

The probabilistic approach to uncertainty in relation to climate change raises some important conceptual issues. Frequency of occurrence can be defined for repeating weather related events, and changes in such frequencies can be derived from model projections. However, global scale climate change in the real world will occur only once and a frequentist definition of probability can only be considered in an academic sense using a sample space of climate outcomes constructed using models. Development of a consistent approach to the probabilistic description of uncertainty as applied to climate projections, and to frequencies of weather related events implied by such projections, appears to require further discussion.

Experience with the TAR has shown that confusion arises when insufficient attention is paid to the definition of what is being assigned a probability or confidence level. This is particularly so when probability or confidence is low but the issue sufficiently important to require discussion. A general issue of language arises in differentiating clearly between the estimated probability of a particular outcome and the confidence level of such an estimate. It is possible to have high confidence in a finding indicating that climate change would lead to a low probability of some outcome and conversely to have low confidence in a finding that climate change would lead to a high probability of another outcome.

There is some evidence that use of specific language to describe probabilities alone may not be interpreted accurately as people link probability descriptors to event magnitude. For example, a study involving 150 undergraduate science students by Patt and Schrag (2003) confirmed the existence of a behavioral tendency for people in general to interpret probability language describing weather events in a way that responds to event magnitude. Thus people are more likely to choose more certain sounding probability descriptors (e.g., *likely* instead of *unlikely*) to discuss more serious consequence events. But people are also sensitive to this practice in others, expecting a certain amount of exaggeration about the likelihood of high magnitude events. A related consequence is that if the language used is based solely on probability of occurrence the reader may have a tendency to over-estimate the likelihood of low-magnitude events, and to under-estimate the likelihood of high-magnitude events.

Characterization of uncertainties should clearly reflect their origin and the ways in which corresponding probabilities or ranges are derived. The origins of different components of uncertainties can be classified into five broad areas as follows:

1. *Incomplete or imperfect observations.* This type of uncertainty is a joint property of the system being studied and and our ability to measure it. Particularly in the natural and physical sciences the implications of observational uncertainty tends to be the best developed of the five sources of uncertainty considered here. It is well recognized that accurate treatment of obervational uncertainties must go beyond simplistic assumptions of normally distributed random errors. The effects of data sparsity, systematic and calibration errors need to be considered as does the sometimes subtle difference between the quantity of interest and the proxy that is generally measured. Comparison of independent observing systems and analyses provide key approaches to this type of uncertainty. Many important findings depend on a combination of observations of different factors having very different uncertainty characteristics, e.g. the use of multiple proxies to draw inferences about past climate change. However, techniques are available to deal with such issues and are generally used in the climate science community. For the AR4 the challenge here will be to provide clear explanations of the sources of uncertainty and how they have been dealt with.

2. *Incomplete conceptual frameworks* (models that do not include all relevant processes, etc). This type of uncertainty arises where there are shortcomings in our understanding that essentially require a "breakthrough" to rectify and is the most difficult aspect of uncertainty to characterize accurately. A major issue here is the extent to which comparison of models with observations can serve to constrain uncertainties (e.g. Allen et al, 2000). The limitations of model validation need to be recognized, particularly where models are used to simulate circumstances that extend beyond ranges over which observations are available. A related issue is the ability of models to identify thresholds for 'state change' in the climate system.

3. *Inaccurate prescriptions of known processes* (poor parameterisations, etc). This type of uncertainty arises where defects in our understanding are subject to incremental improvement. Approaches to constraining uncertainty estimates in these cases tend to rely on comparison of models with observations and on model intercomparisons. It should be noted that the adequacy of observations for testing simulations may limit confidence in some aspects of models. To some extent this component of uncertainty might be treated as a subset of the one above, however, it is important to differentiate between the range of projections produced by a set of models and the broader uncertainty in projections that might arise because all models share a common defect.

4. *Chaos.* This type of uncertainty is a property of the system being studied. Chaos as defined classically arises where future states of a system are highly sensitive to small changes in initial conditions. Meteorology is well recognized as having a chaotic component and this concept is increasingly used in treatments of climate change. We expect recent progress in this area to provide a much clearer picture of projected climatic change in the presence of meteorological chaos.

5. *Lack of predictability.* Lack of predictability applies more broadly and can be extended to socio-economic studies where some aspects of societal behaviour are much less amenable to prediction than others. For example, in considering the rate at which new technology may affect energy systems, attempts are being made to separate uncertainty in the rates of market penetration of new technologies from the less predictable rate of invention of new technologies (Nakicenovic, private communication 2003). A widely used approach to characterize uncertainty in systems where lack of predictability dominates is to explore outcomes implied by a representative range of scenarios. This approach was the basis for treating uncertainty in future greenhouse gas emissions in previous IPCC reports and should be used again in the AR4. However, scenario analysis might be used in other areas of the assessment where predictability is poor.

Most key findings in the AR4 are expected to have component uncertainties corresponding to more than one of the classes identified above. It will be important to present results in such a way as to reflect these different sources of uncertainty. For example, projected ranges of future global mean warming should identify clearly the parts of that range that arise from: lack of predictability (chaos) in the climate system, uncertainty in climate models, and assumptions about emission scenarios.

5 Some specific issues for consideration in the AR4

5.1 Working Group I

Working Group I relies on a strong observational basis for its assessment and extends this using highly sophisticated computer models. This creates a dichotomy in the way uncertainties are treated. Concerning the existence of a global warming trend, recent data are quite reliable and statistical methods allow estimates of the degree of confidence for different components of apparent trends, e.g. global mean temperature, mean temperature over large geographical areas, night and day time increases, etc. Paleoclimatic data typically involve a wider range of more diverse sources of information, are sparse spatially, and involve varying degrees of temporal smoothing. Uncertainties in paleodata should deal with those issues.

Uncertainties regarding model projections are generally more difficult to deal with. It is accepted that many physical processes take place on much smaller spatial scales than the model grid and therefore cannot be modelled or resolved explicitly. Their average effects are approximately included through parameterizations which may take advantage of physically based relationships between the large-sale variables. Evaluating the errors associated with processes that are not explicitly resolved in the model and tracing the effect of these through to major conclusions drawn from model outputs is difficult.

One of the more critical parameters inferred from process based climate models is climate sensitivity, often defined as the equilibrium temperature change resulting from a forcing equivalent to a doubling of CO_2 concentration. Estimates of climate sensitivity in previous assessments by the IPCC and other groups have cited the range 1.5°C to 4.5°C for over 20 years. This factor of 3 uncertainty directly impacts any consideration of scientific and technical information that might guide policy decisions on dangerous levels of greenhouse gas concentrations. However, the TAR, like preceding reports, does not indicate clearly what probability should be assigned to the 1.5°C to 4.5°C range, nor whether the central part of that range should be considered more likely than extremes. Is this factor 3 truly representative of the uncertainty? Does our present understanding merit presentation of the uncertainty as a probability distribution function? Can we indicate what is required to significantly reduce the range and if so can we set a time frame on when that might occur? Each of these questions has very important implications for objective decision making processes.

The introduction of probability distribution functions (pdfs) for key results, such as climate sensitivity or the change in global mean temperature by 2100, into IPCC assessments would raise some significant new issues. Recent literature has produced rather different estimates of the pdf for climate sensitivity based on different models and approaches, but little attention has been given to methods for, or the validity of, pooling such estimates. Decisions would also need to be made as to whether (and how) a range of emission scenarios should be folded into a pdf for global mean temperature change. However, there could be several advantages to presenting some key results in terms of probability distributions. For example, presenting the range of warming in 2100 as a probability distribution would provide more useful information for impact analyses and risk assessment, and could also reduce misunderstanding. The 1.4 to 5.8°C range given in the TAR has been criticized for its opaqueness and the implication that all temperatures in this range are equally plausible in the absence of clear statements to the contrary.

There have been many new studies characterizing uncertainty in climate change since the TAR. The use of statistical approaches in analysing model results is leading to further clarification of the origins and ranges of uncertainty (e.g. Stott and Kettleborough, 2002; Weaver and Zwiers, 2000). The role of observational constraints on near term model projections has been investigated (e.g. Allen et al, 2000). Probability distribution functions for climate sensitivity have been considered by various authors (e.g. Andronova and Schlesinger, 2001; Wigley and Raper, 2001) and the interactions between uncertainty in radiative forcing, particularly of aerosols, and climate sensitivity have been discussed from various perspectives (e.g. Forest et al, 2002; Knutti et al, 2002; Anderson et al, 2003). A further important development is the use of multi-ensemble projections to consider and quantify changes in extreme events (e.g. Palmer and Räisänen, 2002).

Given the importance of regional scale climate change from a policy perspective a careful uncertainty analysis of methods for deriving regional climate projections is necessary. This should include consideration of statistical downscaling techniques as well as regional climate models. The roles of resolved and parameterised scales and processes are likely to be different between regional and global models suggesting that careful treatment of these issues will be necessary.

The issue of assessing the likelihood of a major state change in the climate system as a possible response to increased forcing remains a difficult area. However, some specific attempts to address uncertainty in such areas have been undertaken – e.g. Vaughan and Spouge (2002) have carried out an assessment of the risk of significant collapse of the Western Antarctic ice sheet using an approach similar to a decision tree analysis.

5.2 Working Group II

The impacts associated with a greenhouse gas emissions pathway are estimated in two steps: first an evaluation of the resultant climate change, then an evaluation of the effects of this climate change on the ecological and socio-economic systems. This causes a cascade in the overall uncertainties which come from combination of the uncertainties affecting the two steps. Based on experience in the SAR and the TAR it appears that greater clarity in describing our understanding of the effects of climate change is achieved if Working Group II focuses on the conditional uncertainty in effects for a given climate change scenario and that overall uncertainties are best treated at the synthesis report level.

Note that the conditional premise used in Working Group II is a climate change scenario which should be distinguished from an emission scenario. This distinction is assisted by the work of the Task Group on Climate Scenarios for Impact Assessment (TGCIA) which makes relevant climate scenarios widely available to impacts researchers (e.g. Carter et al, 1999).

However, the interaction between WGs I and II in terms of uncertainty raises other issues. Risk assessment generally requires a focus on lower probability high consequence events, whereas assessment of physical climate changes is most reliable for medium to high probability characteristics where there are better statistics. For example, flood control decisions might plan for a one in a 100 year event while most climate model runs extend for 200 years or less and so could only be expected to capture the background conditions for two such events. In the TAR, WG II naturally tended to use a risk (i.e. probability times consequence) based weighting for different aspects of climate change while WG I tended to use a probability based weighting. This has implications for how information on uncertainties is transferred between the two groups and requires more detailed consideration during the AR4. In particular, high consequence low probability aspects of climate change should be treated in a compatible manner.

In the first three IPCC assessment reports, effects have tended to be evaluated qualitatively rather than quantitatively and through sensitivity to change, rather than in terms of scenario based analyses. More quantitative projections would be appreciated by decision makers. However, if uncertainties in the results are too large then such projections become meaningless. Improving the treatment of uncertainty in cost estimates of climate change requires that the sensitivity of impacts to assumptions made in the models are critically assessed. Even if it turns out that some assumptions have a crucial effect these may be included in an assessment in order to show what might happen, even if the probabilities are unknown. But selection of such cases requires careful judgment, should avoid normative decisions by scientists as to what is policy-relevant, and the larger uncertainty and its more qualitative character need to be made clear.

Treatment of uncertainty in costing impacts should take into account that many factors other than climate change will impact the future and it is necessary to identify clearly the domains and regions which are likely to be mainly affected by climate change. Uncertainty in cost estimates for adaptation measures and their comparison with avoided damages raises specific issues of costing methodologies. This is an area of high policy relevance and should be considered carefully by WGs II and III in connection with the cross cutting theme of integrating Adaptation and Mitigation.

The development of integrated assessment models is leading to a broader understanding of how sensitivity and uncertainty analysis can be carried through an analysis of multi-faceted issues (e.g. Toth et al, 2003) but it must be recognized that results are still systematically dependent on model assumptions.

WG II also appears to face significant challenge in assessing uncertainties surrounding future adaptive capacity and the limits to adaptive responses. This may be a key factor in uncertainty when considering vulnerability.

5.3 Working Group III

Working Group III deals with mitigating future emissions of greenhouse gases and the feasibility and cost (in the broadest meaning of that term) of stabilizing their atmospheric concentration. A large number of factors will play a role: demography, economic and social development, scientific and technical progress, and international frameworks for shared decision making. Outcomes are much less predictable because societal behaviour is not controlled by immutable laws and the corresponding uncertainties become necessarily much broader. For these reasons short term economic predictions are treated with caution and longer term ones are considered more as scenarios of what could happen rather than having some identifiable probability of occurrence.

Some progress may be made in separating the more and less predictable aspects of technical and societal change. To the extent that this may be achieved it would be valuable to identify their separate contributions to uncertainty. However, assessment of our understanding of mitigation options will inevitably rely heavily on scenario based analyses. Treatment of uncertainties in this case can be done through careful identification of how the assumptions made in different scenarios affect results.

5.4 Synthesis Report

If it is decided to prepare a Synthesis Report for the AR4 then it will be necessary to integrate aspects of uncertainty arising from the different WG reports. For example, the uncertainty cascade effect mentioned above would require a reasonable degree of consistency between

Working Groups I and II if overall uncertainties are to be assessed in a systematic way. This would apply in particular to attribution of observed effects to anthropogenic climate change or of projected effects to future anthropogenic climate change. Whether this linkage between Working Groups I and II strictly requires a probabilistic approach to uncertainty on both sides is an issue that should be discussed further within the appropriate expert communities.

There are clearly issues in common between the assessment of key vulnerabilities and issues relating to Article 2 of the UNFCCC and the general approach to uncertainties in the AR4. Some harmonization of approach between these two themes would appear to be necessary. In addition at the synthesis level degrees of uncertainty can be affected by choices of aggregation across regions and timescales. Thus there may be interactions between the regional climate and uncertainty themes.

6 A process for reviewing the treatment of uncertainty during preparation of the AR4

The various facets of uncertainties associated with climate change are sufficiently different that specific treatments may need to be applied in each case. Thus from an editorial standpoint, for each chapter, the Lead Authors should feel free to express their uncertainties in their own way, but be asked to provide all available information on the limits to every statement in ways that can be understood by non-specialists.

Editorial management of the report should also call for an emphasis on clarity and transparency in language relating to uncertainty. Use of specific language constructs and standard uncertainty scales remains an issue to be considered further. It appears these can be restricting for authors and can be misleading for the readers. On the other hand the uniformity they provide may be important when considering syntheses of findings at the level of a Technical Summary, a Summary for Policymakers, or in a Synthesis Report.

It is proposed that, following the second scoping meeting for the AR4, the co-anchors work with selected experts to develop a more substantive background paper on the uncertainty and risk theme. Such a background paper would include discussion of options and suggestions for dealing with different types of uncertainty with references to the recent literature. The aim would be to build on work done for the TAR and, to the extent possible, address issues that arose there using input from some LAs of the TAR.

The background paper would need to be reviewed broadly and a reasonable amount of time would need to be allowed for that. In order to advance this process rapidly it is proposed to hold an expert meeting on “Uncertainty and Risk” early in 2004. Given the need to make the characterization of uncertainty in the AR4 relevant to policymakers, it would be appropriate to include a carefully focused policy perspective in this meeting.

It would clearly be most valuable if the background paper could be completed in advance of the first LA meetings for the AR4. This paper should be placed on a closed IPCC web site reserved for LAs and include an index addressing the reader directly to the issue for which she or he is seeking advice.

As a second step we propose that in the review process specific reviewers be identified to consider the treatment of uncertainty in the WG reports. Some of these reviewers might be drawn from outside the normal pool of climate experts. Their role would be fully consistent with the normal open review process used by the IPCC, although their focus would be specific to the uncertainty issue. This complementary type of review would not displace the IPCC's standard rules governing the roles of LAs and REs. In particular, the LAs and REs would remain pre-eminent in the drafting process.

We suggest that the co-anchors would continue to have a monitoring role during the review process. This would involve maintaining contact with the "uncertainty reviewers" during the review periods and considering any difficulties that arose in dealing with uncertainty issues. However, the co-anchors would not play any role in drafting the reports beyond the normal review process. They might be consulted during the plenaries devoted to the reports acceptance.

If substantive issues regarding treatment of uncertainties arose during the preparation of the AR4, and appeared to merit further consideration, we suggest that these be summarized in a report for the benefit of the next IPCC Bureau and their preparations for the AR5.

7 Conclusions[2]

The way in which uncertainty is treated in the AR4 will have a significant bearing on the overall utility of the assessment for decisionmakers. In this respect a focus on providing assessments of uncertainty that can improve risk analysis appears to be a constructive approach and is consistent with recent studies and literature particularly in the Working Group I and II areas.

The treatment of uncertainty in the TAR was an improvement on that used in previous assessments, and aspects of that approach have been used subsequently in national assessments. Based on this experience and on new approaches appearing in the literature it should now be possible to improve on the approaches to uncertainty used in the TAR.

The best approach to assessment of uncertainty will vary depending on the issue being addressed and the nature of the available research results. This suggests that some flexibility in approach is necessary.

However, some degree of compatibility in the treatment of uncertainty is also necessary if systematic approaches to uncertainty are to be used for issues that require a synthesis of findings from different disciplines or Working Groups. Thus a careful balance between flexibility and compatibility will need to be developed.

Clarity in describing uncertainty requires very careful attention to choices of the ideas being expressed and the language used to do so. Distinctions between the probability of events and

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[2] This conclusion section was added in the final revision to this paper because several review comments appeared to indicate a need for some general summary points and because the general tone of the comments received have suggested a consensus on several aspects.

the confidence in such probability estimates, between subjective and objective assessments of uncertainty, and between uncertainty applying to more observationally based and more model based results, all require careful and consistent use of language.

Description of uncertainty where outcomes are expected to have very high consequence, but where probability is expected to be low or where predictive ability or confidence in present understanding is low, present particular challenges.

While there may be merit in examining how uncertainty issues are dealt with in other disciplines (e.g. financial, chemical and nuclear industries), it appears that climate change presents some unique circumstances that will need to be addressed in an inter-disciplinary way within the climate science community. This should be done in consultation with the future users of the AR4, to avoid any misunderstanding and to ease the adoption of the reports during the relevant plenary.

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