Estimating Climate Sensitivity: Report of a Workshop

Steering Committee on Probabilistic Estimates of Climate Sensitivity, National Research Council

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ESTIMATING CLIMATE SENSITIVITY

REPORT OF A WORKSHOP

Steering Committee on Probabilistic Estimates of Climate Sensitivity
Board on Atmospheric Sciences and Climate
Division of Earth and Life Studies

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CONTENTS

INTRODUCTION

"Climate sensitivity" is a term used to characterize the response of the climate system to an imposed forcing, usually radiative. This term has come to have a variety of usages by the scientific community, but it is most commonly defined as the equilibrium global mean surface temperature change that occurs in response to a doubling of atmospheric carbon dioxide (CO_2) concentration. Climate sensitivity is a function of numerous feedbacks among clouds, water vapor, and many other components of the earth's climate system. It is presently one of the largest sources of uncertainty in projections of long-term global climate change.

Based on analysis of several leading climate models, the Intergovernmental Panel on Climate Change / Third Assessment Report (IPCC/TAR) estimated this climate sensitivity to be in the range of 1.7-4.2°C (IPCC, 2001). Although this range of estimates is very similar to that proposed by a National Research Council (NRC) panel more than two decades ago (NRC, 1979), the confidence in this range is now substantially higher, particularly for the lower limit of 1.7°C. Recent studies have provided valuable insights into the factors that affect climate sensitivity and have introduced new approaches for quantifying this critical parameter. Some recent investigations have suggested that climate sensitivity could be greater than the values encompassed in the IPCC range (e.g., Andronova and Schlesinger, 2001; Forest et al., 2002), which would imply that global warming could be a more severe problem than currently projected. However, considerable skepticism exists regarding the plausibility of these high-end climate sensitivity values. Such issues are of great interest not only to the scientific community, but also to policy makers and others who must consider possible strategies for mitigating and adapting to climate change.

The National Academies were asked to organize a workshop in which a diverse group of top climate modelers and diagnosticians would examine our current capabilities and limitations in quantifying climate sensitivity and consider whether there may be alternative approaches for characterizing climate response to more effectively meet the information needs of policy makers. To help plan the workshop, a small steering committee was drawn from members of the NRC's Climate Research Committee and Board on Atmospheric Sciences and Climate. The workshop was held in Washington, D.C., on January 30-31, 2003. Fifteen scientists were invited to participate as speakers, and were joined by numerous representatives from federal agencies including the Environmental Protection Agency, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, Department of Energy, and National Science Foundation and other organizations (see Appendix B). The meeting was structured as a series of presentations and panel discussions followed by an open discussion among all the participants (see Appendix A). The organization of this report closely mirrors that of the workshop.

Participants were asked to address questions such as the following:

- What accounts for the differences among various climate sensitivity estimates, and what specific physical or chemical feedbacks are factored into most current estimates?
- What are the different approaches that are used to estimate uncertainty ranges and probability density functions for climate sensitivity?
- Are there other possible approaches to quantifying climate response to radiative forcing that would be more useful for policy-relevant analyses?

An overarching goal of this meeting was to provide a forum in which federal agency managers and officials could hear the views of independent experts to ensure that the government has the best available scientific information and judgment as a basis for policy and regulatory deliberations. It should be emphasized that this activity was designed as a workshop and not a consensus study. Although the participants did look for points of common agreement, following standard Academy rules for workshops, they did not attempt to reach consensus on conclusions or recommendations. This report summarizes the workshop discussions; the ideas presented here reflect the views of the individual participants and are not endorsed by the National Academies.

OPENING SESSION

JERRY MAHLMAN

Jerry Mahlman, from the National Center for Atmospheric Research (NCAR) and moderator of the workshop, welcomed the participants. He explained that the goals of the workshop were to discuss, analyze, and synthesize recent work on constraining estimates and probability intervals for climate sensitivity, focusing primarily on work that has been carried out since the production of the IPCC/TAR.

Mahlman noted that this is an exciting time to examine our understanding of the sensitivity of the climate system because valuable insights are being gained from climate model intercomparison and diagnostic studies and because researchers are developing novel ways to think about the problem from a statistical-probabilistic point of view.

He explained that the workshop discussions would include

- elucidating the breadth and complexities of both forcings and feedbacks in the climate system;
- reflecting on lessons gleaned from the paleoclimate record about climatic response to natural forcings;
- examining intrinsic uncertainties in the climate system that affect our ability to constrain climate sensitivity estimates; and
- considering how to frame these concepts in a way that nonscientific audiences can grasp.

JANE LEGGETT

Jane Leggett, from the U.S. Environmental Protection Agency (EPA), discussed how analytical and policy communities utilize the information produced by climate scientists. She expressed a hope that the workshop would provide a "checkpoint" on emerging research and would clarify what scientists do and do not know about climate sensitivity (see Box 1). She asked the speakers to help elucidate the points of agreement and disagreement, the issues that require further resolution, and the priorities for research needed to reduce uncertainties.

BOX 1
CLIMATE SENSITIVITY DEFINITIONS

Before the scientific presentations, workshop participants agreed that they had to work with, at the very least, two different definitions of climate sensitivities:

1. Equilibrium climate sensitivity (S_{eq}): The global mean surface-air temperature warming achieved at long-term equilibrium, for a doubling of atmospheric CO_2 over pre-industrial levels, commonly set at 280 parts per million by volume (ppmv).

2. Transient climate sensitivity (S_{tr}): The global mean surface-air temperature achieved when atmospheric CO_2 concentrations achieve a doubling over pre-industrial CO_2 levels increasing at the assumed rate of one percent per year, compounded.

When a speaker refers specifically to one of these definitions, it is noted as S_{eq} or S_{tr}.[1]

Analysts are increasingly utilizing integrated assessment models to examine scenarios of future climate change. When examining a large number of scenarios, modeling with a full climate model is too costly and time-consuming. Instead they rely on reduced-form climate models in which climate sensitivity is an input assumption,

[1] For specific climate model intercomparisons and evaluations that use "realistic" past and projected radiative forcing, it has sometimes proved useful to use "effective climate sensitivity" (S_{eff}) as a measure of a model time-varying warming responses under "realistic" forcing scenarios. S_{eff} is occasionally referred to in this report to describe a specific participant's or group's research strategy.

rather than a diagnostic. For this, they require guidance from the scientific community about the appropriate range of sensitivity estimates and associated uncertainties. The kinds of questions that analysts and policy makers may pose to climate modelers include the following:

- How has our understanding of the most likely value of sensitivity changed in recent decades? When and how will we have better estimates?
- What do scientists think about the shape of the probability distribution for sensitivity? Can we put more credible limits on the high end of the tail of the distribution?
- How good is sensitivity as a general indicator of the future severity of climate change? Does it take into account possible non-linearities in the climate system?
- How does the value of sensitivity differ for different types of forcings and time scales? Are other indicators needed to express the response of the climate system to non-CO_2 forcings?

Policy makers need quantitative information to better gauge the time scales and susceptibility of the climate system and to assess the potential consequences of global changes for human health, ecosystems, and social well-being. They are often interested in low-probability, high-consequence events, so it is important for the scientific community to provide information about the likelihood of such events.

TOM WIGLEY

Tom Wigley, from the National Center for Atmospheric Research, first provided an overview of the simplified MAGICC-SCENGEN system as an example of an integrated assessment modeling tool that produces probabilistic outputs. MAGICC (Model for the Assessment of Greenhouse-Gas Induced Climate Change) is a coupled gas cycle-energy balance climate model that can simulate the global scale behavior of comprehensive three-dimensional climate models. Users are able to choose emissions scenarios and a number of other model parameters either as single values or as probability density functions (PDFs). SCENGEN (SCENario GENerator) is a global-regional database that contains the results of a large number of climate model experiments. SCENGEN uses a scaling algorithm to provide information about spatial patterns of climate change. The primary purpose of the MAGICC-SCENGEN software is to allow nonexpert users to investigate the implications of different emission scenarios for future global mean and regional climate change and to quantify uncertainties in these changes.

Wigley discussed the general question of how climate sensitivity influences global mean temperature projections. It can be concluded from simple energy-balance climate models that both the magnitude and the timing of climate change depend on sensitivity (Figure 1, pg. 27). In a study by Wigley and Raper (2001), PDFs were created for a number of key inputs, including S_{eq}, greenhouse gas emission rates, aerosol radiative forcing, carbon cycle feedbacks, and ocean mixing (Figure 2, pg. 28). This information was used to run more than 100,000 simulations in a simple upwelling-diffusion energy balance climate model. The resulting output is a PDF for change in global mean temperature, and one can evaluate how the results depend on the assumed input value of sensitivity.

They showed that uncertainties in the climate sensitivity, as characterized by its PDF, are a primary source of uncertainty in the projected values of global mean temperature change, especially the high-end tail of the distribution. This study illustrated the need to better quantify and define a PDF for sensitivity. The probabilistic form of the input value greatly enhances the ability to characterize uncertainties in future projections.

Other points raised by Wigley include the following:

- One can utilize methods to minimize the effects of sensitivity uncertainties. For example, one can reduce the spread in output PDFs by calibrating a model against observed climate change (e.g., twentieth century warming). For given historical forcing, only a subset of the assumed range of sensitivities (and other model parameters) may be consistent with the observed warming (and its uncertainty range), so this would limit the output uncertainty range.
- We must make the best possible use of available observations. Climate modelers can go beyond evaluating model calculations against the historical record of global mean temperature change; they can also try to simulate the diverse spatial and temporal characteristics of our present climate (which is essentially what is done in many current atmosphere ocean general circulation model [AOGCM] based detection studies).

- Currently, modeling approaches tend to give slightly higher central values of sensitivity than estimates based on observational data.
- Further progress will require a multipronged strategy involving both modeling-based and observation-based approaches, as well as new ways to mesh these two approaches.

Discussion

Mahlman: It now seems tractable to quantify the lower limit of the PDF for climate sensitivity, but we remain "in trouble" in regards to defining the upper limit credibly on such statistical grounds. Are there physically based approaches that can rule out some of the very high (but unreasonable) values of sensitivity (S_{tr}) obtained from data-based studies?

Schlesinger: Trying to artificially reduce uncertainties can be dangerous. We have to learn to live with some degree of uncertainty. The biggest problem is that uncertainties in radiative forcing confound the estimates of sensitivity derived from observations.

Ramaswamy: Models should accurately simulate not only past trends, but also the characteristics of the present-day climate variability. Currently, many climate models fail to replicate observations of interannual variability.

Prather: Even if you cannot constrain the "asymptote" of the equilibrium climate change, perhaps you can constrain the rate of change.

Stone: To do this, you need to know the various time constants and reservoirs of the climate system. Note that deep ocean mixing becomes much more important over long time scales and for stabilization scenarios.

Mahlman: Another "wild card" is the indirect effect of aerosols, which currently has a huge range of uncertainty.

Wigley: True, we must keep in mind that model results tell us nothing about the uncertainties associated with many possibly important processes that are not represented in the models.

VENKATCHALAM RAMASWAMY

Venkatchalam Ramaswamy, from the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory (GFDL), provided an overview of how climate sensitivity is used in the IPCC Third Assessment Report. The IPCC/TAR reports that climate sensitivity is within the range of 1.7-4.2°C, as derived from seven ocean-atmosphere general circulation models.[2] There are no stated probabilities associated with any particular values in this range. Climate sensitivity is discussed in several chapters in IPCC/TAR, but unfortunately, the terminology and usage are sometimes inconsistent among these chapters.

In Chapter 6 of the IPCC/TAR "Radiative Forcing of Climate Change", the forcing-response relationship is defined such that the global, annual mean surface temperature is equal to the global, annual mean radiative forcing (evaluated at the tropopause after equilibration of the stratosphere) multiplied by a global mean climate sensitivity factor (λ, given in units of Kelvin per watts per meter squared [K/Wm^{-2}]. Studies of forcing-response relationships originated with simple one dimensional radiative-convective models, where λ was found to be nearly invariant. More complex three dimensional atmosphere-ocean climate models were later used to examine the applicability of λ to a variety of forcings, including species with a globally homogeneous distribution such as CO_2 and species with a highly varied distribution such as aerosols and ozone. The IPCC found that λ remains constant to within ~20 percent for globally homogeneous forcings, but for some ozone and absorbing aerosol cases, λ can vary by up to 50 percent. In such cases, the forcing-response relationship depends critically on the vertical structure of the forcing.

Many climate model simulations include estimates of changes in solar and volcanic forcings, but most simulations do not include other, poorly understood forcings such as land-use changes and nonsulfate aerosols (e.g., mineral dust, black carbon). Another limitation is that sensitivity is only an indicator of the global annual mean surface temperature response. It does not define regional temperature responses or the responses of any other climate variables, nor is it an indicator of the possibility of abrupt changes or extreme events (although a high sensitivity value implies larger amplitudes of decadal-scale natural variability).

[2] IPCC also reports a climate sensitivity range of 1.5-4.5°C, derived from 15 simple models.

At the new climate equilibrium, $F = \alpha T$, where F is the radiative forcing change and αT represents the net effect of processes acting to counteract the changes in mean surface temperature. The variable α is described as the climate sensitivity factor,[3] and the equilibrium climate sensitivity (S_{eq}) is inversely proportional to α.

Ideally, climate sensitivity would be obtained from a coupled atmosphere-ocean general circulation model (GCM) by integrating the model to a new climate equilibrium after doubling the CO_2 concentration. However, this can require very long simulations to evaluate; in some cases, several millennia are required to attain equilibration, due to heat exchange with the deep ocean and the continental ice sheets. Instead, equilibrium climate sensitivities (S_{eq}) are usually estimated with an atmospheric GCM coupled to a mixed-layer (upper ocean) model, where there is no heat exchange with the deep ocean and the model can be integrated to a new equilibrium within a few decades.

In the IPCC's Second Assessment Report (1995), the average sensitivity of the mixed-layer models for a doubling of CO_2 was 3.8°C, with an intermodel standard deviation of 0.78°C. For the 15 mixed-layer models used in the TAR, the average sensitivity of these models was 3.5°C, with an intermodel standard deviation of 0.92°C. Although current models give a slightly lower average value and intermodel scatter has increased somewhat, these differences are not considered as statistically significant.

In IPCC/TAR Chapter 12 "Detection of Climate Change and Attribution of Causes" it was pointed out that different models may yield different patterns of response for the same forcing. Chapter 12 also points out that within a given model, the pattern of response to different types of forcings can be quite similar. Even if the forcing is local (e.g., direct sulfate aerosol), the first-order response is global in nature and determined by many of the same feedback processes that also determine the response to uniformly distributed forcings. This similarity of response pattern is one of the things that makes it so difficult to separate the responses to greenhouse gas and sulfate aerosol forcing in the observed record.

Discussion

Schlesinger: Should the aerosol indirect effect be characterized as a forcing or a response, and how does this affect the estimate of sensitivity?[4]

Ramaswamy: This is an open question that has not been satisfactorily addressed.

Prather: Note that the feedbacks examined in the IPCC/TAR are basically limited to physical feedbacks. There are a number of possibly important chemical and biological feedbacks that have not been considered in IPCC climate projections.

Socci: Is any definition of sensitivity even a practically usable concept, given the amount of regional variability in climate impacts?

Ramaswamy: Generally, global mean metrics are limited in their applicability.

Broccoli: Sensitivity is relevant to the consideration of local and regional climate changes because as sensitivity increases, the mean of the distribution (and thus the probability of a temperature increase in any one place) will increase.

ANTHONY BROCCOLI

Anthony Broccoli, from Rutgers University, discussed some intercomparison studies between recent versions of the GFDL and NCAR climate models (both of which are under development) and their representation of key climate feedbacks (defined as sequences of interactions that determine the response of a system to an initial perturbation). They found that the value of sensitivity (S_{eq}) estimated by the NCAR model is much lower than the value from the GFDL model. We have to understand what causes these differences and determine which (if either) estimate is correct.

Current models are relatively consistent in representing water vapor feedbacks, and model simulations of interannual-decadal variations in tropical mean water vapor match well with observations. In contrast, models

[3] Note that the meaning of climate sensitivity factor α used in IPCC Chapter 9 differs from that of the climate sensitivity factor λ used in IPCC Chapter 6.
[4] Note that this issue is discussed later in the presentation by Joyce Penner.

differ considerably in their simulation of cloud feedbacks. Cloud feedbacks differ substantially between the NCAR and GFDL models, and these very likely account for most of the difference in their respective estimates of climate sensitivity. Even modest changes in cloud parameterizations have been found to affect cloud feedbacks and, hence, sensitivity. The primary difference is that for the NCAR model, there is a strong negative feedback involving low clouds. For the GFDL model, there is a moderate positive feedback involving low clouds, which adds to the positive feedback involving high clouds.

It is important to realize that feedbacks interact. For instance, small changes in the strength of the water vapor feedback may increase or decrease the level of uncertainty due to the cloud feedback. If the water vapor feedback is weak, then the uncertainty due to cloud feedback would be smaller. This interaction must be taken into account when diagnosing feedbacks in models. It is also important to understand that even regional feedbacks can have global-scale impacts. For instance, snow-ice albedo feedbacks are geographically confined to a small percentage of the earth's surface, but can affect temperature patterns over much of the planet.

So how do we go about resolving these uncertainties? Developing better estimates of climate sensitivity requires a multifaceted approach involving model diagnostics, field measurements of important feedback processes, analysis of global observations, comparisons of simulated and observed climate history, and process modeling. GFDL and NCAR, along with their partners, are active in all of these research areas. Within another six months or so, more comprehensive model intercomparison studies will be under way.

In comparisons of models to observations, the GFDL model does seem to capture some features of seasonal variations in cloud climatology, although the model has a general bias toward too much cloudiness. Interannual variability of cloudiness is similar in both the GFDL and the NCAR models, but the cloud response to warming is quite different. Thus, interannual variability may not be an adequate surrogate for global warming.

APPROACHES FOR ESTIMATING CLIMATE SENSITIVITY

PETER STONE

Peter Stone, from the Massachusetts Institute of Technology (MIT), provided an overview of how climate sensitivity estimates have changed over time (see Table 1). After a century of research, how has the climate community's ability to gauge climate sensitivity advanced? Some progress has been made in reducing uncertainty, particularly with respect to distinguishing the responses to different external influences on the climate system. Regardless, many of the sources of uncertainty remain.

TABLE 1

Sensitivity Estimate (°C)	Source	Date
5	Arrhenius	1896
2.3	Manabe and Wetherald	1967
3.0 (+/-1.5)	Charney Committee report[1]	1979
1.5-4.5	IPCC[2]	1990
1.7-4.2	IPCC[2]	2001

[1]NRC, 1979.
[2]The latest IPCC estimate is of an effective sensitivity, while all the earlier ones are equilibrium sensitivities.

In the last five years, we have become aware that climate sensitivity is not a constant, but evolves with time as the climate changes. For example, in a global warming scenario in which sea ice retreats, the ice albedo temperature feedback decreases as the ice retreats, and the temperature sensitivity decreases correspondingly. Thus, the climate sensitivity that one should use in making projections has to be matched to the time scale and scenario for which the projections apply.

Statistical approaches are needed to better characterize the range of sensitivity values given in the IPCC/TAR. An important emerging approach is to use real observations to constrain sensitivity estimates, in this case S_{eff}. However, we cannot worry about sensitivity alone, but must also look at the poorly quantified factors such as aerosol radiative forcing and ocean heat uptake, can strongly affect estimates of sensitivity.

Ocean heat uptake is not well constrained by observations. We need better ocean observations, but this is difficult because of the long time scales involved. Underlying physical constraints are thus needed as well.

Discussion

Gregory: There was logic in the expert judgment choices to exclude high sensitivity (S_{eq}) values, since we've seen that the climate system doesn't exhibit wide swings that would be characteristic of high sensitivity values. This is because the amplitude of natural variability depends on the same feedback processes that determine the value of S_{eq} itself.

Mann: In some contexts, ocean mixing rates can be constrained by using tracer compounds (such as chlorofluorocarbons), as well as ocean heat content measurements from the past several decades.

Mahlman: The finding that sensitivity evolves over time may be a good reason to use S_{tr} for careful, model intercomparisions. However, it can also prove useful to use S_{eff} for evaluation of various model responses to specific radiative forcing scenarios over the "near term" (e.g., 10-50 years from the present).

JONATHAN GREGORY

Jonathan Gregory, from the Hadley Centre for Climate Prediction and Research, explained that surface albedo, water vapor, and cloud feedbacks are among the factors that affect climate sensitivity. It is useful to know how climate will respond in time to forcings that are themselves time dependent. Because of its large heat capacity and thermal inertia, the ocean plays a major role in determining the timing of the climate system's response to exogenous forcing. Research into the climate system's transient response therefore almost always involves an atmospheric model coupled to a model of ocean heat uptake.

Gregory described a very simple approach that he and his colleagues used to estimate a probability distribution for effective climate sensitivity of the real-world climate system (Gregory et al., 2002). It is based on the simple theory that during time-dependent climate change, the imbalance between imposed radiative forcing and radiative response is absorbed by the ocean, which contains most of the heat capacity of the system. Hence, $F = Q - \lambda \Delta T$ where F is the heat flux into the ocean, Q is the radiative forcing, and ΔT is the temperature change. One can solve the equation for the climate response parameter (λ), by estimating the other parameters as follows:

- Ocean heat uptake (F) was estimated from the 5 year running means of observed interior ocean temperature changes (Levitus et al., 2000). This approach was used in lieu of relying on model estimates of ocean heat uptake, which usually involve some very uncertain assumptions. However, a model still has to be used to estimate F in the late nineteenth century, since there are no observations for that period.
- It is not possible to obtain a true steady-state global average temperature, so instead, the temperature change (ΔT) is estimated as a difference in global average temperature between the current period and an earlier period, with the two periods as widely separated as possible, to maximize the climate change signal.
- Radiative forcing (Q) for greenhouse gases, sulfate aerosols, solar irradiance, and volcanic aerosols is estimated by a variety of methods, since there are no direct observations of past changes in radiative forcing.

With these inputs, Gregory and colleagues calculated a PDF for sensitivity (Figure 3, pg. 29) and determined that the lower bound (5th percentile) is 1.6 K. This method of constraining the lower bound for sensitivity is objective and largely independent of climate models. Sensitivity could be further constrained if we could reduce uncertainties in the radiative forcing.

Gregory reviewed other approaches that have been used to develop estimates of climate sensitivity, including:

- equilibrium "slab" experiments with atmospheric models coupled to mixed-layer ocean models;
- time-dependent atmosphere-ocean climate model experiments;
- simple climate models constrained by the twentieth century temperature record, which are used to develop PDF of climate sensitivity and forcing; and
- paleoclimate records that are used as an observational constraint.

Reasons for differences among these various estimates include the fact that climate models have different feedbacks and sea surface temperature changes. Also, different studies employ different assumptions about natural and anthropogenic forcings, ocean heat uptake, and the "initial" (pre-industrial) state of the climate system.

Discussion

Mahlman: If we had a perfect climate observing system, including aerosols, could you use these simple model approaches to better constrain sensitivity? How long would it take?

Schlesinger: It may take almost a century of observations to reduce the uncertainty, although you would learn faster if sensitivity is large (since the signal is larger).

Mahlman: It wouldn't take another century if the measured climate variables and the climate forcings were well known. In such a case, all that would be left is global natural variability, which averages out over a few decades.

Stone: There are opportunities to reduce uncertainties in aerosol forcing through new observations.

Mahlman: However, we don't even know how to observe the indirect effects of aerosols.

Ramaswamy: We also need to learn more about how to quantify direct radiative forcing from black carbon aerosols.

NATALIA ANDRONOVA

Natalia Andronova, from the University of Illinois, identified the different tools that are used for studies of climate sensitivity, including both comprehensive and simple climate models and simple statistical models such as a first-order autoregression model (e.g., Miles and Gildersleeves, 1977; Tol and Vellinga, 1998). She recommended that statistical models not be used for climate sensitivity estimation because their equilibration time to doubling CO_2 is two orders of magnitude smaller than that of simple climate models and coupled of atmosphere-ocean general circulation models.

Some estimates of climate sensitivity that have been published in recent years are shown in Table 2. Two general approaches that can be used for climate sensitivity estimation are "mapping" and "optimal estimation." One can use mapping with constrained input, wherein the observed temperature record and a defined PDF for radiative forcing and ocean heat uptake are used as input to calculate a PDF for climate sensitivity (e.g., Gregory et al., 2002). Alternately, one can run the model with constrained output, wherein subjective PDFs for climate sensitivity, radiative forcing, and ocean heat uptake are used as model input, and the output (constrained by the observed data record) updates the input PDFs for climate sensitivity and model parameters (e.g., Forest et al., 2002; Harvey and Kaufman, 2002).

TABLE 2

Sensitivity Estimate (°C)	Source
2.3±0.9	Hoffert and Covey (1992)
1.0-9.3	Andronova and Schlesinger (2001)[2]
1.0-5.0	Harvey and Kaufman (2002)[3]
1.4-7.7	Forest et al. (2002)[2]
1.6-∞, (median 6.1)	Gregory et al. (2002)[2]

[1]The Hoffert and Covey study presented the mean and standard deviation for climate sensitivity derived from paleoclimate data.
[2]The Andronova and Schlesinger, Forest et al., and Gregory et al. studies present 90 percent confidence intervals.
[3]The Harvey and Kaufman study used prescribed climate sensitivity values ranging from 1.0-5.0°C in their model.

There are two methods for the optimal estimation: the single-value optimal estimation (see, e.g., Andronova and Schlesinger, 2000) and multiple-value optimal estimation techniques (Andronova and Schlesinger, 2001). The single-value optimal estimation traces the value of the climate sensitivity in a domain of the model parameters that gives the best fit between the observed and simulated temperature changes. The multiple-value optimal estimation technique is based on multiple realizations of the single-value optimal estimation for the set of "surrogate observations." The surrogate observations are the sum of the simulated temperature departure and "surrogate residuals." The surrogate residuals are obtained by randomly mixing (bootstapping) the single observed residuals—the difference between the observed and simulated temperature departures. Running the model for many surrogate observations yields a PDF for climate sensitivity, as well as for other parameters.

In general, the resulting PDFs for climate sensitivity obtained from these different techniques should coincide. The main difference between existing estimations obtained by these two methods comes from description of the "climate noise" and uncertainties in forcing models.

Discussion

Broccoli: Perhaps they could get more constraints by further exploiting observational data (for instance, going beyond just global and hemispheric mean temperatures and looking at zonal mean temperature differences).

Prather: What about uncertainty related to ozone forcing?

Andronova: Some forcing models include tropospheric ozone radiative forcing, while others do not. When this forcing is included, its hemispheric distribution is similar to the aerosol radiative forcing distribution.

Stone: Our group at MIT is currently working on including other important forcings, such as solar irradiance and land-use changes, in simple climate models.

Mahlman: The low inferred paleo-estimation of climate sensitivity (presumably S_{eq}) needs further explaining. The original Milankovich orbital climate forcing that preceded the last ice age was originally -1 Wm^{-2}. Roughly 10,000 years later, the inferred effective total forcing was roughly -4 to 6 Wm^{-2}. The total positive feedbacks that led to this remarkably large climate cooling came mainly from ice albedo, water vapor, and CO_2 feedbacks. However, these inferred large positive feedbacks do not necessarily imply higher-than-expected positive feedbacks in the human-caused climate warming problem that we currently face.

CLIMATE FEEDBACKS

EUGENE RASMUSSON

Eugene Rasmusson, from the University of Maryland, provided a brief overview of an ongoing National Academies' study Climate Change Feedbacks: Characterizing and Reducing Uncertainty. This study is being carried out by a panel of the Climate Research Committee and is sponsored by NOAA, the National Science Foundation (NSF), the Department of Energy (DOE), and the National Aeronautics and Space Administration (NASA). The specific tasks of the committee are described as follows.

> The study will attempt to address climate change feedbacks in a manner that accounts for the climate system as a fully coupled physical, chemical, and biological entity. Within this holistic perspective, the range of feedbacks to be addressed will include, but not be limited to, those associated with changes in lapse rate, water vapor concentration and distribution, cloud characteristics, natural modes of climate variability, ocean circulation, biogeochemistry, land cover, and terrestrial hydrology. The committee will: (1) characterize the uncertainty associated with climate change feedbacks that are important for projecting the evolution of Earth's climate over the next 100 years, and (2) define a research strategy to reduce the uncertainty associated with these feedbacks, particularly for those feedbacks that are likely to be important and for which there appears to be significant potential for scientific progress.

He explained that the study was still undergoing peer review, and thus the committee's findings and recommendations could not be discussed at the workshop. However, this topic is obviously of great relevance to those interested in quantifying climate sensitivity, and thus the workshop participants were urged to contact BASC if they are interested in being notified about the report release.

WILLIAM COLLINS

William Collins, from the National Center for Atmospheric Research, discussed cloud feedbacks. NCAR and GFDL models yield substantially different estimates for S_{eq} (2.2 °C for NCAR, 3.78-4.14 °C for GFDL). This disparity has provided a great learning opportunity, particularly with regard to understanding the models' differences in cloud feedbacks.

NCAR and GFDL scientists ran a series of experiments in which the climate system response is decomposed into components associated with individual atmospheric fields (e.g., atmospheric moisture, temperature lapse rate, surface albedo, cloud amount) and then the climate feedback associated with each of those changes was quantified. In these experiments, they changed the global average ocean surface temperature and examined the resulting shortwave and longwave feedbacks (Coleman and McAvaney, 1997).

It was found that the NCAR and GFDL models have very similar clear-sky feedbacks (i.e., changes in atmospheric water vapor and temperature lapse rate), but there are big differences in the longwave feedback parameter. The NCAR model had a strong negative cloud feedback (two to three times larger than the GFDL model), which was driven primarily by shortwave forcing from increasing cloud cover and liquid water content in the lower atmosphere. Positive cloud feedbacks from infrared absorption in high clouds were weaker in the NCAR model than in the GFDL model.

Another class of NCAR model experiments was carried out to look at cloud feedbacks in a transient integration of a 1 percent annual increase in CO_2 (ranging from $2*CO_2$ to $4*CO_2$). They found a steady increase in the longwave trapping associated with increasing high clouds (a positive feedback), but the dominant feedback is still associated with the shortwave. Now the challenge is to understand this result and compare it to results from the GFDL model.

Observational studies may confirm the idea of negative forcing from increasing low cloud cover. In a global survey of cloud cover taken from shipboard observations, Norris et al. (1999) found an increase in global average low cloud cover of 3.6 percent between 1952 and 1995. It is not clear what is driving this change; it could potentially be related to aerosol indirect effects.

It appears that the NCAR model may have a problem with predicting cloud optical properties in the upper troposphere and thus be missing additional negative feedbacks from tropical high clouds. Once this bias is corrected for, the model probably will end up with an even stronger net negative cloud feedback.

To address these uncertainties, we need a multifaceted approach to testing models against observations. Two strategies for future diagnosis of cloud parameterizations may involve (1) compositing observed response of low clouds to different meteorological conditions and (2) analysis of high cloud characteristics using Webb-Klein International Satellite Cloud Climatology Project (ISCCP cloud) simulations.[5]

VENKATCHALAM RAMASWAMY

Venkatchalam Ramaswamy discussed the results of a study to examine water vapor feedbacks in the Hadley and GFDL models, in comparison with available observations (Allan et al., 2002). Both models were input with the same reported sea surface temperatures and run over the specified period. The two models were quite consistent with regard to interannual changes in column water vapor and clear-sky outgoing longwave radiation. However, they appear to have given the same result for different reasons. The GFDL model has a stronger positive lapse rate feedback, while the Hadley model had a stronger water vapor feedback. So there was compensation between these two effects, yielding a similar net sensitivity. The differences between the GFDL and Hadley models have not been evaluated quantitatively. They are probably due primarily to different convection schemes, but possibly to different treatments of advection of water vapor. Regardless, it points to the fact that two models can give the same value for climate sensitivity, for different reasons.

Ramaswamy's GFDL colleagues evaluated an Atmospheric Model Intercomparison Project (AMIP)[6] study of the ability of atmospheric models to simulate interannual variability in tropical hydrological cycle intensity (30 models were included in the study) (Boyle, 1998). The models gave a reasonable simulation of variations in temperature, water vapor, and outgoing longwave radiation, but they underpredicted precipitation variations by a factor of four. Although there are substantial uncertainties associated with the satellite observations themselves, this disparity suggests that the models may be missing some process that causes variations in tropical organized convection and evaporation. This problem must be reconciled in order to have confidence in projecting future changes in hydrological cycle intensity.

MICHAEL PRATHER

Michael Prather, from the University of California, Irvine, discussed feedbacks related to changes in atmospheric composition. The observational record of increasing trace gas concentrations makes it clear that current atmospheric composition is significantly different from the pre-industrial era (e.g., see greenhouse gas atmospheric concentration time series in Figure 4, pg. 30), and it is likely that future atmospheric composition will be much different than today. Thus, we must be careful about extrapolating from one era to another and calibrating models to paleo-era data records.

Paleo-records (such as the Vostok ice core records) make it clear that natural feedback processes can lead to large changes in atmospheric concentrations of CO_2, CH_4 (methane), N_2O (nitrous oxide), and other trace gases. In such a context, these changes can be viewed as climate feedbacks, rather than forcings. The relationships

[5] This is a code developed by M. Webb and S. Klein that can be used to take information from atmospheric models and convert it into something that is comparable to data from the ISCCP. ISCCP is a collection of weather satellite radiance measurements that are used to infer the global distribution and temporal variation of clouds and their properties.

[6] AMIP is a standard experimental protocol for global atmospheric general circulation models, which provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation, and data access. The infrastructure is supported by the PCMDI (Program for Climate Model Diagnosis and Intercomparison).

between temperature and trace gas concentrations seem to vary substantially in different time periods and in different paleo-records. Thus, one cannot simply scale the trace gas concentrations with temperature.

Even today we still do not fully understand what is driving interannual-decadal variations in the growth rate of CO (carbon monoxide), CO_2 and CH_4, observed over the past few decades. It is particularly difficult to quantify and interpret observed trends and patterns in tropospheric ozone. These trace gas changes probably result from some combination of human-driven sources and sink changes, spotty data coverage or quality, and short time scale natural feedbacks including coupled chemical interactions among CH_4, CO, OH (hydroxyl radical), O_3, VOCs (volatile organic compounds) and other trace species.

IPCC/TAR examined future scenarios of changes in atmospheric composition and chemistry. In the high-emission scenarios, significant regional increases in surface ozone were projected. However, other studies project that the warmer, wetter atmosphere resulting from climate change will tend to increase the destruction of ozone in the troposphere (Fuglestvedt et al., 1995; Brasseur et al., 1998). Thus, the net impacts of ozone concentration are very difficult to project with confidence. Scientists are just starting to understand these complex climate-chemistry feedbacks (including biogenic feedbacks), and these processes are not yet included in the IPCC climate projections.

Another important set of feedbacks that deserves more attention involves anthropogenically driven changes in hydrology and freshwater transport. Today, most freshwater and riverine systems in the world are heavily managed. This leads to changes in river discharge rates, which affects biogeochemical cycling, sea surface temperature, and salinity and thus could even potentially affect North Atlantic deepwater formation processes.

Discussion

Socci: Is the issue of methane hydrate releases a serious possibility?

Prather: I have not seen much convincing evidence for this being a major factor, although this doesn't rule out the idea that it could be important.

Mahlman: What about feedbacks related to stratospheric ozone?

Prather: This is worth careful consideration because the patterns of stratospheric ozone depletion will change over the course of the next century. The atmospheric concentration of CFCs (the major driver of ozone depletion in the polar regions) will lessen, but there will be an increase in CH_4 and N_2O-related ozone depletion, which is more globally distributed and has different altitude profiles. We also need to consider the coupling of ozone depletion with climate change. Some studies claim that climate change (and the associated cooling of the stratosphere) will exacerbate stratospheric ozone losses, although the magnitude of this feedback is a matter of debate.

Prather: Another interesting global change to consider is that over the past 20 years, there has been a slow increase in lower stratospheric water vapor. This, by itself, results in another addition to the greenhouse effect. We don't understand what is driving this trend, but it is presumably related to gradual warming and moistening of the tropical upper troposphere. Unfortunately, the data quality is inadequate for testing this.

JOYCE PENNER

Joyce Penner, from the University of Michigan, discussed feedbacks and uncertainties related to aerosol radiative forcing.

Determining climate sensitivity by fitting the observational temperature record requires specifying radiative forcing from aerosols. Most climate models currently consider only forcing from fossil fuel sulfate aerosols. Ultimately, however, one has to consider several other types of atmospheric aerosols, including organic carbon and black carbon from fossil fuels, smoke from biomass burning, and fossil fuel nitrate and associated ammonium. These each have different time histories (Figure 5, pg. 31) and different spatial distributions, thus making it very difficult to determine a net sensitivity and uncertainty range. So how can we assign unbiased estimates of uncertainty associated with aerosol forcing?

In IPCC/TAR (Chapter 5) a "bottom-up" approach was used to estimate uncertainty associated with direct forcing from fossil fuel and biomass-burning aerosols. A simple box model based on what we know about critical aerosol parameters such as aerosol concentration, size distribution, and composition was employed. This approach yielded the following estimates:

- Fossil fuel direct: -0.6 Wm^{-2} (-0.1 to -1 Wm^{-2}) Main source of uncertainty: upscatter fraction, burden (with emissions), mass scattering efficiency.
- Biomass smoke direct: -0.3 Wm^{-2} (-0.1 to -0.5 Wm^{-2}) Main source of uncertainty: single scattering albedo, upscatter fraction, burden (with emissions).

Estimating the indirect effect of aerosols and associated uncertainties poses a far more complex problem, as it involves at least three different processes:

1. The "first indirect effect" (Twomey effect, or cloud albedo effect): changes to cloud albedo associated with changes in droplet number concentration.
2. The "second indirect effect" (Albrecht effect, or cloud lifetime effect): changes to cloud albedo and cloud fraction associated with changes in precipitation efficiency
3. The "semidirect effect" (Hansen effect): rises in local temperature causing changes to cloud amount due to absorbing aerosols (i.e., soot) within the atmospheric column.

The bottom-up estimate of uncertainty in Twomey (the first) indirect forcing from fossil fuel aerosols was -1.4 Wm^{-2} (0 to -2.8 Wm^{-2}). The main uncertainties in this estimate were cloud height, liquid water content, and the relationship between aerosol number concentration and cloud droplet number concentration. The uncertainty also depends on how the effects of aerosols on cloud droplets are parameterized. For sulfates, it depends on how much is formed through aqueous versus homogeneous chemical means and what the natural background aerosol is in the model.

Uncertainties associated with the second indirect effect were not estimated. In fact, some scientists argue that this should be considered a response (and part of the climate sensitivity) rather than a forcing. Rotstayn and Penner (2001) tested whether the second indirect effect should or should not be considered a forcing. Their approach was to run the model twice, calculating temperature change with only the first indirect effect, and then with both the first and the second effects. They found that if the second indirect effect is not included as a forcing, the climate sensitivity changes by a factor of two, but if the second indirect effect is included as a forcing, the climate sensitivity factor remains nearly constant (i.e., within 20 percent of that from 2*CO_2)

All such estimates of uncertainty are only as good as our theoretical and observational understanding, and some potentially important aerosol forcing effects have not yet been considered. This includes positive forcing from aerosol semidirect effects and from changes in ice concentration (cirrus clouds), which may lead to a substantial positive forcing. Likewise, recent studies have emphasized that biomass-burning aerosols have very different spatial and seasonal patterns than fossil fuel aerosols and cannot be ignored in future climate modeling studies.

The summary points are the following:

- Bottom up estimates of uncertainty must be developed to provide unbiased estimates of spatial distribution of uncertainty in forcing.
- Efforts should be made to extend the uncertainty estimates to temporally varying estimates of both direct forcing and first indirect forcing.
- Substantial variations apparently exist between different model estimates of the effects of black carbon and organic matter.
- There is conflicting evidence regarding the importance of the second indirect effect based on combined observation and modeling studies, but including this factor could change results substantially.
- Feedbacks due to the effects of climate change on aerosol sources (e.g., impacts on dust, sea salt) have not been included in the climate models.

Discussion

Andronova: If biomass burning aerosols were included in simple climate models, then aerosol radiative forcing patterns would become more symmetric (since biomass burning aerosols are not concentrated in the northern midlatitudes like the fossil fuel aerosols). The result would be lower inferred values for sensitivity, but remains uncertain due to the still unquantified net radiative effects of carbonaceous aerosols.

Mahlman: The high indirect forcing estimates are thought to be physically implausible because they would suggest that the climate of the past 40 years should have been cooling.

Schlesinger: Agreed, the inferred large negative aerosol radiative forcing is hard to reconcile with temperature observations. If total aerosol radiative forcing is as large as -2.8 Wm^{-2}, this implies that sensitivity must be huge.

Penner: Models are probably overestimating the large negative forcing, but this might be offset by positive forcing from ice clouds, which is not yet included in any model estimates. Modeling studies that fit the observational record may give a reasonably accurate net forcing, but if they are not capturing the spatial and temporal pattern of forcing, you will not have an accurate representation of the true forcing or the capability to predict the future.

Ramaswamy: Models indicate that a large percentage of aerosol radiative forcing occurs over the oceans. Do these models include interactions between sea salt and pollution aerosols?

Penner: Only one model includes this effect, and the results are difficult to understand.

Mahlman: Another huge uncertainty is the role of large-scale atmospheric dynamical phenomena that produce widespread thick clouds. These dynamical effects could overwhelm the indirect effects on cloud physics.

JONATHAN GREGORY

Jonathan Gregory discussed feedbacks related to sea ice and oceanic processes. Sea ice covers only 5 percent of the earth's surface but may have a disproportionately large influence on global climate sensitivity, as the main driver of the large polar amplification of climate change (i.e., the large projected warming at high latitudes). Reduced sea ice affects sensitivity in two distinct ways: (1) the local warming effect, which occurs primarily in winter when the ice insulates the ocean from the atmosphere, and (2) the albedo effect, which occurs only in the summer when there is sunlight.

Northern hemisphere sea ice cover has been declining over the past few decades (~2.5 percent per decade in real annual-average sea-ice cover). Projections of how arctic sea ice will be affected by future climate change vary greatly from model to model. There are many different aspects of parameterizing sea ice in models that could be responsible for these differences. In the Hadley Centre's third-generation coupled ocean-atmosphere GCM (HadCM3), sea ice cover declines at 13 percent per Kelvin of global warming, and in some "high-end" projections, summer sea ice disappears entirely by the end of the century.

In all models there seems to be a fairly linear relationship between rise in global average temperature and reduction in the aerial extent of sea ice cover. This relationship is scenario independent, which implies that sea ice responds rapidly to climate warming and thus provides a useful rapid feedback diagnostic. There is also a scenario-independent relationship between declining volume and declining area, but this relationship is not linear. The volume initially declines about twice as fast as the area, but the volume-area relationship tends to flatten out as the ice decreases.

The reason oceans are important for climate change projections is because of the long time scales required to reach equilibrium and the possibility of nonlinear responses (e.g., disruption of thermohaline circulation or other rapid, irreversible changes). On shorter time scales, the important questions are related to oceanic heat uptake, a process that effectively mitigates global warming by taking up some of the heat that would otherwise increase atmospheric temperatures. Oceanic heat uptake effectively sets the rate of climate change. There is substantial variation among models in heat uptake efficiency. Many processes involved in heat uptake that have to be parameterized in models are not known with certainty. In scenarios in which the radiative forcing is increasing with time, it is found that the heat flux into the ocean is roughly proportional to global average temperature change and therefore looks like a negative feedback term in sensitivity. However, this linear relationship holds only in the nearer time scales; as equilibrium is approached, the heat uptake goes to zero, but the temperature increase does not.

Discussion

Broccoli: One complication of modeling ice albedo effects is that during the summer, sea ice is often masked by clouds, which effectively reduces the albedo feedback.

CHARACTERIZING UNCERTAINTY

PETER STONE

Peter Stone, from the Massachusetts Institute of Technology, explained that in order to provide useful information about climate change given all the uncertainties, you have to use probabilistic approaches. In the MIT model, PDFs are developed for the key uncertain elements of the climate system, including sensitivity (S_{tr}), rate of ocean heat uptake, and aerosol radiative forcing. In addition, the model includes the major economic uncertainties that affect CO_2 emissions, including changes in labor productivity (which implicitly includes population growth), efficiency of energy use, and the cost of non-carbon technologies. These inputs are propagated through the model and yield an output in the form of a PDF for global mean temperature change and other climate variables of interest. With this approach, they can show how the potential distribution of climatic changes would differ for various policy responses.

The main advantage of the model is its broad scope (that is, its inclusion of economic variables along with critical physical variables of the oceans and atmosphere). The trade-off is that it is a two-dimensional zonal mean model, and thus cannot represent longitudinal details. Also, the lack of a third dimensional leads to important challenges in simulating the two-dimensional character of the circulation properly.

The value of this type of analysis is that it provides a measure of how much you reduce the high-risk outcomes under various policy response scenarios (i.e., future emissions). They find that the different policy response options do not lead to significant changes in the most probable outcome, but large effects are seen in the tail of the distribution (Webster et al., 2003). Thus, understanding the probability of high-risk outcomes may depend strongly on constraining uncertainties in the various input functions.

A Monte Carlo approach is used to define the PDF of the outcomes (such as the increases in global mean surface temperature by 2100), and the distribution limits are basically determined by the number of runs carried out. More than 250 model runs are required to accurately define the 5-95 percent confidence limits. To further constrain the tail of the distribution (i.e., get a 99 percent confidence limit), you have to consider whether it is worth the resources required to carry out the extra runs that would be needed.

Discussion

Leggett: Some people feel that defining the distribution tail is an important goal, but can we use this information, even if it is obtainable? Can we really assign any meaningful difference between the 98th, 99th, 99.99th percentiles of a distribution?

Wigley: His simple model allows an essentially unlimited number of runs, but the problem is that the high-end tail of the output distribution is strongly affected by small changes in the input values. This presents an inherent uncertainty.

Stone: Since uncertainty increases the farther you go into the future, part of the problem may be our insistent focus on projecting to the year 2100. The uncertainties in many critical variables are much smaller if one focuses on shorter time spans.

Mahlman: However, the use of shorter time spans omits critical information on how global warming plays out over its natural time scales (many centuries).

Prather: It would be useful to look at the range and distribution of potential impacts, not just a global mean temperature change. Even a relatively low climate sensitivity value may yield some significant impacts (for instance, high-latitude warming that leads to melting of the Greenland ice sheet).

MICHAEL SCHLESINGER

Michael Schlesinger, from the University of Illinois, discussed the major uncertainties that affect estimates of climate sensitivity obtained by simulating the record of observed hemispheric-mean near-surface air temperatures using a simple climate-ocean model.

One of the largest uncertainties is in radiative forcing. With a simple energy balance climate/upwelling diffusion-ocean model, he and Natalia Andronova carried out a series of simulations using various combinations of radiative forcing agents (including long-lived greenhouse gases [GHGs], tropospheric ozone, volcanoes, solar irradiance changes, and anthropogenic sulfate aerosols), and determined which values for sensitivity (S_{eq}) and sulfate radiative forcing in a year (1990) gave the best reproduction of the observed temperature record. They found that the sensitivity value obtained from the model is highly dependent upon which forcings are included (Schlesinger and Ramankutty, 1992; Andronova and Schlesinger, 2000, 2001).

The climate sensitivity needed to reproduce the observed changes in near-surface temperature from the middle of the nineteenth century to the present is inversely proportional to the magnitude of the radiative forcing at the top of the atmosphere (or tropopause). Thus, if the radiative forcing is increased—for example, by including putative changes in the solar irradiance—the climate sensitivity needed to reproduce the observed changes in near-surface temperature decreases by about 50 percent (see Schlesinger and Ramankutty, 1992; Andronova and Schlesinger, 2001). However, we do not know whether the solar irradiance changed as has been constructed from indirect evidence. This uncertainty in the radiative forcing, not only by the sun but also by volcanoes and anthropogenic aerosols, contributes significant uncertainty in the inferred climate sensitivity.

As the model simulation proceeds through the decades of the last century, the researchers determine what sensitivity value is needed in order to reproduce the observational record, given the radiative forcing that occurred up to that time. If the sulfate radiative forcing is known, one can home in on the true sensitivity value by learning over time. In addition, if they can estimate (rather than prescribe) sulfate radiative forcing, then they can continue this learning process into the future. Thus, the uncertainty in climate sensitivity due to climate noise can be reduced by learning over time, that is, by performing future estimations using longer observational records.

These studies utilized two different temperature records (Folland et al., 2001; Jones and Moberg, 2003) that differed in their southern hemisphere values, and thus in the interhemispheric temperature difference. As a result, the estimated sulfate radiative forcing, and thus the estimated sensitivity value, differed significantly depending upon which data record was used. Thus, if the radiative forcing by aerosols cannot be learned exogenously, but only endogenously from the observed temperature changes, then the uncertainty in southern hemisphere temperature changes must be reduced. With better aerosol radiative forcing observations, one could prescribe the forcing in the model, rather than the current approach of estimating forcing from the interhemispheric temperature difference. As a result, one could use global mean temperature values as a constraint, and thus diminish the uncertainties related to climatic noise.

Discussion

Leggett: Another problem is that the model considers only sulfate; the uncertainties related to other types of aerosols have not even been accounted for.

Penner: Note that the interhemispheric temperature differences would be amplified if the radiative forcing associated with biomass aerosols were included in the analysis. Neglecting this influence means that the uncertainty in southern hemisphere temperature changes is even more important.

Schlesinger: The effect of other aerosol types was indirectly considered in one model scenario in which there was no aerosol forcing. This case represented the possible cancellation of the negative radiative forcing from sulfate aerosol by the (putative) positive radiative forcing from carbonaceous aerosol.

MICHAEL MANN

Michael Mann, from the University of Virginia, explained that a potential strategy to constrain the PDF of climate sensitivity, and particularly to address the dilemmas raised by previous speakers (i.e., our inability to quantify the radiative forcing from anthropogenic aerosols), is to make use of information from the paleo-record. This is a period in which anthropogenic forcing effects are not a factor, and one can make use of the relationships between natural forcings and temperature variations on longer time scales. The trade off is that the temperature reconstructions have a much greater uncertainty than direct observations from recent decades (Figure 6, pg. 32).

Comparisons of proxy-reconstructed northern hemisphere mean temperature with model-based estimates of climate-forced variability over the past millennium imply a sensitivity value in the range of 1.5 to 4.5°C. The University of Bern (Switzerland) coupled climate-carbon cycle model, furthermore, allows prediction of natural variations in CO_2 as a response to large-scale surface temperature changes, albeit with substantial uncertainty. Using this model, researchers were able to reproduce both reconstructed surface temperatures and observed pre-anthropogenic natural variations in CO_2 concentration (as derived from ice core records) within this same climate sensitivity range.

When interpreting historical temperature reconstructions, it is important to recognize that many proxy records are subject to geographical and/or seasonal biases. For instance, some temperature reconstructions emphasize continental, extratropical, summer temperatures. Some climatic responses to forcings are regional in nature, and this too affects how one interprets proxy records.

For example, some people think that the northern hemisphere temperature reconstruction by Esper and colleagues (Esper, 2002) may reflect an exaggerated hemispheric surface temperature response to volcanic activity, due to the restricted extratropical geographical locations and limited (summer) seasonal sensitivity of the proxy data used. Likewise, proxy reconstructions that target integrated annual mean temperature tend to mask seasonally specific anomalies that could provide potential dynamical insights. Spatial and seasonal variability in the response to forcing underscores the importance of taking regional and seasonal sampling into account in estimating global sensitivity.

Discussion

Prather: I am worried about using the paleo-temperature record as an indicator of sensitivity (S_{eq}) because it depends on the state of the atmosphere, and today's atmospheric composition and radiative forcing are much different than in past eras.

Mahlman: Also, the quality of the paleodata may be inadequate to provide clear values of S_{eq}.

RICHARD MOSS

Richard Moss, from the U.S. Global Change Research Program (USGCRP) and the Climate Change Science Program (CCSP), noted that policy makers understand the concept of global climate sensitivity in a narrower way than does the scientific community. They may be familiar with the standard definition of global average equilibrium surface temperature change due to a doubling of CO_2, but they usually do not understand that the other definitions of climate sensitivity (see Box 1) depend on other aspects of the climate system such as the rate of increase of greenhouse gases and the rate of oceanic heat uptake.

From the policy maker's perspective, the global sensitivity estimate is a useful way to cut out a lot of details that they do not understand, but this gives a false impression that the problem can be reduced to a single number. Scientists must think carefully about alternate ways to communicate climate response, and the resulting impacts, to the policy community. Sensitivity is a useful tool for communicating, but it should not be viewed as a "holy grail" or as the best way to communicate in a simple and understandable fashion.

Moss described his work with Steve Schneider to persuade scientists involved in the IPCC/TAR to use a more systematic approach in defining uncertainties (see Box 2). They had mixed experience in getting the different IPCC working groups to adhere to these principles. Working Group I (science) followed the proposed framework in general, but substituted its own terminology in some cases. Working Group III (mitigation) disregarded the idea entirely.

BOX 2
SUMMARY OF STEPS RECOMMENDED FOR ASSESSING UNCERTAINTY IN THE IPCC/TAR

1. *Identify the most important factors and uncertainties that are likely to affect the conclusions.* Also specify which important factors or variables are being treated exogenously or fixed.
2. *Document ranges and distributions in the literature*, including sources of information about the key causes of uncertainty. It is important to consider the types of evidence available to support a finding (e.g., distinguish findings that are well established through observations and tested theory from those that are not so well established).
3. Given the nature of the uncertainties and the state of science, *make an initial determination of the appropriate level of precision.* Is the state of science such that only qualitative estimates are possible, or is quantification possible and if so, to how many significant digits?
4. Quantitatively or qualitatively *characterize the distribution of values that a parameter, variable, or outcome may take*. First identify the end points of the range and/or any high-consequence, low-probability outcomes. Specify what portion of the range is included in the estimate (e.g., this is a 90 percent confidence interval) and what the range is based on. Then provide an assessment of the general shape of the distribution and its central tendency, if appropriate.
5. Using the terms described below, *rate and describe the state of scientific information* on which the conclusions and/or estimates (i.e., from step 4) are based.
6. *Prepare a "traceable account"* of how the estimates were constructed that describes the reasons for adopting a particular probability distribution, including important lines of evidence used, standards of evidence applied, approaches to combining or reconciling multiple lines of evidence, and critical uncertainties.
7. OPTIONAL: *Use formal probabilistic frameworks for assessing expert judgment* as appropriate.

Moss and Schneider, 2000

So how should we go forward in characterizing uncertainty related to climate sensitivity? In terms of research needs, there is value in the multiplicity of approaches being used by the research community. Note that the leadership of the next IPCC assessment intends to carefully examine recent developments in our scientific understanding of the sensitivity (S_{eq} and S_{tr}) parameters. In terms of communication needs, we have to think about the concept of multiple metrics. What are we conveying to policy makers about the seriousness of the problem and the progress we are making? How does a reduction in uncertainty have the potential to affect the decision-making process? Moss would like to see the scientific community be more systematic in describing uncertainties and levels of confidence. Using a Bayesean updating process is one important way to make the products more useful.

MEETING THE NEEDS OF THE USER COMMUNITY

ROSINA BIERBAUM

Rosina Bierbaum, from the University of Michigan, discussed the various ways in which climate sensitivity estimates may be applied for decision-making purposes. For instance, S_{tr} and S_{eff} provide important input parameters for integrated assessment models. These models, in turn, are used to evaluate the temperature commitment and impacts resulting from various emission scenarios. This information may ultimately be used to identify "levels of dangerous interference" in the climate system and to set specific emission reduction targets.

The climate sensitivity uncertainty range is often misunderstood or misrepresented by policy makers, for instance, with the range of 1.5 to 4.5°C presented in the IPCC/TAR commonly characterized as a "factor of three" uncertainty. Since the sensitivity estimate range is the same as it was in 1979, it is also often incorrectly assumed that there has been no scientific progress in recent decades, even though today this range is far more confidently stated (roughly 67 percent confidence in the range from 1979 versus greater than 90 percent confidence in 2001).

Some questions about climate sensitivity that are of interest to policy makers, but are not yet clearly answered by the scientific community include:

- What is the central, most likely value?
- What does this value tell us about the rate of change and possibilities for abrupt changes?
- How does the concept of sensitivity apply to radiative forcing agents other than CO_2 (solar, aerosols, etc.)?
- Is S_{tr} constant or does it vary as feedback mechanisms change with time?
- Is the full range of possible values encompassed in current estimates, since these estimates neglect some feedbacks (e.g., land-use changes, surface vegetation)?

The general questions that decision-makers focus on include the following: How serious is this problem? What does it mean to me in my "place"? What can I do about it? They may be seeking to evaluate vulnerability to changes in climate means and extremes, or seeking to enhance flexibility, robustness, and capacity to adapt to such changes. Finally, they may be seeking near-term response options, including possible management, institutional, technological, and legal or policy changes.

To answer such questions and to provide useful information for risk assessments and other policy-relevant analyses, the scientific community has to provide more information than just estimates of global average temperature change. We must consider whether it may be possible to develop metrics of climate response that go beyond just a global average warming at $2*CO_2$. For instance, could one define sensitivity functions for precipitation, extreme weather events, sea-level rise, and so forth? Could a sensitivity parameter define regional spatial patterns for any of these parameters? Are there approaches that would help characterize rates of change, including possible abrupt, discontinuous changes? It is also important to think in terms of "multiple stresses," that is, the interactions of climate change impacts with factors such as urbanization and other land-use changes, air pollution, and invasive species. These pieces of information are needed for robust decision making, but we do not yet have approaches to tackle many of these questions.

Bierbaum showed examples of the types of regional-scale changes that are projected to occur as a result of climate change (e.g., degradation of various ecosystems, fire hazard in boreal regions, shifts in forest biomes, regional precipitation changes). The huge uncertainties associated with many of today's regional-scale impact projections make it difficult for decision makers to know what to do with this information. For instance, in the U.S. National Assessment, the different models that were used projected widely varying regional impacts, and as a result, Congress simply dismissed them. Similarly, in projections for the Lake Ontario region, models do not even agree on whether the lake levels will be higher or lower than the current average, which makes it very difficult to plan response strategies for managing water levels.

Regardless, it is still useful for policy makers to get a sense of the kinds of changes that could occur, even if these are not precise projections. Clearly, the above questions highlight a key insight from this workshop: the capability of scientists to communicate the nuances of climate change science to policy makers and decision makers lags behind the level of efficient internal communication within the scientific community. This suggests the value of continued discussion of this subject, with emphasis toward optimal communication of global warming science to policy makers and decision makers.

TOM WIGLEY

Tom Wigley addressed several topics related to communicating about climate change and sensitivity.

Characterizing Uncertainty in the Spatial Patterns of Climate Change. Climate sensitivity is the primary method for characterizing the magnitude of climate change, but this can be misinterpreted and does not address impacts of climate change directly. For impact analysis, we need spatial details of change. Currently, the best way to get a handle on uncertainty related to the spatial patterns of climate change is to compare the results of different models. The MAGICC-SCENGEN system allows one to compare the results of different AOGCMs and assess the intermodel S/N (signal-to-noise) ratio (defined as the average signal across all of the models divided by the intermodel standard deviation). For annual mean temperature projections, S/N for most of the world is high, meaning that the models agree well, but for projections of precipitation, the S/N is low for most of the world (with S/N less than 1 everywhere but in the high latitudes), indicating a much greater level of uncertainty. Note that in some cases, the inferred noise level may simply reflect the realization-to-realization variability within any one model, as well as the differences between different models, thus demonstrating the need for intercomparing multiple-member ensembles of climate model runs.

Characterizing Progress in Climate Modeling Capabilities. It appears to some people that little progress has been made since current uncertainties in sensitivity estimates are similar to those of a few decades ago. However, there has in fact been substantial progress in many important aspects of climate modeling (e.g., see Covey et al., 2003). This progress was illustrated with a comparative study of 16 models, showing how well the annual mean precipitation patterns projected by the various models agreed with observations. The best models have ~80 percent of their variance in common with observations, while the worst have ~40 percent of their variance in common with observations. In the past 10 years, all of the models have improved dramatically in their ability to simulate present-day precipitation patterns accurately. The Hadley model explains twice as much of the observational variability as it could when first created, and the worst models in the analysis are now performing better than Hadley and other leading models did a decade ago.

New Approaches for Reducing Uncertainty. Some researchers are developing ways to use probabilistic information to circumvent uncertainties in sensitivity and provide useful input to policy. For instance, Myles Allen's group uses an approach wherein a large set of models is calibrated against past observations and then only the best of these models are used to make future projections. (It still is unclear, however, whether such approaches make the most credible projections.) Similarly, Wigley tried an approach of evaluating various PDFs for key input values, determined which cases give twentieth century changes that lie within the observed range, and used only those cases to produce a probabilistic projection of global mean temperature change. (For example, it was found that the combination of a low aerosol radiative forcing with a low sensitivity would not fit the observations and thus could be discarded.) These studies found that the output was not strongly dependent on the input sensitivity value, which indicates that it is very difficult to derive a PDF for sensitivity directly from observations.

Determining CO_2 Stabilization Targets. Probabilistic approaches can also be used to address a question of central interest to policy makers: What is a "dangerous level of interference" in the climate system? With a simple climate model, Wigley input PDFs for sensitivity, for non-CO_2 forcing, and for a desired global warming limit and then generated a PDF for the resulting CO_2 concentration stabilization target.

Spatial Scaling. A question of great interest to researchers is whether one can use a scaling method to translate global mean values into spatial patterns of climate change, without having to rely on climate models. Spatial scaling is an attempt to decouple those components of change that are and are not related to sensitivity; that is, the global mean change (which is the sensitivity-dependent term) is separated from the patterns of change per unit of global mean warming (normalized patterns).

The simplest form of scaling is represented by the equation: $DY(x,t) = DT(t)\, D\hat{Y}(x)$, where the change in some climate variable of interest (as a function of space and time) equals the global mean temperature change multiplied by some normalized pattern of change. In a more general form of the equation, one can distinguish between global-scale forcings due to well-mixed greenhouse gases and spatially confined forcings due to short-lived species such as aerosols. Scaling is a way to assess whether we can linearly combine different types of forcings to get the overall response.

Most modelers are not aware that these types of spatial scaling techniques were introduced many years ago and are widely applied in the climate impacts community, in software such as SCENGEN and COSMIC, and in several integrated assessment models. These scaling techniques are extremely valuable and should be applied more widely to studies of other forcing agents such as ozone and soot aerosols.

Note, however, that these scaling techniques employ some fundamental assumptions that have not been adequately tested. Questions that may require further investigation include the following: How valid is this assumption that various types of forcings, which exhibit different spatial and temporal patterns, can be added linearly? How much do the normalized patterns of change depend on the sensitivity? To answer such questions we need more information about the climate effects of individual forcing factors, as well as their net effect.

CLOSING SESSION

The final session of the workshop was devoted to open discussion among all of the participants, and it focused on identifying critical issues that emerged from the previous sessions. The participants generally agreed that there have been significant developments in our understanding on a number of relevant fronts, and it is encouraging that all of the recent model estimates are within the same range of each other and within that of empirically derived values. However, participants also identified a number of challenges that inhibit further progress in quantifying and understanding climate sensitivity. The following is a brief summary of some key points raised in these discussions. Although often more than one person expressed many of the ideas listed below, they are presented as a record of the discussion and are not intended to be consensus conclusions (which were neither possible, nor desirable, given the workshop format used for this meeting).

CLIMATE SENSITIVITY CAN BE DEFINED IN NUMEROUS WAYS

- Not all researchers define sensitivity in the same way. In some contexts, it is treated strictly as an input coefficient for a parameterized model or as a model's response to a doubling of CO_2. In this case, there are a limited number of degrees of freedom or feedbacks allowed. In the most restrictive sense, sensitivity includes only the feedbacks on tropospheric water vapor and clouds. In other approaches, sensitivity is more broadly defined as a measure of the sensitivity of the whole earth system, including ecosystem and CO_2 feedbacks that result from a specific external forcing (e.g., orbital changes, solar, or volcanoes).
- In essence, the definition of climate sensitivity depends upon what processes in a model are treated as exogenous and are thus viewed as forcings, and what processes are treated as endogenous and are thus viewed as feedbacks (see earlier discussions about whether indirect aerosol effects should be treated as a forcing or a feedback). Even when two models include the same feedbacks, they may handle such processes very differently (see earlier discussion of GCM cloud parameterizations)
- There may be inherent limitations in our ability to quantify climate sensitivity.
- Some uncertainties that currently limit our ability to quantify climate sensitivity could be removed if we were able to obtain better temperature records and better estimates of past radiative forcing, but it must be acknowledged that some uncertainties (including the internally generated noise of the climate system) will never be removed.
- It may be unrealistic to focus on developing a perfect projection of future changes or a perfect re-creation of the historical climate record. The earth's climate system is not deterministic on longer time scales and since the historical record is just one realization out of many that could have occurred, it thus may not be a "stable platform" for projecting future changes.
- The chaos of the system may preclude the kinds of specific projections about local or regional climate that decision makers really want, but the general magnitude and rates of change may be predictable with knowledge of the forcings and feedbacks and with knowledge of the low frequency natural variability acting within the changing climate.

A REMAINING CHALLENGE IS CONSTRAINING THE HIGH END OF THE PDF FOR CLIMATE SENSITIVITY

- Statistical approaches have been useful for constraining the low end of the PDF for climate sensitivity, but this approach seems to fail in constraining the high end (the "tail") of the distribution curve.
- Further studies will have to explore whether the distribution tail can be better constrained using observational data, both from the modern record and from paleo-records. There may be physical constraints or GCM diagnostic tests that can be used to assess the plausibility of the high-end sensitivity values (i.e., tests that

would allow us to reject some high-end estimates as unrealistic by finding clear inconsistencies between models and observations.)

- Currently, we rely on global average temperature as the primary observational constraint. With greater use of all available observational data (e.g., information about regional precipitation patterns), we may be able to define additional constraints. However, our progress in constraining the high end of the distribution may remain limited until we can better quantify aerosol radiative forcing.
- With climate models there is a computational trade-off because going further out on the distribution tail can require a prohibitive number of computer runs. On the other hand, simple models allow an essentially unlimited number of runs, but the output is often highly sensitive to small changes in the input values, which results in an inherent uncertainty.
- There may be some important gaps in our understanding of basic physical processes in the climate system, which limits our ability to credibly project high-consequence, low-probability events. There also seem to be problems in our statistical approaches for predicting such events (which may be why we find that some areas are hit with a "500-year" flood multiple times within a few decades). Such problems deserve attention because high-risk, low-probability events are often of great interest to policy makers.

FURTHER PROGRESS WILL REQUIRE A VARIETY OF MODELING APPROACHES

- It would be useful to policy makers if we could provide other, more complex indicators of climate response that are tied more directly to regional-scale changes in temperature, precipitation, and other critical parameters. Perhaps we should consider new approaches to interpreting global climate model results that would allow us to calculate how important variables (such as precipitation and sea ice cover) change in direct relation to radiative forcing, rather than just scaling everything with the global average temperature estimated by a climate model.
- Improving the understanding of how climate sensitivity evolves over time could be achieved by developing models that include more regional scale information about anthropogenically driven changes in the climate system, such as human influences on land surface characteristics and hydrological and biogeochemical cycles, as well as aerosol radiative forcing changes from biomass-burning aerosols.
- Model comparison studies are valuable for helping people understand the effects of particular feedbacks on sensitivity. For instance, the recent NCAR-GFDL-Hadley intercomparison studies confirmed the essential role of cloud feedbacks. Such studies are most useful if they focus on evaluating those aspects that differ most among models, and against observations, and use this to improve the models. The goal should not be to look for one "best" modeling approach or to get the same answers from all models; if that were the case, we would have a tendency to believe the models, even if there is no real basis for doing so.
- Probabilistic estimates of uncertainty will continue to have an important role in advancing understanding. The output of a model is inherently statistical, and there is no escaping the need for PDFs and for ensemble modeling. The scientific community has previously advised that an assessment requires the use of at least three models and three realizations from each model. Otherwise, you cannot know whether the difference between two models is significant relative to the difference between ensemble runs from the same model.
- There is reason to hope that we can further narrow the range of sensitivity estimates through a combination of climate model results and PDFs derived from simple models. These approaches are complementary for a variety of reasons. GCMs are crucial for getting the regional details correct, but simple models are needed for probabilistic studies of global mean changes. Simple modeling approaches can indicate areas of interest that can be explored in greater detail with GCMs. Finally, PDFs from simple models could perhaps be added as a new type of routine diagnostic to understand the statistics of GCMs.

OTHER ISSUES EXIST FOR THE SCIENTIFIC COMMUNITY

- Current approaches focus primarily on the simple 2*CO_2 scenario. Interpretation of model output will be most useful if it focuses more explicitly on the role of other radiative forcing agents, including the recognition that climate sensitivity may vary somewhat, depending on the type of forcing

- El Niño-Southern Oscillation (ENSO) cycle realizations provide an opportunity to evaluate the role of some climate feedbacks associated with model sensitivity, perhaps most notably variations in cloudiness and other aspects of global hydrology.
- Narrowing the range of forcings associated with aerosols is likely to aid in constraining the high end of the PDF for climate sensitivity. Moreover, if radiative forcing from aerosol-induced changes to ice clouds were included in climate models, it could change our understanding of the future projected temperature change associated with a given climate sensitivity.
- Continued interaction between modelers and observational specialists is important. Modeling studies can be used to determine what types of observational data are needed (relative to what we have) and to explore the potential "information content" of proposed new observational networks.
- In addition to improved technical modeling capabilities there is the question of how to use this information. Currently, our capability to translate climate model results into useful information about local and regional impacts is limited. The sophistication of climate impact research is rapidly improving, but more interaction with the modeling community could improve the way model results are used and help define the metrics of local and regional change.
- As the workshop concluded, participants talked in general about how scientists might continue to improve their ability to communicate about uncertainties. Concern was raised that scientists (particularly in the realm of climate change research) have a tendency to emphasize uncertainties so much that it can appear to policy makers and others that nothing is known. More careful and creative communication could help so that policy makers are told clearly what is known, what progress has been made, and what remains to be learned.

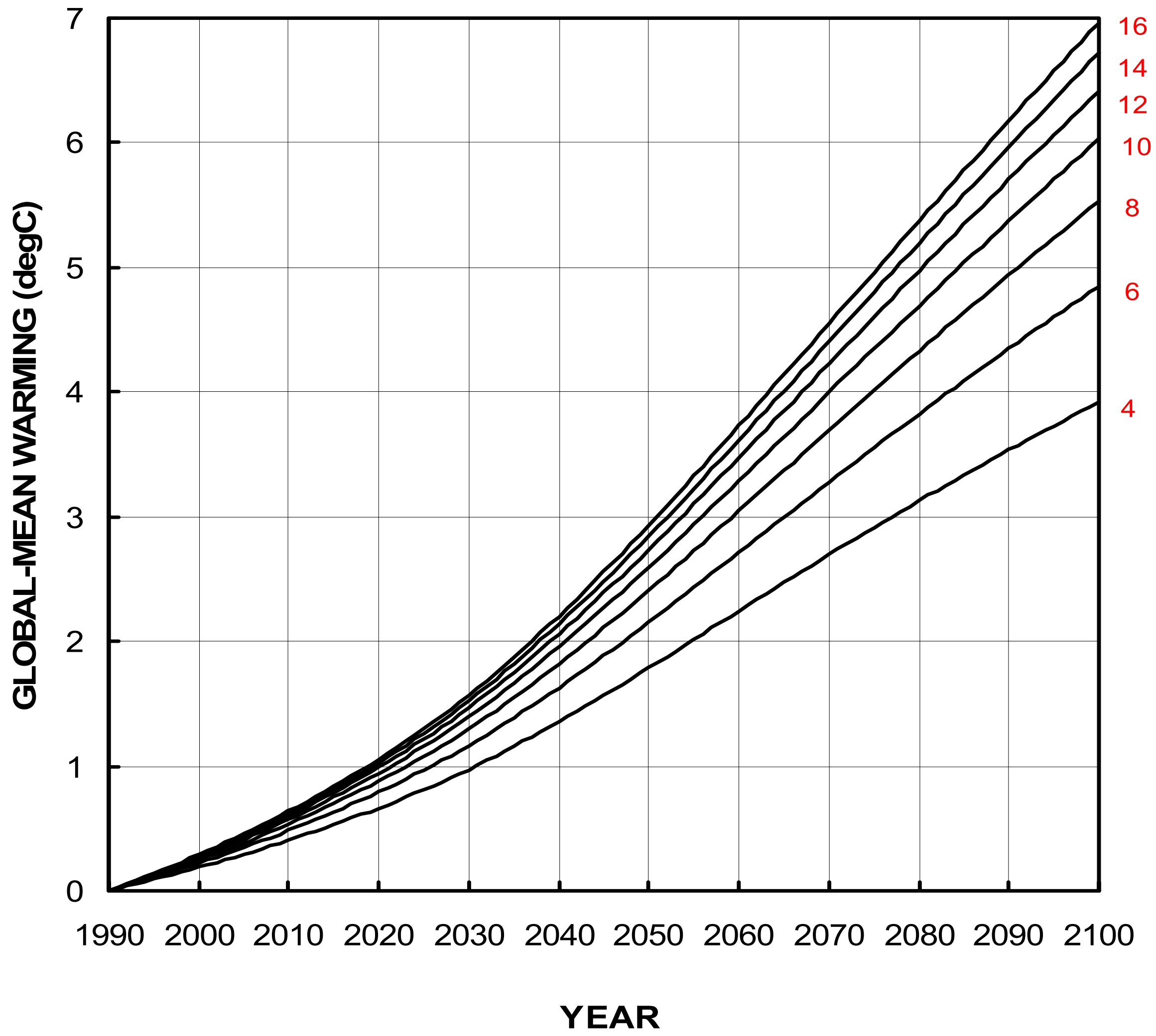

Figure 1. Projected global mean warming for the median of the 35 complete IPCC emission scenarios and different values of climate sensitivity. SOURCE: Compiled by T. Wigley.

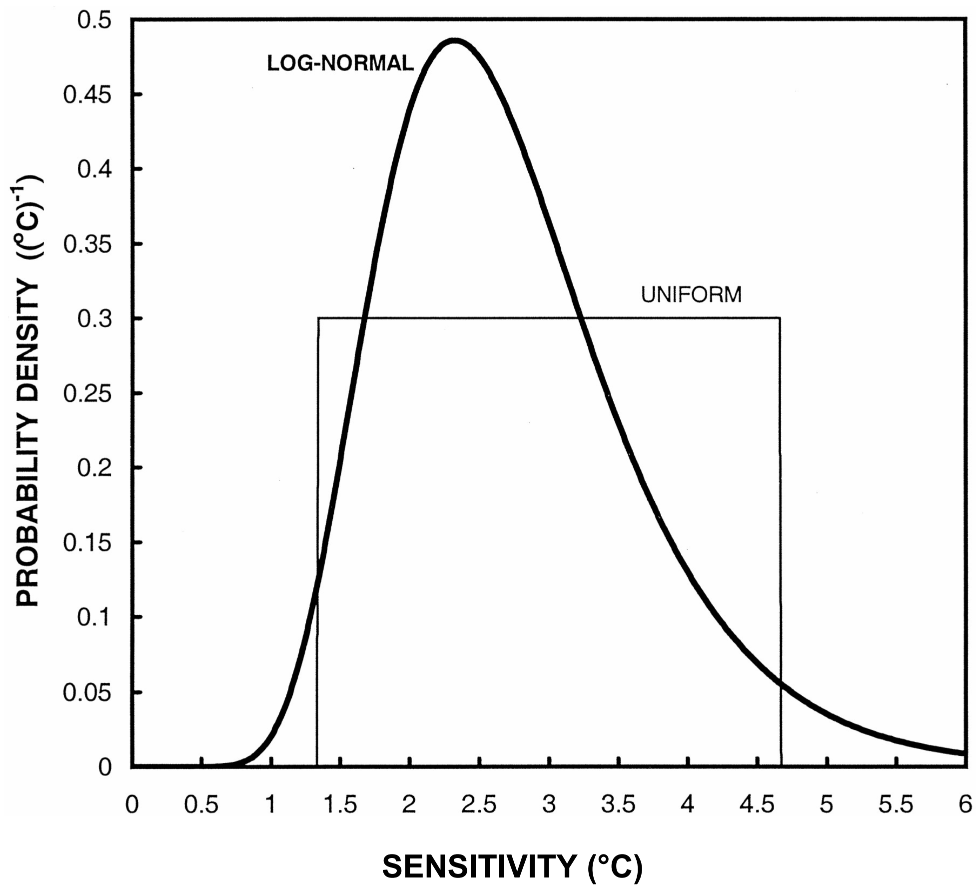

Figure 2. Distribution functions (probability densities) assumed for the climate sensitivity, expressed as the equilibrium warming for $2*CO_2$. Both cases have 1.5 to 4.5°C as the 90 percent probability interval. SOURCE: Wigley and Raper, 2001.

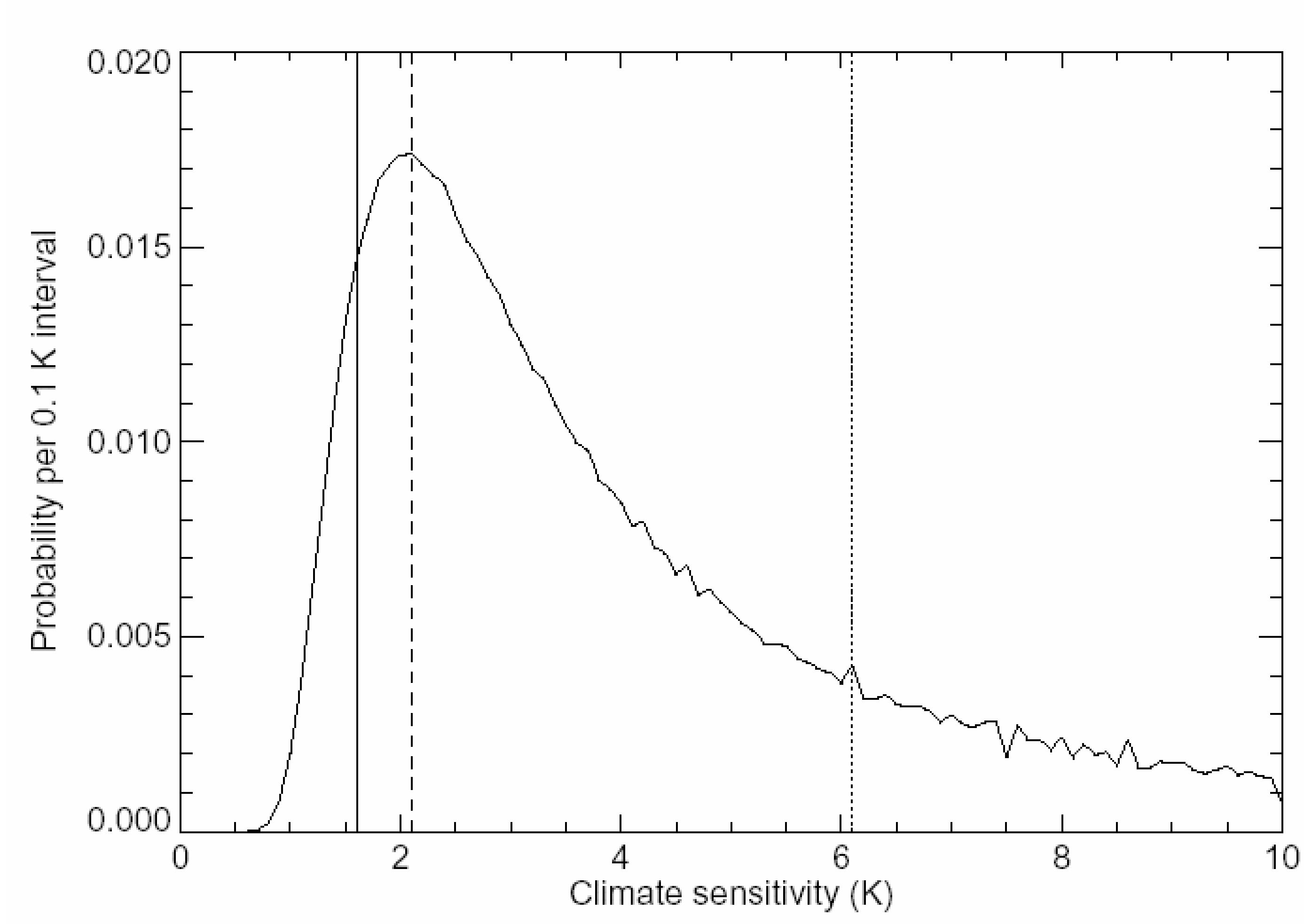

Figure 3. Probability distribution for the effective climate sensitivity, computed assuming ΔT, ocean heat uptake, and radiative forcing to be normally distributed. The bin width is 0.1 K. The vertical solid line marks the lower bound of the 90 percent confidence interval (fifth percentile); the vertical dashed line, the modal value of sensitivity; and the vertical dotted line, the median. Although the distribution is shown here only up to 10 K, the probability of higher values was accounted for in deriving the statistics and confidence interval. SOURCE: Gregory et al., 2002.

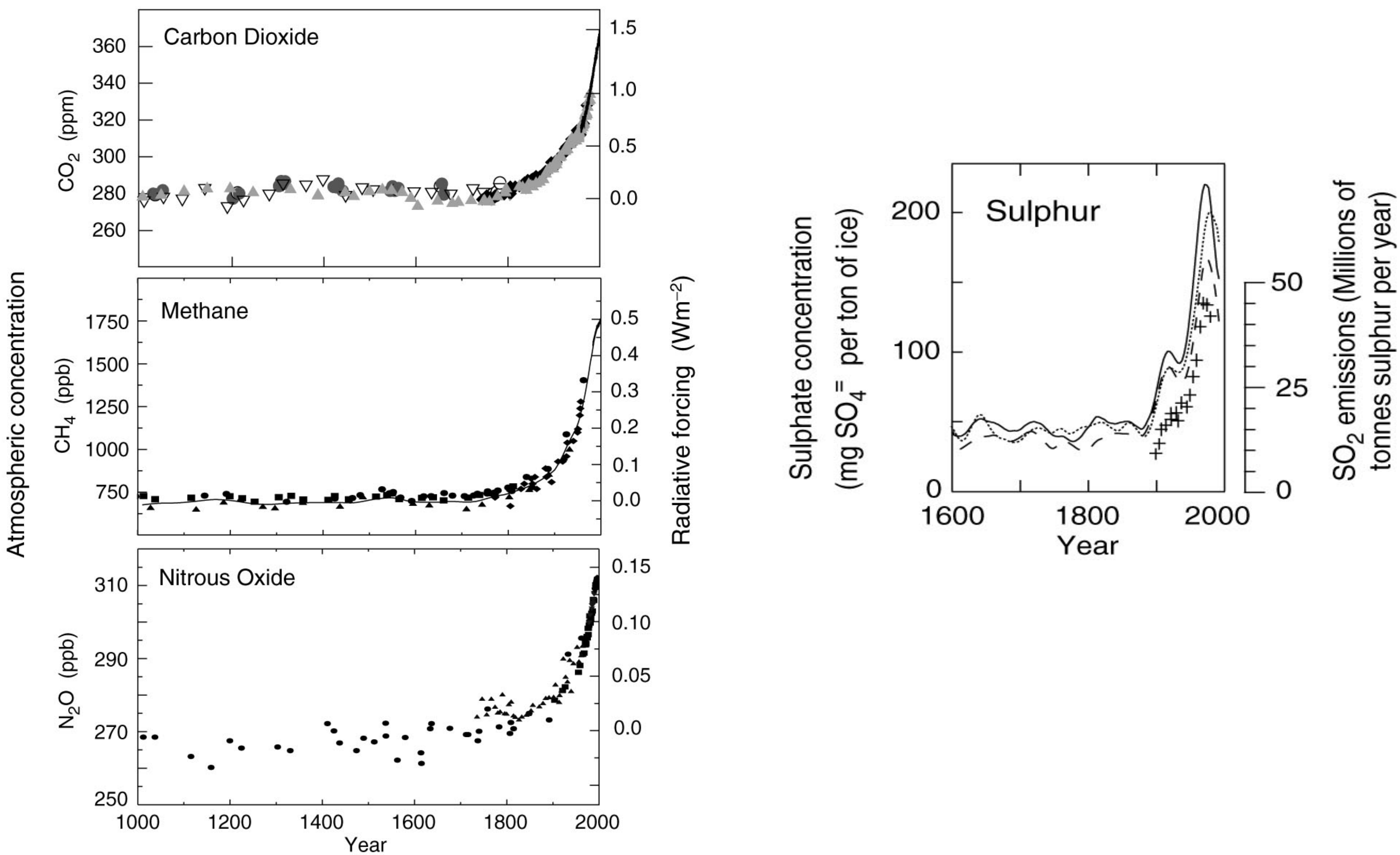

Figure 4. *left:* Records of changes in atmospheric concentrations of CO_2, CH_4, and N_2O over the past 1000 years. Ice core and firn data for several sites in Antarctica and Greenland are supplemented with data from direct atmospheric samples over the past few decades. The estimated radiative forcing from these gases is indicated in the right-hand scale.
right: Sulphate concentration in several Greenland ice cores (*lines*); and total SO_2 emissions from sources in the United States and Europe (*crosses*). SOURCE: Adapted from IPCC, 2001.

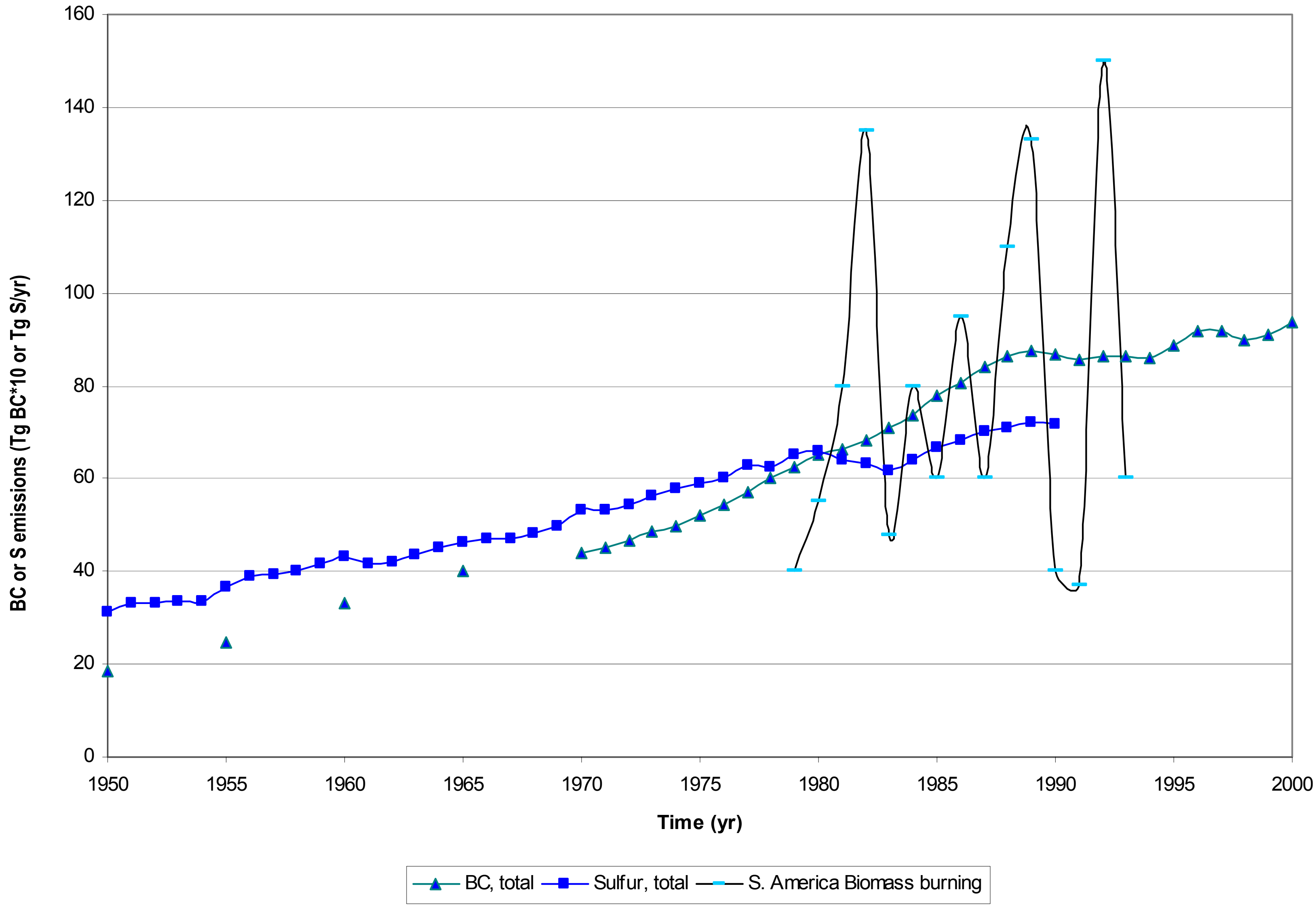

Figure 5. Time history of black carbon (BC), sulfur, and biomass-burning aerosol emissions. Sulfur emission data are from LeFohn et al., (1999). BC emission data are from Cooke et al., (1999). The biomass-burning data (from Torres et al., 2002) are shown in units of annual peak optical depth (x100) inferred from the TOMS (Total Ozone Mapping Spectrometer) satellite instrument over Brazil. SOURCE: Figure compiled by J. Penner.

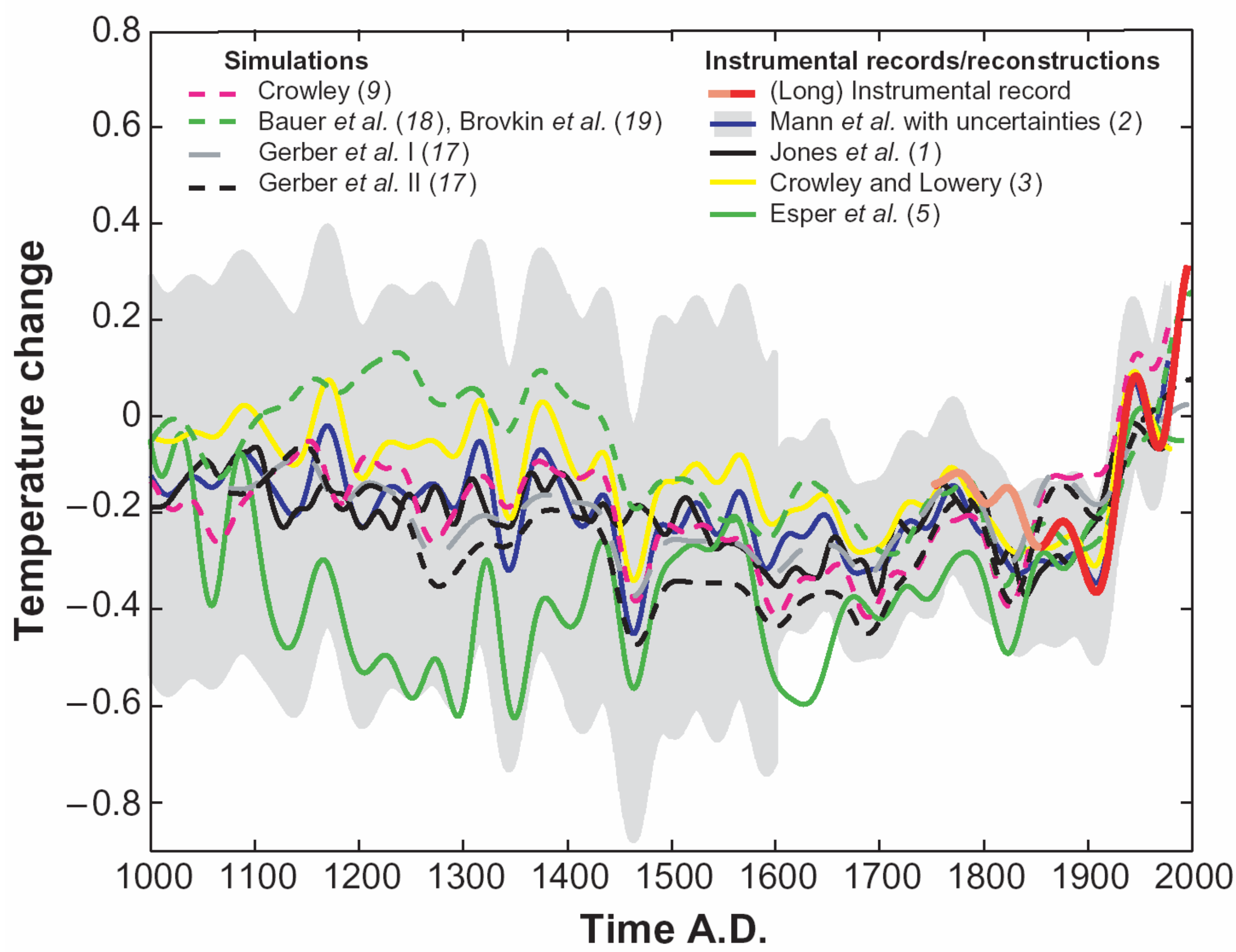

Figure 6. Northern hemisphere (NH) temperature histories. Comparison of multiproxy reconstructions of the NH annual mean temperature (1-3) with model simulations (9, 17-19). Gerber I, 1.5ºC for CO_2 doubling; Gerber II, 2.5ºC for CO_2 doubling. Also shown is a reconstruction of summer extratropical continental NH temperatures (5). All reconstructions have been scaled to the NH instrumental record (20) over the 1856 to 1980 period and have been smoothed on time scales of >40 years to highlight the long-term variations. Source: Mann, 2002.

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APPENDIX A

ACRONYMS AND ABBREVIATIONS

AMIP	Atmospheric Model Intercomparison Project
AOGCM	atmospheric-ocean general circulation model
BASC	Board on Atmospheric Sciences and Climate
BC	black carbon
CCSP	Climate Change Science Program
CFC	chlorofluorocarbon
DOE	Department of Energy
ENSO	El Niño-Southern Oscillation
EPA	Environmental Protection Agency
GCM	general circulation model
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	greenhouse gas
HadCM3	Hadley Centre's Third-generation coupled ocean-atmospheric GCM
IPCC/TAR	Intergovernmental Panel on Climate Change Third Assessment Report
ISCCP	International Satellite Cloud Climatology Projects
MAGICC	Model for the Assessment of Greenhouse-Gas Induced Climate Change
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
PCMDI	Program for Climate Model Diagnosis and Intercomparison
PDF	probability density function
ppmv	parts per million by volume
RF	radiative forcing
S_{eff}	effective climate sensitivity
S_{eq}	equilibrium climate sensitivity
S_{tr}	transient climate sensitivity
SCENGEN	a global and regional climate SCENario GENerator
S/N	signal-to-noise ratio
SPARC	Stratospheric Processes and Their Role in Climate (WCRP)
TCR	transient climate response
TOGA	Tropical Oceans and Global Atmosphere Program
TOMS	Total Ozone Mapping Spectrometer
USGCRP	U.S. Global Change Research Program
VOC	volatile organic compound
WCRP	World Climate Research Program
WMO	World Meteorological Organizarion

APPENDIX B

WORKSHOP AGENDA

Thursday, January 30, 2003

9:00-9:30 Welcome, introductions; review agenda and goals of the meeting
Jerry Mahlman, NCAR

9:30-10:00 Information needs regarding climate sensitivity
Jane Leggett, EPA
Example: the MAGICC/SCENGEN model and its use of climate sensitivity estimates
Tom Wigley, NCAR

10:00-10:30 An overview of the IPCC/TAR process for determining climate sensitivity estimates
Venkatchalam Ramaswamy, NOAA/GFDL

10:30-11:00 Recent intercomparison studies between the GFDL and NCAR climate models
Anthony Broccoli, NOAA/GFDL

11:00-12:30 Discussion Panel: Approaches to Estimating Climate Sensitivity

- What are the various methods used to estimate climate sensitivity?
- What accounts for the differences among published estimates?

Peter Stone, MIT; **Jonathan Gregory**, Hadley Centre; **Natalia Andronova**, University of Illinois

1:15-1:30 An overview of the NRC Climate Research Committee's 'Climate Feedbacks' Study
Eugene Rasmusson, University of Maryland

1:30- 3:00 Discussion Panel**:** Climate Feedbacks

- Do the climate sensitivity studies discussed above adequately account for the relevant feedbacks in the earth's climate system?
- Do they account for the different timescales over which these various feedbacks operate?

William Collins, NCAR (clouds, aerosols)*;* **Venkatchalam Ramaswamy**, NOAA/GFDL (water vapor); **Michael Prather**, University of California, Irvine (chemistry); **Joyce Penner**, University of Michigan (aerosols); **Jonathan Gregory**, Hadley Centre (ocean, sea ice)

3:30- 5:00 Discussion Panel: Characterizing Uncertainty

- What approaches are used for characterizing uncertainty in climate sensitivity? (a single "best estimate"?
- A range of values derived from various models?
- Probabilistic approaches? Expert opinion and Baysean statistical approaches?
- How does the present uncertainty in climate sensitivity estimates compare with uncertainties in radiative forcing, emission scenarios, etc.?

Peter Stone, MIT; Michael **Schlesinger**, University of Illinois; **Michael Mann**, University of Virginia; **Richard Moss**, CCSP

Friday, January 31, 2003

9:00- 10:30 Discussion Panel: Meeting the Needs of the User Community

- What are the various uses for which the concept of climate sensitivity is applied?
- What climate response metrics could be developed for these various applications?
- What do the users find deficient with the information that science currently provides; what do they want science to do better?
- How meaningful is the concept of climate sensitivity, as currently defined, for climate change risk assessment studies? Are there other possible approaches to characterizing climate response that might be more useful for policy-relevant analyses?

Rosina Bierbaum, University of Michigan; **Tom Wigley**, NCAR

10:30-noon Closing Session

- Review and integrate lessons learned in the various panel discussions.
- Discuss key information needs and research priorities.

APPENDIX C

WORKSHOP ATTENDEES

Panelists and Presenters

Natalia Andronova, University of Illinois
Rosina Bierbaum, University of Michigan
Anthony Broccoli, NOAA/GFDL
William Collins, NCAR
Jonathan Gregory, Hadley Centre
Jerry Mahlman, NCAR
Michael Mann, University of Virginia
Richard Moss, Climate Change Science Program/U.S. Global Change Research Program
Joyce Penner, University of Michigan
Michael Prather, University of California, Irvine
Venkatchalam Ramaswamy, NOAA/GFDL
Eugene Rasmusson, University of Maryland
Michael Schlesinger, University of Illinois
Peter Stone, MIT
Tom Wigley, NCAR

Guests

Don Anderson, NASA
David Bader, DOE / PNNL
Randy Dole, NOAA
Britt Erickson, American Chemical Society ES&T
Charles Hakkarinen
John Houghton, DOE
Jane Leggett, EPA
David Legler, US CLIVAR
Michael Leifman, EPA
Michael MacCracken
Kuan- Man Xu, NASA
Christopher Miller, NOAA
Stephen Reid, NSF
Richard Rood, NSF
Tony Socci, EPA

NRC Staff

Chris Elfring, BASC Director
Laurie Geller, BASC Senior Program Officer
Elizabeth A. Galinis, BASC Project Assistant

APPENDIX D

INVITED SPEAKERS

Natalia Andronova is a research scientist with the Department of Atmospheric Sciences, University of Illinois. Her research interests center around the fields of global and regional climate change, interactions between climate and the chemical composition of atmosphere, feedbacks in the climate-chemistry system, and the response of the climate-chemistry system to different radiative forcings, of both natural and anthropogenic origin. Her current research interest is in using simple climate models and a complicated climate-chemistry model to detect and attribute climate change. Her recent work has included use of a simple climate model to perform a statistical estimation of the uncertainties of the climate sensitivity, in which it was found that the 90 percent confidence interval for climate sensitivity is 1.0- 9.3°C, and that the magnitude of the climate sensitivity critically depended on historical changes in solar irradiance.

Rosina M. Bierbaum is the dean of the University of Michigan School of Natural Resources and Environment and professor of natural resources and environmental policy. Previously, she served as acting director of the Office of Science and Technology Policy (OSTP) in the Executive Office of the President. Before her appointment as acting director, she was the OSTP associate director for environment, serving as the administration's senior scientific adviser on environmental research and development on a wide range of issues, including global change, air and water quality, ecosystem management, and energy research and development. Dr. Bierbaum worked closely with the President's National Science and Technology Council and co-chaired its Committee on Environmental and Natural Resources. She is a fellow of the American Association for the Advancement of Science and served on the Government-University-Industry Research Roundtable of the National Academy of Sciences.

Anthony J. Broccoli is a research meteorologist in the Climate Dynamics Group of the NOAA Geophysical Fluid Dynamics Laboratory. His research interests focus on climate modeling, with particular emphasis on the simulation of past climates and climate change, and the use of such simulations to evaluate climate model performance. His current research projects include simulation of the climate of the last glacial maximum; orbital forcing of climate variations during the last glacial cycle; extratropical forcing of tropical interhemispheric asymmetry; and diagnosis of climate model feedbacks and sensitivity. He recently began a new position on the faculty of Rutgers University in the Department of Environmental Sciences.

William D. Collins is an atmospheric scientist in the Climate and Global Dynamics Division of the National Center for Atmospheric Research in Boulder, Colorado. His doctoral dissertation in astrophysics was granted by the University of Chicago in 1989. He serves as the chair of the Atmospheric Radiation Committee for the American Meteorological Society and as co-chair of the Atmospheric Model Working Group at NCAR. Dr. Collins also teaches as an adjunct professor in the Program of Atmospheric and Oceanic Sciences at the University of Colorado. His research interests are the role of clouds and aerosols in climate change; the development of new methods for modeling clouds and aerosols in GCMs; and fundamental aspects of radiative transfer in the terrestrial atmosphere.

Jonathan Gregory earned his Ph.D. in experimental particle physics at the University of Birmingham and joined the climate change group at the Hadley Centre for Climate Prediction and Research in 1990. In autumn 2001 he was a visiting scientist in the climate modeling group at the University of Victoria. Dr. Gregory currently manages the Hadley Centre research theme on predictions and understanding of climate change. He has worked on analyses of many aspects of climate change, in particular sea-level rise; ocean heat uptake, climate sensitivity; and changes in the thermohaline circulation, sea ice, and extremes of daily precipitation. He was joint coordinating lead author of the sea-level chapter of the IPCC Third Assessment Report. He has also been involved in the development of the Hadley Centre AOGCMs, especially the sea ice and coupling components, of the data analysis and database software used at the Hadley Centre, and of a common metadata standard for data exchange among climate centers.

Jerry D. Mahlman is a senior research fellow at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. He was director of the Geophysical Fluid Dynamics Laboratory at the National Oceanic and Atmospheric Administration in Princeton, New Jersey, for 16 years before his retirement in 2000. He was also a professor in atmospheric and oceanic sciences at Princeton University for 28 years. Much of Dr. Mahlman's research career has been directed toward understanding the behavior of the stratosphere and troposphere. This has involved extensive mathematical modeling and diagnosis of the interactive chemical, radiative, dynamical, and transport aspects of the atmosphere, as well as their implications for climate and chemical change. Over the past decade, he has occupied a central role in the interpretation of climate change to policy makers and affected communities. Dr. Mahlman has served on numerous committees and boards including the NASA Advisory Council and the Board on Sustainable Development of the National Research Council. In 1994 he received the prestigious Carl-Gustaf Rossby Research Medal from the American Meteorological Society and the Presidential Distinguished Rank Award—the highest honor awarded to a federal employee. He received his Ph.D. from Colorado State University.

Michael E. Mann is assistant professor in the Department of Environmental Sciences at the University of Virginia. Dr. Mann was a lead author on the "Observed Climate Variability and Change" chapter of the IPCC Third Assessment Report (and a contributor to several other chapters). He is a member of numerous international and U.S. scientific advisory panels and steering groups. He currently serves as an editor of the *Journal of Climate*. Dr. Mann's research focuses on the application of statistical techniques to understanding climate variability and climate change from both empirical and climate model-based perspectives. A specific area of current research is paleoclimate data synthesis and statistically based climate pattern reconstruction during past centuries using climate proxy data networks. A primary focus of this research is deducing empirically the long-term behavior of the climate system and its relationship to possible external (including anthropogenic) forcings of climate. His other areas of active research include model-based simulation of natural climate variability, climate model-data intercomparison, and long-range climate forecasting.

Michael J. Prather is a professor in the Earth System Science Department at the University of California, Irvine. He received his Ph.D. in astronomy from Yale University. His research interests include simulation of the physical, chemical, and biological processes that determine atmospheric composition, and the development of detailed numerical models of photochemistry and atmospheric radiation and global chemical transport models that describe ozone and other trace gases. Dr. Prather has played a significant role in the IPCC's second and third assessments and its special report on aviation and in the World Meteorological Organization's (WMO) Ozone Assessments (1985-1994). He is a fellow of the American Geophysical Union and a foreign member of the Norwegian Academy of Science and Letters; he has served on several NRC committees, including BASC's Panel on Climate Variability on Decade-to-Century Time Scales.

Joyce Penner is a professor of atmospheric, oceanic, and space sciences at the University of Michigan-Ann Arbor. She is a former leader of the Global Climate Research Division at the Lawrence Livermore National Laboratory. She is an associate editor for the *Journal of Geophysical Research* and the *Journal of Climate*. She was recently elected to the International Commission on Atmospheric Chemistry and Global Pollution and has served on numerous committees of the National Academies. Professor Penner has ongoing research relating to improving climate models through the addition of interactive chemistry and the description of aerosols and their direct and indirect effects on the radiation balance in climate models. These models run in both a parallel computing environment and vector supercomputers. She has an ongoing interest in urban, regional, and global tropospheric chemistry and budgets, cloud and aerosol interactions and cloud microphysics; climate and climate change, and model development and interpretation.

Venkatchalam Ramaswamy is a senior scientist and leader of the Atmospheric Processes Group at the NOAA Geophysical Fluid Dynamics Laboratory. He is also a professor in the Atmospheric and Oceanic Sciences Program at Princeton University. His principal research interests are modeling of climate, its variations, and change; diagnostic analyses of models and observations to understand climate processes; radiative and climatic effects due to greenhouse gases and aerosols; chemistry-climate interactions; natural and anthropogenic perturbations of climate; and understanding the interactions linking water vapor, clouds, and climate. He has served as lead author for numerous reports of the IPCC (1992, 1995, 1996, and 2001) and the WMO Scientific Assessment of Ozone Depletion (1992, 1994, 1999, and 2002). He is also project leader for the World Climate Research Program—

Stratospheric Processes and their Role in Climate (SPARC) project on Stratospheric Temperature Trends and had served on several panels of the National Academies.

Eugene M. Rasmusson is a research professor emeritus at the University of Maryland. In 1999, Dr. Rasmusson was awarded membership in the National Academy of Engineering. His research expertise lies broadly in general climatology with an emphasis on seasonal-to-interannual climate variability. Dr. Rasmusson's NRC experience includes chairing the Climate Research Committee and membership on the Board on Atmospheric Sciences and Climate, the Global Ocean-Atmosphere-Land System Panel, the Panel on Model-Assimilated Data Sets for Atmospheric and Oceanic Research, the Committee on USGS Water Resources Research, and the Advisory Panel for the Tropical Oceans and Global Atmosphere (TOGA) Program.

Michael Schlesinger is professor of atmospheric sciences at the University of Illinois at Urbana-Champaign. Professor Schlesinger directs the Climate Research Group within the Department of Atmospheric Sciences. He is an expert in the modeling simulation and analysis of climate and climate change, with interests in simulating and understanding past, present, and possible future climates, climate impacts, and climate policy. He carried out the first detailed comparison of climate and climate changes simulated by different atmospheric general circulation models and has led the development of tropospheric GCMs, stratospheric-tropospheric GCMs, oceanic GCMs, and a variety of simpler climate models, including the energy balance climate/upwelling-diffusion ocean model with which he made projections of global temperature change for the 1990 IPCC report. His research currently focuses on estimating the temperature sensitivity of the earth's climate system; determining the effects on past and future climate of the sun, sulfate aerosols, and natural variability; simulating and understanding the onset of the last ice age; performing integrative assessment of climate change; and understanding the roles of clouds in climate and climate change.

Peter Stone is a professor of climate dynamics in the Massachusetts Institute of Technology Department of Earth, Atmospheric, and Planetary Sciences. He is an expert in atmospheric dynamics who has made important contributions to the development of climate models of all kinds, ranging from the simplest one-dimensional process models to full-scale three-dimensional general circulation models. He is a member of the team that developed the NASA/Goddard Institute for Space Studies general circulation climate model and has been applying it to climate change problems. He is the director of MIT's Climate Modeling Initiative, which is engaged in developing a new state-of-the-art three-dimensional climate model, with a focus on studies of the predictability of climate. He is involved in many studies aimed at understanding dynamical transports of heat and moisture in the atmosphere and oceans and how they affect climate sensitivity. These studies include the development and analysis of simple climate models and coupled atmosphere-ocean models, diagnostic studies of the general circulation of the atmosphere, and numerical studies of the interaction of baroclinic eddies with mean flows.

Tom M. L. Wigley formerly director of the Climatic Research Unit, University of East Anglia, Norwich, U.K., currently holds a senior scientist position with the National Center for Atmospheric Research, Boulder, Colorado. His research interests span diverse aspects of the broad field of climatology, including carbon cycle modeling; projections of future climate and sea-level change; and interpretation of past climate change, particularly with a view to separating anthropogenic influences from natural (including solar-induced) variability. Recently, he has concentrated on facets of the global warming problem and has contributed on many occasions to IPCC reports and assessments. He is a member of Academia Europaea, recipient of the Sixth Annual Climate Institute Award, and a fellow of the American Meteorological Society.