

## **Climate Models (including uncertainties)**

**S. Schneider**

## **Overview of Climate Modeling Fundamentals and Their Implications for Integrated Assessment Modelling**

**Dr. Stephen H. Schneider**

Department of Biological Sciences  
Stanford University, Stanford, CA 94305 USA  
Tel: 650-725-9978 Fax: 650-725-4387 Email: shs@leland.stanford.edu

**Abstract:** Mathematical models of climate are the primary tools used to project human influences on climate. General circulation models (GCM) are based on known laws of physics applied to the climate system: land (and biota), oceans, ice and atmosphere. Discretization into gridboxes several hundred kilometers on a side implies that processes (e.g. cloud formation or precipitation) which occur on smaller scales must be treated by semi-empirical parametric representations (i.e. "parameterizations"). Validation of parameterizations and overall model performance is the prime concern of climate modelers. IPCC Working Group I lead authors suggest that current coupled atmosphere-ocean-ice-biosphere models, though at early stages of development, can still make useful projections of time-evolving climate changes at large scales (e.g. continental), but that their regional projections are more problematic. Decision analytic techniques to assess the subjective probability distribution of experts are presented, and their relevance to Integrated Assessment Modelling is discussed. The need for a hierarchy of models to perform a variety of sensitivity analyses, and the requirement for periodic reassessment of the evolving state-of-the-art of both climatic effects and impacts models in order to provide insights to the policy-making community, is stressed.

Engineers and scientists build models - either mathematical or physical ones - primarily to perform tests that are either too dangerous, too expensive, or perhaps impossible to perform with the real thing. To simulate the climate, a modeler needs to decide which components of the climatic system to include and which variables to involve. For example, if we choose to simulate the long-term sequence of glacials and interglacials (the period between successive ice ages), our model needs to include explicitly the effects of all the important interacting components of the climate system operating over the past million years or so. These include the atmosphere, oceans, sea ice/glaciers (cryosphere), land surface (including biota), land sub-surface and chemical processes (including terrestrial and marine biogeochemical cycles), as well as the external or "boundary forcing" conditions such as input of solar radiant energy (e.g., see IPCC, 1996a).

The problem for earth systems scientists is separating out quantitatively cause and effect linkages from among the many factors that interact within the earth system. It is a controversial effort because there are so many sub-systems, so many forcings and so many interacting complex sets of processes operating at the same time, that debates about the adequacy of models often erupt.

**Modeling the Climate System.** So how are climate models constructed? First, scientists look at observations of changes in temperatures, ozone levels and so forth. This allows us to identify correlations among variables. Correlation is not necessarily cause and effect - just because one event tracks another doesn't mean it was caused by it. One has to actually prove the relationship is causal and explain how it happened. Especially for cases where unprecedented or unexplored events are being considered, a first principles rather than a purely empirical-statistical approach is desirable. However, observations which create empirical-statistical associations can lead to a hypothesis of cause and effect - "laws" - that

can be tested (for example, see Root and Schneider, 1995). The testing is often based on simulations with mathematical models run on a computer. The models, in turn, need to be tested against a variety of observations - present and from the geologic past, so-called paleoclimatic. That is how the scientific method is typically applied to climate models. When a model, or set of linked models, appear plausible, they can be fed "unprecedented" changes such as projected human global change forcings - changes that are unexplored or have not happened before - and then be asked to make projections of future climate, ozone levels, forests, species extinction rates, etc.

The most comprehensive weather simulation models produce three dimensional details of temperature, winds, humidity, and rainfall all over the globe. A weather map generated by such a complex computer model - known as a general circulation model or GCM - often looks quite realistic, but it is never faithful in every detail. To make a weather map generated by computer we need to solve six partial differential equations that describe the energy flows and fluid motions in the atmosphere. In principle it appears that there's no problem: we know that those equations work in the laboratory, we know that they describe fluid motions and energy and mass relationships. So why then aren't the models perfect simulations of the atmospheric behavior?

One answer is that the evolution of weather from some starting weather map (known as the initial condition) is not deterministic beyond about 10 days - even in principle. A weather event on one day cannot be said to determine an event 20 days in the future, all those commercial "long-range" weather forecasts notwithstanding. But the inherent unpredictability of weather details much beyond ten days (owing to the chaotic internal dynamics of the atmosphere) doesn't preclude accurate forecasts of long-term averages (climate rather than weather). The seasonal cycle is absolute proof of such deterministic predictability, as winter reliably follows summer and the cause and effect is known with certainty.

**Grids and Parameterization.** The other answer to the imperfection of general circulation model simulations, even for long-term averages, is that nobody knows how to solve those six complex mathematical equations exactly. It's not like an algebraic equation where one can get the exact solution by a series of simple operations. There isn't any known mathematical technique to solve such coupled, nonlinear partial differential equations exactly. We approximate the solutions by taking the equations, which are continuous, and breaking them down into discrete chunks which we call grid boxes. A typical GCM grid size for a "low resolution" model is about the size of the Island of Borneo horizontally and that of a "high resolution" GCM is about the size of Sri Lanka. In the vertical dimension there are two (low resolution model) up to about twenty (high resolution model) vertical layers that are typically spanning the lowest 10 to 40 kilometers of the atmosphere.

Clouds are very important to the energy balance of the earth-atmosphere system since they reflect sunlight back to space and trap infrared heat in the lower atmosphere. But because none of us have ever seen a single cloud the size of Sri Lanka, let alone Borneo, we have a problem of scale - how can we treat processes that occur in nature at a smaller scale than we can resolve by our approximation technique of using large grid boxes. For example, we cannot calculate clouds explicitly because individual clouds are typically the size of a dot in this grid box. But we can put forward a few reasonable propositions on cloud physics: if it's a humid day, for example, it's more likely to be cloudy. If the air is rising, it's also more likely to be cloudy.

These climate models can predict the average humidity in the gridbox, and whether the air is rising or sinking on average. So then we can write what we call a parametric representation or "parameterization" to connect large scale variables that are resolved by the grid box (such as humidity) to unresolved small scale processes (individual clouds). Then we get a prediction of grid box-averaged cloudiness through this parameterization. So-called "cumulus parameterization" is one of the important-and controversial-elements of GCMs that occupy a great deal of effort in the climate modelling community. Therefore, the models are

not ignoring cloudiness, but neither are they explicitly resolving individual clouds. Instead, modelers try to get the average effect of processes that can't be resolved explicitly at smaller scales than the smallest resolved scale (the grid box) in the GCM. Developing, testing and validating many such parameterizations is the most important task of the modelers since these parameterizations determine critically important issues like "climate sensitivity." The climate sensitivity is the degree of response of the climate system to a unit change in some forcing factor: typically, in our context, the change in globally-averaged surface air temperature to a fixed doubling of the concentration of atmospheric carbon dioxide above pre-industrial levels. This brings us to one of the most profound controversies in earth systems science, and one of the best examples of the usefulness, and fragility, of computer modeling.

**The Greenhouse Effect.** If the earth only absorbed radiation from the sun without giving an equal amount of heat back to space by some means, the planet would continue to warm up until the oceans boiled. We know the oceans are not boiling, and surface thermometers plus satellites have shown that the earth's temperature remains roughly constant from year to year (the interannual globally-averaged variability of about  $0.2^{\circ}\text{C}$  or the  $0.5^{\circ}\text{C}$  warming trend in the 20th century, notwithstanding). This near constancy requires that about as much radiant energy leave the planet each year in some form as is coming in. In other words, a near-equilibrium or energy balance has been established. The components of this energy balance are crucial to the climate.

All bodies with temperature give off radiant energy. The earth gives off a total amount of radiant energy equivalent to that of a black body - a fictional structure that represents an ideal radiator -with a temperature of roughly  $255\text{K}$  ( $-18^{\circ}\text{C}$ ). The mean global surface air temperature is about  $14^{\circ}\text{C}$  ( $287^{\circ}\text{K}$ ) some,  $32^{\circ}\text{C}$  warmer than the earth's black body temperature. The difference is due to the well-established greenhouse effect.

The term greenhouse effect arises from the classic analogy to a greenhouse, in which the glass allows the solar radiation in and traps much of the heat inside. However, the mechanisms are different, for in a greenhouse the glass primarily prevents convection currents of air from taking heat away from the interior. Greenhouse glass is not primarily keeping the enclosure warm by its blocking or re-radiating infrared radiation; rather, it is constraining the physical transport of heat by air motion.

Although most of the earth's surface and thick clouds are reasonably close approximations to a black body, the atmospheric gases are not. When the nearly black body radiation emitted by the earth's surface travels upward into the atmosphere, it encounters air molecules and cloud and aerosol particles. Water vapor, carbon dioxide, methane, nitrous oxide, ozone, and many other trace gases in the earth's gaseous envelope tend to be highly selective - but often highly effective - absorbers of terrestrial infrared radiation. Furthermore, clouds (except for thin cirrus) absorb nearly all the infrared radiation that hits them, and then they reradiate energy almost like a black body at the temperature of the cloud surface -- colder than the earth's surface most of the time.

The atmosphere is more opaque to terrestrial infrared radiation than it is to incoming solar radiation, simply because the physical properties of atmospheric molecules, cloud and dust particles tend on average to be more transparent to solar radiation wavelengths than to terrestrial radiation. These properties create the large surface heating that characterizes the greenhouse effect, by means of which the atmosphere allows a considerable fraction of solar radiation to penetrate to the earth's surface and then traps (more precisely, intercepts and re-radiates) much of the upward terrestrial infrared radiation from the surface and lower atmosphere. The downward re-radiation further enhances surface warming and is the prime process causing the greenhouse effect. It is not a speculative theory, but a well understood and validated phenomenon of nature.

The most important greenhouse gas is water vapor, since it absorbs terrestrial radiation over most of the infrared spectrum. Even though humans are not altering the average amount of water vapor in the atmosphere very much by direct injections of this gas,

increases in other greenhouse gases which warm the surface cause an increase in evaporation which increases atmospheric water vapor concentrations, leading to an amplifying or "positive" feedback process known as the "water vapor-surface temperature-greenhouse feedback." The latter is believed responsible for the bulk of the climate sensitivity (IPCC, 1996a). Carbon dioxide is another major greenhouse gas. Although it absorbs and re-emits considerably less infrared radiation than water vapor,  $\text{CO}_2$  is of intense interest because its concentration is increasing due to human activities. Ozone, nitrogen oxides, sulfur oxides, some hydrocarbons, and even some artificial compounds like chlorofluorocarbons are also greenhouse gases. The extent to which they are important to climate depends upon their atmospheric concentrations, the rates of change of those concentrations and their effects on depletion of stratospheric ozone - which, in turn, can indirectly modify the radiative forcing of the lower atmosphere thus changing climate.

The earth's temperature, then, is primarily determined by the planetary radiation balance, through which the absorbed portion of the incoming solar radiation is nearly exactly balanced over a year's time by the outgoing terrestrial infrared radiation emitted by the climatic system to earth. As both of these quantities are determined by the properties of the atmosphere and the earth's surface, major climate theories that address changes in those properties have been constructed. Many of these remain plausible hypotheses of climatic change. Certainly the natural greenhouse effect is established beyond a reasonable scientific doubt, accounting for natural warming that has allowed the coevolution of climate and life to proceed to this point (e.g., see Schneider and Londer, 1984). The extent to which human augmentation of the natural greenhouse effect (i.e., global warming) will prove serious is, of course, the current debate.

**Model Validation.** There are many types of parameterizations of processes that occur at a smaller scale than our models can resolve, and scientists debate which type is best. In effect, are they an accurate representation of the large-scale consequences of processes that occur on smaller scales than we can explicitly treat? These include cloudiness, radiative energy transport, turbulent convection, evapotranspiration, oceanic mixing processes, chemical processes, ecosystem processes, sea ice dynamics, precipitation, mountain effects and surface winds.

In forecasting climatic change, then, validation of the model becomes important. In fact, we can not easily know in principle whether these parameterizations are "good enough." We have to test them in a laboratory. That's where the study of paleoclimates has proved so valuable (e.g., Hoffert and Covey, 1992). We also can test parameterizations by undertaking detailed small-scale field or modeling studies aimed at understanding the high resolution details of some parameterized process the large-scale model has told us is important. The Second Assessment Report of IPCC (IPCC, 1996a) Working Group I devoted more than one chapter to the issue of validation of climatic models, concluding that:

the most powerful tools available with which to assess future climate are coupled climate models, which include three-dimensional representations of the atmosphere, ocean, cryosphere and land surface. Coupled climate modelling has developed rapidly since 1990, and current models are now able to simulate many aspects of the observed climate with a useful level of skill. [For example, good skill is found in simulating the very large annual cycle of surface temperatures in Northern and Southern Hemispheres, or the cooling of the lower atmosphere following the injection of massive amounts of dust into the stratosphere after explosive volcanic eruptions such as Mt. Pinatubo in the Philippines in 1991.] Coupled model simulations are most accurate at large spatial scales (e.g., hemispheric or continental); at regional scales skill is lower. *[sentence in square brackets added]*

One difficulty with coupled models is known as "flux adjustment"-a technique for accounting for local oceanic heat transport processes that are not well simulated in some

models. Adding this element of empirical-statistical “tuning” to models that strive to be based as much as possible on first principles has been controversial. However, not all models use flux adjustments, yet nearly all models, with or without this technique, produce climate sensitivities within or near to the standard IPCC range of 1.5 to 4.5°C. Flux adjustments do, however, have a large influence on regional climatic projections, even if they are not a major impact on globally-averaged climate sensitivity. Improving coupled models is thus a high priority for climate researchers since it is precisely such regional projections that are so critical to the assessment of climatic impacts on environment and society (e.g., IPCC, 1996b; IPCC, 1997).

**Transient versus Equilibrium Simulations.** One additional issue needs to be addressed in the context of coupled climate simulations. Until recently, climate modeling groups did not have access to sufficient computing power to routinely calculate time evolving runs of climatic change, given several alternative future histories of greenhouse gases and aerosol concentrations. That is, they did not perform so-called transient climate change scenarios. (Of course, the real Earth is undergoing a transient “experiment”, e.g., see Schneider, 1997a). Rather, the models typically were asked to estimate how the Earth’s climate would eventually be altered (i.e., in equilibrium) after CO<sub>2</sub> was artificially doubled and held fixed indefinitely rather than increased incrementally over time, as it has in reality or in more realistic transient model scenarios. The equilibrium climate sensitivity has remained fairly constant for over twenty years of assessments by various national and international groups, with the assessment teams repeatedly suggesting that, were CO<sub>2</sub> to double, climate would eventually warm at the surface somewhere between 1.5 and 4.5°C. (Later on we will address the issue of the probability that warming above or below this range might occur, and how probabilities can even be assigned to this climate sensitivity factor).

Transient model simulations exhibit less immediate warming than equilibrium simulations because of the high heat holding capacity of the thermally massive oceans. However, that “unrealized warming” eventually expresses itself decades to centuries later. This thermal delay, which can lull us into underestimating the long-term amount of climate change, is now being accounted for by coupling models of the atmosphere to models of the oceans, ice, soils, and biosphere (so-called earth system models - ESMs). Early generations of such transient calculations with ESMs give much better agreement with observed climate changes on Earth than previous calculations in which equilibrium responses to CO<sub>2</sub> doubling were the prime simulations available. When the transient models at the Hadley Center in the United Kingdom and the Max Planck Institute in Hamburg, Germany were also driven by both greenhouse gases and sulfate aerosols, these time evolving simulations yielded much more realistic “fingerprints” of human effects on climate (e.g., Chapter 8 of IPCC, 1996a). More such computer simulations are needed to provide higher confidence levels in the models, but scientists using coupled, transient simulations are now beginning to express growing confidence that current projections are plausible.

**Transients and Surprises.** However, such a very complicated coupled system like an ESM is likely to have unanticipated results when forced to change very rapidly by external disturbances like CO<sub>2</sub> and aerosols. Indeed, some of the transient models run out for hundreds of years exhibit dramatic change to the basic climate state (e.g., radical change in global ocean currents). Thompson and Schneider (1982) used very simplified transient models to investigate the question of whether the time evolving patterns of climate change might depend on the rate at which CO<sub>2</sub> concentrations increased. For slowly increasing CO<sub>2</sub> buildup scenarios, the model predicted the standard model outcome: the temperature at the poles warmed more than the tropics.

Any changes in equator-to-pole temperature difference help to create altered regional climates, since temperature differences influence large-scale atmospheric wind patterns and ocean currents. However, for very rapid increases in CO<sub>2</sub> concentrations a reversal of the

equator-to-pole difference occurred in the Southern Hemisphere. If sustained over time, this would imply difficult to forecast, transient climatic conditions during the century or so the climate adjusts toward its new equilibrium state. In other words, the harder and faster the enormously complex earth system is forced to change, the higher the likelihood for unanticipated responses. Or, in a phrase, the faster and harder we push on nature, the greater the chances for surprises - some of which are likely to be nasty.

Noting this possibility, the Summary for Policymakers of IPCC Working Group I concluded with the following paragraph:

Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature, difficult to predict. This implies that future climate changes may also involve "surprises." In particular these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behavior. Progress can be made by investigating non-linear processes and sub-components of the climatic system. Examples of such non-linear behavior include rapid circulation changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes.

Of course, if the Earth system were somehow less "rapidly forced" by virtue of policies designed to slow down the rate at which human activities modify the land surfaces and atmospheric composition, this would lower the likelihood of non-linear surprises. Whether the risks of such surprises justify investments in abatement activities is the question that Integrated Assessment (IA) activities are designed to inform (IPCC, 1996c). The characterization of various climatic changes, along with estimates of the probabilities of such potential changes, are the kinds of information IA modelers need from earth systems scientists in order to perform IA simulations. We turn next, therefore, to a discussion of methods to evaluate the subjective probability distributions of scientists on one important climate change issue, the climate sensitivity.

**Subjective Probability Estimation.** Finally, what does define a scientific consensus? Morgan and Keith (1995) and Nordhaus (1994) are two attempts by non-climate modelers, who are interested in the policy implications of climate science, to tap the knowledgeable opinions of what they believe to be representative groups of scientists from physical, biological and social sciences on two separate questions: first, the climate science itself and second, impact assessment and policy. Their sample surveys show that although there is a wide divergence of opinion, nearly all responsible scientists assign some probability of negligible outcomes and some probability of very highly serious outcomes, with one or two exceptions, like Richard Lindzen at MIT (who is scientist number 5 on Fig. 1 of Morgan and Keith).

**Table 1: Experts interviewed in the study. Expert numbers used in reporting results are randomised. They do not correspond with either alphabetical order, or the order in which the interviews were performed.**

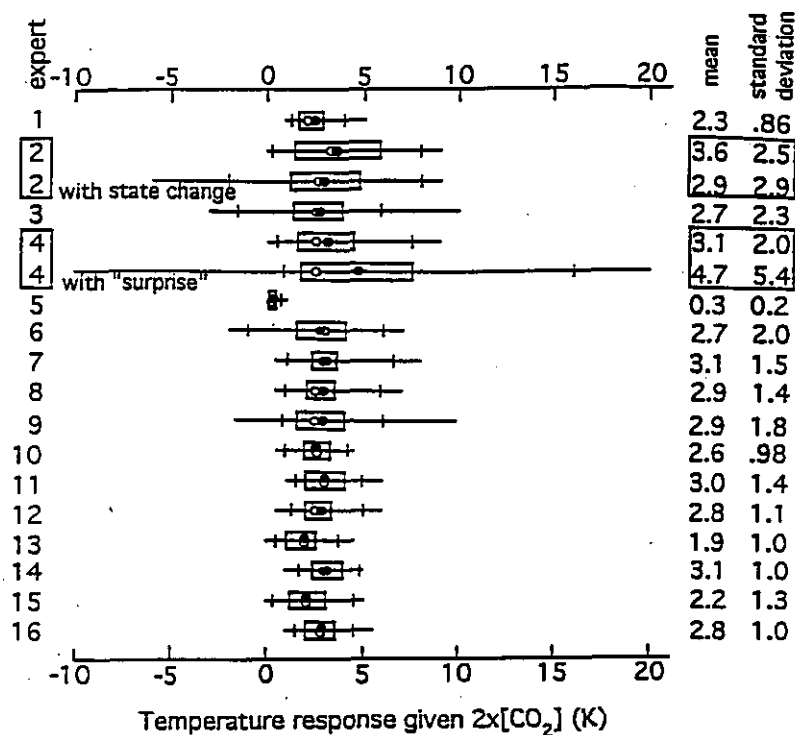
James Anderson, Harvard University	Michael MacCracken, US Global Change Research Programme
Robert Cess, State University of New York at Stony Brook	Ronald Prinn, Massachusetts Institute of Technology
Robert Dickinson, University of Arizona	Stephen Schneider, Stanford University
Lawrence Gates, Lawrence Livermore National Laboratories	Peter Stone, Massachusetts Institute of Technology

William Holland, National Center for Atmospheric Research	Starlet Thompson, National Center for Atmospheric Research
Thomas Karl, National Climatic Data Center	Warren Washington, National Center for Atmospheric Research
Richard Lindzen, Massachusetts Institute of Technology	Tom Wigley, University Center for Atmospheric Research/National Center for Atmospheric Research
Syukuro Manabe, Geophysical Fluid Dynamics laboratory	Carl Wunsch, Massachusetts Institute of Technology

In the Morgan and Keith study, each of the 16 scientists listed in Table 1 were put through a several hour, formal decision-analytic elicitation of their subjective probability estimates for a number of factors. Figure 1 shows the elicitation results for the important climate sensitivity factor. Note that 15 out of 16 scientists surveyed (including several IPCC Working Group I Lead Authors) assigned something like a 10% subjective likelihood of small (less than 1°C) climatic change from doubling of CO<sub>2</sub>. Most of these scientists also assigned a 10% or so probability for extremely large climatic changes--greater than 5°C, roughly equivalent to the temperature difference experienced between a glacial and interglacial age, but occurring some hundred times more rapidly. In addition to the lower probabilities assigned to the mild and catastrophic outcomes, the bulk of the scientists interviewed (with the one exception) assigned the bulk of their subjective cumulative probability distributions in the center of the IPCC range for climate sensitivity. What is most striking about the exception, scientist 5, is the lack of variance in his estimates--suggesting a very high confidence level in this scientist's mind that he understands how all the complex interactions within the earth-system described above will work. None of the other scientists displayed that confidence, nor did the Lead Authors of IPCC. However, several scientists interviewed by Morgan and Keith expressed concern for "surprise" scenarios--for example, scientists 2 and 4 explicitly display this possibility on Figure 1, whereas several other scientists (myself included-I am scientist #9 in Fig. 1) allow for both positive and negative surprises since they assigned a considerable amount of their cumulative subjective probabilities for climate sensitivity outside of the standard 1.5 to 4.5 range. This concern for surprises is consistent with the concluding paragraph of the IPCC Working Group I Summary for Policymakers, quoted above.

Climatic change estimates are not the only variables that can be studied by subjective probability estimates of experts. Similarly, in the estimation of climate damages as a result of projected climatic changes, formal decision-analytic interviews have been conducted. Economist William Nordhaus surveyed the opinions of mainstream economists, environmental economists and natural scientists (e.g. I am respondent #10, in Nordhaus, 1994), finding that the former expressed a factor of twenty less anxiety about the economic or environmental consequences of climate change than the latter. However, the bulk of even the conservative group of economists considered there to be at least a ten percent probability that typically projected climate changes could still cause economic damages worth several percent of gross world product (the current US GNP is around six trillion dollars -- about twenty percent of the global figure). And, some of these economists didn't include estimates for possible costs of "non-market" damages (e.g., harm to nature). One ecologist who did explicitly factor in non-market values for natural systems went so far as to assign a ten percent chance of a hundred percent loss of GNP -- the virtual end of civilization! While Nordhaus asserted that those who know most about the economy are less concerned, I countered with the obvious observation that those who know the most about nature are very concerned.





**Figure 1:** Box plots of elicited probability distributions of climate sensitivity, the change in globally averaged surface temperature for a  $2x[CO_2]$  forcing. Horizontal line denotes range from minimum assessed possible values. Vertical tick marks indicate locations of lower 5 and upper 95 percentiles. Box indicates interval spanned by 50% confidence interval. Solid dot is the mean and open dot is the median. The two columns of numbers on right hand side of the figure report values of mean and standard deviation of the distributions.

We will not easily resolve the paradigm gulf between the optimistic and pessimistic views of these specialists with different training, traditions and world views, but the one thing that is clear from both the Morgan and Keith and Nordhaus studies is that the vast bulk of knowledgeable experts from a variety of fields admit to a wide range of plausible outcomes in the area of global environmental change -- including both mild and catastrophic eventualities -- under their broad umbrella of possibilities. This is a condition ripe for misinterpretation by those who are unfamiliar with the wide range of subjective probabilities most scientists attach to global change issues. The wide range of probabilities follows from recognition of the many uncertainties in data and assumptions still inherent in earth systems models, climatic impact models, economic models or their synthesis via integrated assessment models. It is necessary in a highly interdisciplinary enterprise like the integrated assessment of global change problems that a wide range of possible outcomes be included, along with a representative sample of the subjective probabilities that knowledgeable assessment groups like the IPCC believe accompany each of those possible outcomes.

IPCC Lead Authors who wrote the Working Group I Second Assessment Report were fully aware of both the wide range of possible outcomes and the broad distributions of attendant subjective probabilities. After a number of sentences highlighting such uncertainties, the Report concluded: "nevertheless, the balance of evidence suggests that there is a discernible human influence on the climate." The reasons for this now-famous

subjective judgment were many, such as the kinds of factors listed above. These include a well-validated theoretical case for the greenhouse effect, validation tests of both model parameterizations and performance against present and paleoclimatic data, and the growing "fingerprint" evidence that suggests horizontal and vertical patterns, of climate change predicted to occur in coupled atmosphere-ocean models, have been increasingly evident in observations over the past several decades. Clearly, more research is needed, but enough is already known to warrant assessments of the impacts of such projected climatic changes and the relative merits of alternative actions to both mitigate emissions and/or make adaptations less costly. That is the ongoing task of integrated assessment analysts, a task that will become increasingly critical in the next century. To accomplish this task, it is important to recognize what is well established in climate theory and modelling and to separate this from aspects that are more speculative. That is precisely what IPCC (1996a) has attempted to accomplish.

**Summary of Conclusions.** A condensed summary, of the principal conclusions I would like to draw to the attention of integrated assessment modelers interested in using climatic model results, is as follows:

*Hierarchy of models.* A hierarchy of models, ranging from simple zero or one-dimensional, highly parameterized models up to coupled three-dimensional models that simulate the dynamics and thermodynamics of connected physical and biological sub-systems of the earth-system are needed for climatic effects assessment. The simpler models are more transparent - allowing cause-and-effect processes to be more easily traced - and are much more tractable to construct, run and diagnose. Multi-dimensional, dynamical models can provide geographic and temporal resolution needed for regional impact assessments and-hopefully-provide more realistic and detailed simulations, even if at much higher costs for construction, computation, diagnosis and interpretability. Downscaling techniques to connect the results of global models to regional impact studies also need further development. Since the real climate system is undergoing a transient response to regionally heterogeneous forcings (e.g., aerosols and greenhouse gasses combined which both vary over time and space), eventually it will be necessary to run fully-coupled three-dimensional earth systems' models in order to "hand off" their results to a variety of impact assessment models. In the interim, lower resolution "simple" climate models (analogous to "reduced form" models in economics) can be hybridized along with more comprehensive models to produce hybrid estimates of time-evolving regional patterns of climatic changes from a variety of emissions and land use change scenarios. Such estimates, while tentative, may be instructive to policy makers interested in the differential climatic impacts of various climate forcing scenarios and/or various assumptions about the internal dynamics of both climate and impact models.

*Sensitivity studies are essential.* It is unlikely that all important uncertainties in either climatic or impact models will be resolved to the satisfaction of the bulk of the scientific community in the near future. However, this does not imply that model results are uninformative. On the contrary, sensitivity analyses in which various policy-driven radiative forcing assumptions are made can offer insights into the potential effectiveness of such policies in terms of their differential climatic effects and impacts. Even though high absolute accuracy is not likely to be attainable for the foreseeable future, considerable precision concerning the sensitivity of the physical and biological sub-systems of the earth can be studied via carefully planned and executed sensitivity studies across a hierarchy of models. In essence, sensitivity studies allow us to evaluate quantitatively the logical consequences of alternative process or policy assumptions.

*Validation and testing are required.* Although it may be impractical, if not theoretically impossible, to validate the detailed future course of climate given the

uncertainties that remain in forcings, internal dynamics and unpredictable surprise events, many of the basic features of the coupled physical and biological sub-systems of the earth can already be realistically simulated to a considerable degree. Testing models against each other when driven by the same sets of forcing scenarios, testing the overall simulation skill of models against empirical observations; testing model parameterizations against high resolution process models or data sets, testing models against proxy data of paleo-climatic changes and testing the sensitivity of models to radiative forcings of anthropogenic origin by computing their sensitivity to natural radiative forcings (e.g., seasonal radiative forcing, volcanic dust forcing, orbital element variation forcings etc.), comprise a necessary set of validation-oriented exercises that all modelers should agree to perform. Similarly, IAMs should also be subjected to an analogous set of validation protocols if their insights are to gain a high degree of credibility (e.g., impact of historical droughts on crop yields and food prices, or impacts of trade embargoes on energy prices and technical efficiency).

*Subjective probability assessment.* In addition to standard simulation modeling exercises in which various parameters are specified or varied over an uncertainty range, formal decision-analytic techniques can be used to provide a more consistent set of values for uncertain model parameters or functional relationships. The embedding of subjective probability distributions into climatic models is just beginning (e.g., Titus and Narayanan, 1996), but may become an important element of integrated assessment modeling in future generations of model building (e.g., see the discussion of the hierarchy of integrated assessment models in Schneider, 1997b). In particular, the search for synergisms and surprises in global change issues that is so critical to the policymaking process could be explored by subjective probability analysis.

*"Rolling reassessment".* It is obvious that the projection of climatic effects and related impacts will continue to change as the state-of-the-art in both kinds of models improves over the next few decades. Therefore, flexible management of a global commons like the Earth's climate seems a necessity, since the potential seriousness of the problem-or even the perception of that seriousness-is virtually certain to change with new discoveries and climatic and other environmental events. Therefore, an ongoing series of assessments of climatic effects, related impacts, and policy options to prevent potentially dangerous impacts will be needed periodically-perhaps every five years as IPCC has chosen for the repeat period of its major Assessment Reports that treat climatic effects, impacts and policy issues. It seems important that whatever policy instruments are employed (to either mitigate anthropogenic forcings or help reduce damage from projected climatic effects) be flexible enough to respond quickly and cost-effectively to the evolving science that will emerge from this rolling reassessment process.

## References

- Hoffert, M.I. and Covey, C. (1992). "Deriving global climate sensitivity from paleoclimate reconstructions," *Nature* 360, 573-76.
- Intergovernmental Panel on Climatic Change (IPCC), (1996a). *Climate Change 1995. The Science of Climate Change: Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., and Maskell, K., eds. Cambridge: Cambridge University Press. 572 pp.
- Intergovernmental Panel on Climatic Change (IPCC), (1996b). *Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Watson, R.T., Zinyowera, M.C., and Moss, R.H., eds. Cambridge: Cambridge University Press. 878 pp.
- Intergovernmental Panel on Climatic Change (IPCC), (1996c). *Climate Change 1995. Economic and Social Dimensions of Climate Change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Bruce, J.P., Lee, H., and Haites, E.F., eds. Cambridge: Cambridge University Press.
- Intergovernmental Panel on Climatic Change (IPCC), (1997). *Report of the Workshop on Regional Climate Change Projections for Impact Assessment*, London, UK, 24-26 September 1996, IPCC Working Group I Technical Support Unit, Hadley Centre, Bracknell, Berks. UK (in preparation).
- Morgan, M.G. and Keith, D.W. (1995). "Subjective judgments by climate experts," *Environmental Science and Technology* 29, 468A-476A.
- Nordhaus, W.D. (Jan-Feb 1994). "Expert opinion on climate change," *American Scientist* 45-51.
- Root, T. L. and Schneider, S. H. (1995). "Ecology and climate: Research strategies and implications," *Science* 269: 331-341.
- Schneider, S.H. and Londer, R. (1984). *The Coevolution of Climate and Life*. Sierra Club Books, San Francisco, CA.
- Schneider, S.H. (1997a). *Laboratory Earth. The Planetary Gamble We Can't Afford to Lose*. Basic Books, New York, NY.
- Schneider, S.H. (1997b). "Integrated assessment modelling of global climate change: Transparent rational tool for policy making or opaque screen hiding value-laden assumptions?" *Environmental Modelling and Assessment* (submitted).
- Thompson, S. L. and Schneider, S. H. (1982). "CO<sub>2</sub> and Climate: The importance of realistic geography in estimating the transient response," *Science* 217, 1031-1033.
- Titus, J. and Narayanan, V. (1996). "The risk of sea level rise: A Delphic Monte Carlo analysis in which twenty researchers specify subjective probability distributions for model coefficients within their respective areas of expertise," *Climatic Change* 33 (2), 151-212.