# Complexities in the Climate System and Uncertainties in Forecasts

Ronald G. Prinn

*Department of Earth Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, Massachusetts*

The global atmosphere is a chemically complex and dynamic system, interacting both internally, mostly within the troposphere and stratosphere, and with the oceans, land, and living organisms. Its composition is changing today, and has also changed markedly over the last 400,000 yr. Current understanding of this complex system resulting from recent observations, theory, and laboratory and modeling studies is reviewed. Also, results are presented from the Integrated Global System Model (IGSM). This is a coupled model of economic development, atmospheric chemistry, climate dynamics and ecosystem processes that explores possible future changes in atmospheric composition and climate. The results of an uncertainty analysis involving hundreds of runs of the IGSM imply that, without specific mitigation policies, the global average surface temperature may rise between 1.0 and 4.9°C from 1990 to 2100 (95% confidence limits). Polar temperatures, absent policy, are projected to rise from about 1 to 12°C (95% limits) with obvious great risks for high latitude ecosystems and ice sheets at the high end of this range. Analysis of the Kyoto Protocol, and a more stringent climate mitigation policy, shows the difficulties in accounting simply for the effects of other greenhouse gases relative to carbon dioxide. Also, the greatest effect of these policies is to lower the probability of extreme changes as opposed to lowering the medians.

## 1. INTRODUCTION

Global climate change is the subject of policy debate within most nations, and of negotiations within the Conference of Parties (COP) to the Framework Convention on Climate Change (FCCC). Climate is usefully defined as the average of the weather we experience over a ten-or twenty-year time period. Long-term temperature and rainfall changes are typical measures of climate change, and these changes can be expressed at the local, regional, country, or global scale.

Fundamentally, global warming or cooling can be driven by any imbalance between the energy the Earth receives, largely as visible light, from the sun, and the energy it radiates back to space as invisible infrared radiation. The greenhouse effect is a warming influence caused by the presence in the air of gases and clouds, which are very efficient absorbers and radiators of this infrared. The greenhouse effect is opposed by substances at the surface (such as snow and desert sand) and in the atmosphere (such as clouds and white aerosols) that efficiently reflect sunlight back into space, and thus act as a cooling influence.

Easily the most important greenhouse gas is water vapor, which typically remains for a week or so in the atmosphere. Water vapor and clouds are handled internally in climate models, although with considerable uncertainty. Concerns about global warming, however, revolve around somewhat less important but much longer-lived greenhouse gases, especially carbon dioxide. The concentrations of carbon dioxide and

The State of the Planet: Frontiers and Challenges in Geophysics
Geophysical Monograph 150, IUGG Volume 19

10.1029/150GM23

some other long-lived gases (methane, nitrous oxide, chlorofluorocarbons, perfluorocarbons, hydrochlorofluorocarbons, sulfur hexafluoride) have increased substantially over the past two centuries due wholly or at least in part to human activity. When the concentration of a greenhouse gas increases (with no other changes occurring), it temporarily lowers the flow of infrared energy to space and increases the flow of infrared energy down toward the surface. The Earth then temporarily receives more energy—for example, 1 percent—than it radiates to space (1 percent is about the radiative energy imbalance caused by the rise of long-lived greenhouse gases from preindustrial to present times). This small imbalance, which is often called "radiative forcing", tends to raise temperatures at the surface and in the lower atmosphere. The rate of surface temperature rise is slowed significantly by uptake of heat by the world's oceans. The greenhouse effect as quantified by radiative forcing is real and the physics relatively well understood. What is more uncertain, and the cause of much scientific debate, is the magnitude of the warming response of the complex system that determines our climate to radiative forcing. Feedbacks in the system can either amplify or dampen the response in ways that are not fully understood at present (*IPCC*, 2001a, b, c).

There are also complex connections between air pollution, land-use change and climate change that must be taken into consideration [*Prinn*, 1994]. Environmentally-significant chemical processes occurring in the atmosphere include those affecting urban air pollution, the ozone layer and the levels of radiatively active gases and particles. Carbon dioxide levels are governed by a complex set of natural and human activities at the land surface and in the oceans. Methane, another important greenhouse gas, has major natural and anthropogenic sources; it is destroyed largely by reaction with the hydroxyl radical in the troposphere. Both its sources and sinks are strongly influenced by human activity through agriculture and air pollution. Nitrous oxide, with a similar range of sources, and chlorofluorocarbons with purely anthropogenic sources, are also greenhouse gases; however, their potency is offset partially by the ozone they destroy. Ozone, a key chemical and protective ultraviolet shield, has a complex chemistry influenced by many other trace species and is also an important greenhouse gas. Many other trace gases play a key role in air pollution and climate through their influence on the concentrations of ozone, the hydroxyl radical, and methane. Gaseous sulfur compounds, both natural and anthropogenic, are oxidized to particulate sulfates that have an important effect on albedo, counteracting the influence of the greenhouse gases. Naturally and anthropogenically produced organic compounds contribute to the ozone and hydroxyl radical budgets as well as producing carbon-rich aerosols that can absorb and/or reflect sunlight. All these various aerosols can also indirectly change the reflection properties and lifetimes of clouds. Atmospheric chemistry is therefore closely linked to human activity, climate, and land use through numerous interactive environmental processes.

Clearly, integrating and understanding the diverse human and natural components of the problem is a must when informing policy development and implementation. As a result, climate research should focus on predictions of key variables such as rainfall, ecosystem productivity, and sea level that can be linked to estimates of economic, social, and environmental effects of possible climate change. Projections of emissions of greenhouse gases and atmospheric aerosol precursors should be related to the economic, technological, and political forces at play, and to the expected results of international agreements. In addition, such assessments of possible societal and ecosystem impacts, and analyses of mitigation strategies, should be based on realistic representations of the uncertainties of climate science. At MIT, we have developed an Integrated Global System Model (IGSM) to address some of these issues and to help inform the policy process.

## 2. INTEGRATED GLOBAL SYSTEM MODEL

The IGSM consists of a set of coupled sub-models of economic development and associated emissions, natural biogeochemical cycles, climate, air pollution, and natural ecosystems [*Prinn et al.*, 1999; *MIT*, 2004]. It is specifically designed to address key questions in the natural and social sciences that are amenable to quantitative analysis and are relevant to climate change policy. For example, how do the uncertainties in key component models, like those for ocean circulation and atmospheric convection, affect predictions? Are feedbacks between component models, such as climate-induced changes in oceanic and terrestrial uptake of carbon dioxide, atmospheric chemistry, and terrestrial emissions of methane, important? To answer such questions, and allow examination of a wide variety of proposed policies, the global system model must address not only the major human and natural processes involved in climate change [*Schneider*, 1992; *Prinn*, 1994; *IPCC*, 2001a, b, c], but it must also be computationally feasible for use in multiple 100-year predictions. The IGSM attempts to meet these challenging criteria.

Priorities must be set as to what is and what is not important in the model to ensure computational feasibility. Although we could have simply coupled together the most comprehensive existing versions of component models, the result would have been computationally so demanding that the many runs required to understand inter-model feedbacks, address a wide range of policy measures, and study uncertainty would not have been feasible with current computers. Thus a major challenge in developing our global system model involved deter-

mining what processes required inclusion in detail, and what processes could be omitted or simplified. The current structure of the IGSM is shown in Figure 1.

Human activity leads to emissions of chemically and radiatively important trace gases. The Emissions Prediction and Policy Analysis (EPPA) model incorporates the major relevant demographic, economic, world trade, and technical forces involved in this process at the national and international levels. Natural emissions of trace gases must also be predicted, and for this purpose the natural emissions model takes account of changes in both climate and ecosystem states in wetlands and soils around the world.

The coupled atmospheric chemistry and climate model is driven by a combination of anthropogenic and natural emissions. The essential components of this model are chemistry, atmospheric circulation, and ocean circulation, and each of these components by itself can require very large computer resources. The atmospheric chemistry component is modeled in sufficient detail to capture its sensitivity to climate and different mixes of emissions, and to address the effects on climate of policies proposed for control of air pollution, and vice-versa [*Wang et al.*, 1998; *Mayer et al.*, 2000]. For the atmosphere and ocean components, however, a computer has yet to exist that can adequately resolve the important small-scale eddies on a global scale for thousands of century-long integrations. Thus, simplified treatments of these circulations are included in the version of the model used for the Monte Carlo uncertainty and multiple policy applications discussed here [*Sokolov and Stone*, 1998; *Sokolov et al.*, 2003]. Linking these complex models together leads to many challenges, well illustrated by the failure of essentially all existing coupled ocean-atmosphere models (including ours) to simulate current climate over the globe very accurately without arbitrary adjustments to the air-to-sea fluxes of heat, water and (sometimes) momentum. Depending on the model, these non-physical adjustments range from relatively small values to significant fractions of the annual mean fluxes, and indicate deficiencies in the model formulations of air-sea interactions [*IPCC*, 2001a].

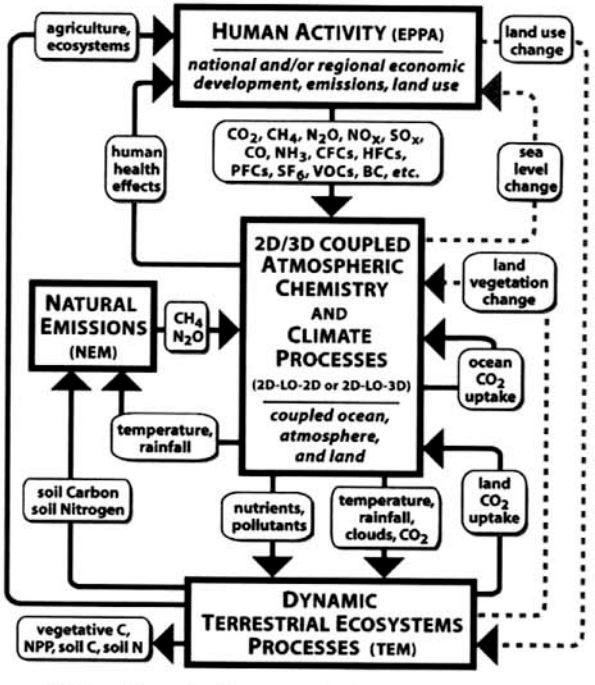


**Figure 1.** The schematic illustrates the framework and processes of the MIT Integrated Global System Model. Feedbacks between the component models that are currently included, or proposed for inclusion in the next generation, are shown as solid and dashed lines, respectively (adapted from *Prinn et al.*, 1999; MIT, 2004).

Urban air pollution has an impact on global chemistry, and thus on climate. Air pollution is a problem in a steadily growing number of giant cities worldwide. The emissions of chemicals important in air pollution and climate are often highly correlated due to shared generating processes like combustion, which produces $CO_2$, CO, $NO_x$, black carbon (BC) aerosols, and $SO_x$ (which forms white sulfate aerosols). Also the atmospheric lifecycles of air pollutants such as CO, $NO_x$ and volatile organic compounds (VOCs), and some climatically important species (e.g. $CH_4$, sulfate aerosols), both involve the fast photochemistry of the hydroxyl free radical (OH). Indeed, OH removes about 3.7 Pg per year of reactive trace gases from the atmosphere, which is similar to the total mass of carbon removed annually from the atmosphere by the land and ocean [*Ehhalt*, 1999; *Prinn*, 2003]. There is evidence, based on global measurements of the industrial gas methyl chloroform ($CH_3CCl_3$) which reacts with hydroxyl, that OH levels in the atmosphere are changing, perhaps due to the joint effects of air pollution and climate change [*Prinn et al.*, 2001]. The interconnection of pollution and climate hinders effective policy and decision making. To help unravel the interactions, an urban-scale air chemistry module was added to the IGSM to simulate the chemical reactions occurring in large cities, which are ignored in all other integrated assessment models. In a study of these phenomena [*Mayer et al.*, 2000], the inclusion of urban air chemistry processes led to lower global tropospheric $NO_x$, ozone, and OH concentrations, and hence to more methane than in forecasts that neglect urban processing. The resulting changes, interestingly, have limited impact on the global mean surface temperature because ozone decreases partially offset the methane increases. However, this advance in the IGSM framework enables the simultaneous consideration of control policies applied to local air pollution and global climate. It also provides the capability to assess the effects of air pollution on ecosystems, and to predict levels of irri-

tants important to human health, such as ozone, in the growing number of megacities around the world.

The coupled chemistry/climate model outputs then drive a Terrestrial Ecosystems Model [TEM; *Xiao et al.*, 1998], which is capable of predicting vegetation properties including the difference between carbon uptake by plant photosynthesis and carbon loss by plant respiration (net primary production or NPP), land-atmosphere carbon dioxide ($CO_2$) fluxes, and soil composition. TEM outputs then feed back to the climate model, chemistry model, and Natural Emissions Model (NEM). Finally, NEM, which predicts wetland and soil emissions of methane ($CH_4$) and nitrous oxide ($N_2O$), is driven jointly by outputs from the TEM and climate models, and in turn provides inputs to both the atmospheric chemistry and climate models. Not included in the present IGSM, but planned for future versions, are the effects of anthropogenic changes in land cover on ecosystems, hence climate, and the effects of changes in climate and ecosystems on agriculture, hence anthropogenic emissions.

Our IGSM has several capabilities not currently present or simplified in other integrated models of the global climate system. The prediction of global anthropogenic emissions is based on a regionally disaggregated model of global economic growth. This allows for treatment of a shifting geographical distribution of emissions over time and changing mixes of emissions, both of which affect atmospheric chemistry. Also, our model of natural emissions is coupled to climate and land ecosystems models, which provide the needed explicit predictions of temperature, rainfall, and soil organic carbon concentrations.

To attain the necessary computational efficiency, while retaining plausible treatments of key climate processes, we use a longitudinally averaged statistical-dynamical climate model that is two-dimensional (2D) but that also resolves the land and ocean (LO) at each latitude (and so is referred to as the 2D-LO model). It includes a simplified ocean model, which is coupled to the atmosphere with representations of horizontal heat transport in the uppermost ("mixed") layer and heat exchange between the mixed layer and deep ocean [*Sokolov and Stone*, 1998]. It is capable of reproducing many characteristics of the current zonally-averaged climate, and its behavior and predictions are similar to those of coupled atmosphere-ocean three-dimensional general circulation models (GCMs), including the NASA Goddard Institute for Space Studies (GISS) GCM from which it is derived. Specifically, through appropriate choices of the oceanic vertical diffusivity and climate sensitivity in the 2D-LO model, this model can closely mimic the global mean temperature and sea level changes in transient forced runs of 11 GCMs investigated [*Sokolov and Stone*, 1998; *Forest et al.*, 2001; *Sokolov et al.*, 2003]. Climate sensitivity, which is the temperature difference between equilibrium runs of the model with reference and double-reference levels of $CO_2$, is altered by changing the model cloud parameterization. The 2D-LO model is about 20 times faster than the GISS GCM with similar latitudinal and vertical resolution.

By choosing this climate model, we are able to incorporate detailed atmospheric and oceanic chemistry interactively with climate in sufficient detail to allow study of key scientific and policy issues. However, to better address ocean circulation, the latest version of the IGSM includes a low-resolution three-dimensional (3D) ocean model that can simulate changes in the rate of the deep (thermohaline) oceanic circulation; changes that go untreated in the previous 2D-LO model [*Kamenkovich et al.*, 2002]. In common with several other 3D ocean models (*IPCC*, 2001a), this model shows a slowing down of the thermohaline circulation with rising carbon dioxide levels and is computationally efficient enough to be used in future sensitivity and uncertainty studies with the IGSM [*Kamenkovich et al.*, 2003]. All else being equal, the uptake of heat and carbon by the 3D model should evolve to be less than the 2D model, with higher predicted temperatures, particularly beyond the year 2100.

Fundamental ecosystem biogeochemical processes in 18 globally distributed terrestrial ecosystems are included in the ecosystem model. This model, with its significant biogeochemical and spatial detail, also enables us to study how changes in climate and atmospheric composition affect ecosystems, and the relationships between ecosystems and chemistry, climate, natural emissions [*Xiao et al.*, 1998], and (in the latest version) agriculture. The accuracy of this, and similar models, depends on how adequately they treat key processes, such as the response of vegetation to rising carbon dioxide levels ($CO_2$ fertilization effect).

In summary, the above judicious choices and compromises have enabled detailed process-resolving models for the relevant phenomena to be coupled in a computationally efficient form. With this computational efficiency comes the capability to perform uncertainty analyses using large ensembles of model runs, to identify and understand important feedbacks between model components, and to compute sensitivities of policy-relevant variables (*e.g.*, rainfall, temperature, ecosystem state) to assumptions in the various sub-components in the coupled models. Sensitivity analysis then enables our assessment of strengths, weaknesses, and means of improvements for future versions of the global system model.

At the same time, I must caution the reader to keep in mind that the various components of the IGSM do contain simplifications when interpreting its climate projections. The climate system contains a number of nonlinearities, feedbacks and critical thresholds that are not present in the IGSM, or most other models [*Rial et al.*, 2004]. In addition to the issues

regarding the ocean noted above, the IGSM does not include irreversible conversions of ecosystems and the related releases of greenhouse gases, or the dynamics of the Greenland and Antarctic ice sheets (although it does include the melting of mountain glaciers). These omissions, however, are not expected to be important until after the year 2100.

In the following sections, I will review the application of the IGSM to the science of two policy-relevant issues. Alternative approaches to all these issues exist as reviewed in *IPCC* [2001a,b,c]. These alternative approaches involve the use of scenarios rather than specific economic model outputs to project emissions, and informal expert elicitation rather than large ensemble (Monte Carlo) model runs to estimate warming during the next 100 years. But the IGSM is arguably unique in its combination of scientific and economic detail, climate-atmospheric chemistry-ecosystem feedbacks, and computational efficiency.

## 3. UNCERTAINTY ANALYSIS

To help decision-makers evaluate how policies might reduce the risk of climate impacts, quantitative assessments of uncertainty in climate projections are very useful. *Webster et al.* [2002, 2003] use several hundreds of runs of the IGSM together with quantitative uncertainty techniques to achieve this assessment. Absent mitigation policies, the median projection in this study shows a global average surface temperature rise from 1990 to 2100 of 2.4°C, with a 95% confidence interval of 1.0°C to 4.9°C (*Webster et al.*, 2003). For comparison, the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reports a range for the global mean surface temperature rise by 2100 of 1.4 to 5.8°C (IPCC, 2001a). Unfortunately, the IPCC does not provide likelihood estimates for this key finding although it does for others. This omission by the IPCC has been criticized by *Reilly et al.* [2001] and defended by *Allen et al.* [2001].

The IGSM physical climate model is flexible, which enables it to reproduce quite well the global behavior of coupled atmosphere-ocean general circulation models (AOGCMs) [*Sokolov & Stone*, 1998; *Sokolov et al.*, 2003]. This flexibility allows for analysis of the effect of some of the structural uncertainties present in existing AOGCMs (*Forest et al.*, 2001, 2002). The Webster *et al.* [2003] study includes uncertainties in natural and anthropogenic emissions of all climatically important gases and aerosols [*Prinn et al.*, 1999; *Reilly et al.*, 1999, *Webster et al.*, 2002], in critical atmospheric and oceanic interactions, and in carbon-cycle feedbacks in land ecosystems and the ocean. Their estimates of key climate model uncertainties (oceans, clouds or equivalently climate sensitivity, aerosols) are constrained by observations of the climate system for the period 1906-1995 [*Forest et al.*, 2002]. Also, uncertainty in emissions reflect errors in measurement of current emissions, and include expert judgment about variables that influence key economic projections [*Webster et al.*, 2002].

The probability distribution functions (pdfs) for the mean global surface temperature and sea level increases between 1990 and 2100 are shown in Figure 2 for two hypothetical cases: no explicit climate policy, and a stringent policy which is the same as that adopted by *Reilly et al.* [1999]. The stringent policy assumes that the Kyoto Protocol is implemented in 2010 by all the (largely developed) countries that were included in the original 1997 Protocol (the so-called Annex-B countries), including the U.S., which has not subsequently ratified the Protocol. For these Annex B countries, the stringent policy then assumes that they lower their emissions by 5% every 15 years after 2010 so that by 2100 their emissions are 35% below their 1990 levels. For the (largely developing) non-Annex B countries, including China and India, the stringent policy assumes that they lower their emissions in 2025 to 5% below their (unconstrained) 2010 levels. They then continue to lower their emissions by 5% every 15 years so that they are 30% below their 2010 levels in 2100. This stringent policy keeps $CO_2$ levels in the year 2100 in the median case to be just below 550 ppm (which is about twice the preindustrial $CO_2$ level).

The peak in the pdf denotes the most probable amount (i.e. mode) of warming or sea level rise. The total area under each pdf is (by definition) unity. The percentage probability of an increase in temperature or sea level being greater or less than

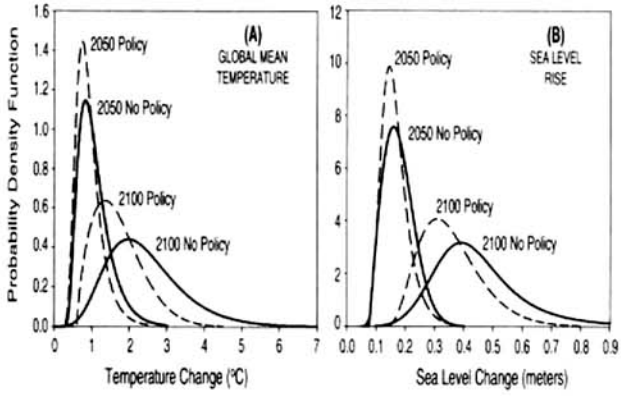


**Figure 2.** Probability density function (pdf) for the change in global-mean: (A) surface temperature, and (B) sea level rise, from 1990 to 2050 or 2100, estimated as a best-fit to 250 simulations using Latin Hypercube sampling from input pdfs for uncertain variables. The solid lines show the pdfs resulting from no explicit emissions restrictions, and the dashed lines are the pdfs under hypothetical emissions policy leading to steady levels of atmospheric $CO_2$ of about twice preindustrial values (adapted from *Webster et al.*, 2003). The *IPCC* (2001, a, b, c) upper estimate of 5.8°C is well beyond the 95% confidence limit. The usefulness of the IPCC estimates is weakened by their omission of confidence limits on their results.

any particular value is given by 100 times the area to the right or left of the value respectively. For example, there is a 2.5% probability (i.e. 1 chance in 40) that the temperature rise from 1990 to 2100 will be greater than 4.9°C or less than 1.0°C (i.e. 95% range) in the no-policy case. When compared to the no-policy case, the stringent policy case has a median of only 1.6°C and 95% range of only 0.8 to 3.2°C. There is a 1 in 2 chance of warming exceeding 2.4°C in the no-policy case and only 1 in 7 chance in the stringent policy case. The policy obviously lowers the probability of large amounts of warming by very significant factors.

Of some interest is the fact that the pdfs for the policy and no-policy cases are not very different in 2050 and only become distinct in 2100. This is caused first by the fact that the world is already committed to significant future warming even at present greenhouse gas levels (due to the delay in warming associated with heat uptake by the ocean), and second because the policy case has its greatest reductions in emissions relative to the no-policy case only after 2050. Because the mitigating effects of the policy only appear very distinctly in the pdf after 50 years, this implies that there is significant risk in waiting for very large warming to occur before taking action.

To better appreciate the risks in the no-policy case, it is also important to examine the latitudinal distribution of the projected warming. In common with other climate models, the computed temperature increases in polar regions are much greater than those in equatorial regions (see Figure 3 for the no-policy case). Polar regions contain vulnerable ecosystems (permafrost, tundra) with large carbon storage, and the Greenland and Antarctic ice sheets with large water storage. Release of some of this stored carbon and water is clearly of concern. The 1 chance in 40 of warming of 8 to 12°C or greater in polar regions for the no-policy case (Figure 3) is worrisome in this respect. The policy case lowers the polar warmings in the 1 in 40 calculation to 5 to 7°C [*Webster et al.*, 2003]. For comparison with Figure 3, the observed long-term surface warming computed from the differences between thirty-year average temperatures centered on 1915 and 1985 was only about 0.6°C for 60°N to 65°N and 0.75°C for 45°S-50°S (C. Forest, private communication; *Jones et al.*, 1999).

Similar significant reductions in the probability of large and risky amounts of sea level rise due to the hypothetical policy are also evident in Figure 2. Emissions reductions will therefore lower the chance of exceeding an extreme climate outcome but not eliminate the risk entirely, and analysis of the reduction in probability is an important policy consideration. We emphasize that due to the simplifications or possible omissions in the various IGSM components, this exercise of determining probabilities has its own implicit uncertainties. Hence it is the qualitative (rather than the exact quantitative) results that should be emphasized. Nevertheless, future climate assessments would better serve the policy process by including formal analysis of uncertainty for key projections, with an explicit description of the methods used [*Reilly et al.*, 2001; *Allen et al.*, 2001]. The great value of such formal probability analyses for policy decision-making lies in the ability to compare relative risks of various policies, which are less affected by the above climate system model uncertainties. These applications to policy are addressed more explicitly by *Jacoby* [2004].

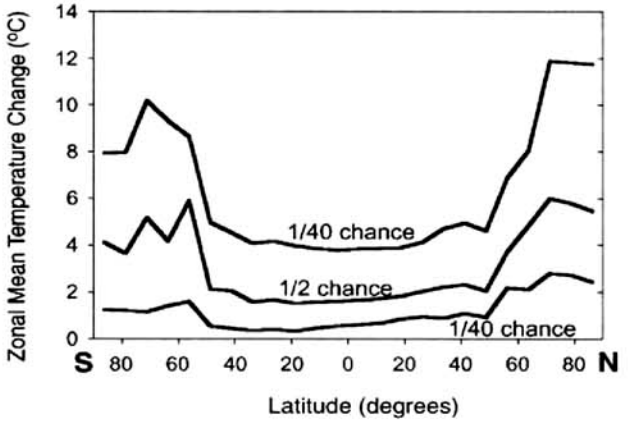


**Figure 3.** Zonal mean temperature change in surface warming by latitude band between 1990 and 2100 in the case assuming no explicit policy in Figure 2. There is one chance in 40 of being above or below the upper and lower curves and one chance in 2 of being above or below the middle curve respectively (adapted from *Webster et al.*, 2003).

## 4. ASSESSMENT OF POLICIES

The IGSM can also be used to assess specific policy proposals in detail. Under the FCCC, the Kyoto Protocol, which addresses the period up to 2010, allows reductions in emissions of several radiative gases to be credited against a $CO_2$-equivalent emissions cap. For this purpose, the Protocol adopts the concept of Global Warming Potentials (GWPs), which are the masses of $CO_2$ required to match the radiative forcing of climate changes caused by unit masses of each non-$CO_2$ gas over a given time horizon (100 years in the Protocol). A study using the IGSM [*Reilly et al.*, 1999] showed that, absent any policy, total $CO_2$ plus CO emissions in 2100 would be about 19 Pg carbon/year compared to about 8 Pg carbon/year in 1990. They also show that economic analyses that leave out gases other than $CO_2$ and CO, err in several important ways: reference (no policy) emissions are understated, allowable emissions in the period up to 2010 are too low, and opportunities to reduce emissions of other gases are not considered in abatement options. Although the

effects are partially offsetting, the inclusion of other relevant gases (e.g. methane) and carbon sinks (e.g. forests) reduces the costs in 2010 of achieving $CO_2$ emissions reductions specified by the Kyoto agreement. Specifically, while essentially the same reduction in warming is obtained either by control of fossil $CO_2$ only, or by control of fossil $CO_2$ and other gases and sinks, the fossil $CO_2$-only approach could cost over 60% more in the year 2010. Two extensions of the Kyoto Protocol are considered from 2010 to 2100: a policy where only Kyoto signatories (Annex B countries) keep their emissions constant at 2010 levels resulting in global $CO_2$ plus CO emissions in 2100 of about 13 Pg carbon/year; and a more stringent policy involving all countries (discussed in the previous section) that results in global $CO_2$ plus CO emissions in 2100 of only 3 to 7 Pg carbon/year, depending on the amounts of reductions in non-$CO_2$ and non-CO gases used. Extending the Kyoto Protocol using the more stringent emissions policy, in which reductions in non-$CO_2$ gases like methane ($CH_4$) are large, shows that the use of GWPs as defined in the Protocol leads to considerably less mitigation of climate change for $CO_2$-only control than for the supposedly equivalent multi-gas strategies (i.e. in Figure 4, which shows projected warming from 1990 to 2100, cases 2' and 3' differ significantly). This illustrates

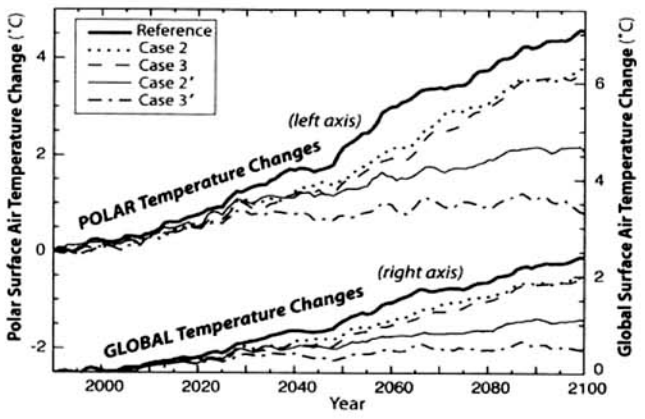


**Figure 4.** Predicted global and polar temperature changes from 1990 levels for four different policy cases. With the Kyoto Protocol targets simply extended unchanged to 2100 (cases 2 and 3) there is a 17% reduction in warming from the reference. With more stringent policies after 2010 (cases 2' and 3'), which approach a post-2100 steady-state of about twice pre-industrial atmospheric $CO_2$ concentrations (i.e. 550 ppm), warming is reduced by about 55 and 85% respectively from the reference. Cases 2 and 2' convert non-$CO_2$ emissions reductions into $CO_2$ emissions reductions for use in the chemistry and climate model using the approximate approach of Global Warming Potentials (GWPs; *IPCC, 2001a*). Cases 3 and 3' more correctly consider reductions in all gases explicitly in the chemistry and climate model (adapted from *Reilly et al.*, 1999).

the limits of GWPs as a tool for political decision and the need to develop improved methods especially for use in the longer term. The effects of the Kyoto Protocol on temperatures in 2010 are not distinct from the no-policy (reference) case but become very obvious in the extensions after about 2040 (Figure 4). Note once again the significantly greater predicted temperature changes in polar regions compared to the global average in the cases in Figure 4.

## 5. CONCLUSIONS

Recent research has solidified the need to consider interactions between human activity, atmospheric chemistry and physics, climate dynamics, and ecosystem processes in order to understand how the earth responds to changes in air pollutant and greenhouse gas emissions. With the above two examples, I have attempted to demonstrate that integrated assessments using fully interactive models like the IGSM are invaluable tools for addressing a variety of important issues. These include discovery and elucidation of previously undetected feedbacks between natural and human-related components of the climate system, objective and quantitative assessments of uncertainty in forecasts of key climate and economic variables, and critical analysis of specific policy proposals [see also *Jacoby*, 2004].

However, nonlinear processes are very important in the climate system, and while the IGSM contains some of these (e.g. climatically modulated greenhouse gas fluxes from current ecosystems, sea ice cover, mountain glaciers, and thermohaline circulation [in 3D ocean version]), it does not contain others (e.g. climatically modulated ecosystem transitions, ice sheet ablation, volcanic eruptions, and solar variability). And even if we were to add treatments of all these missing processes, current knowledge of the stability of the great ice sheets, stability of the thermohaline circulation, ecosystem dynamics, connections between climate change and severe storms, future technological innovation, human population dynamics, and political change are all sufficiently inadequate to allow "surprises" not currently evident from our (or indeed all other) model studies to occur. Therefore, as with all investigations and simulations of complex and only partially understood systems, the results presented here must be treated with appropriate caution.

Looking to the future, there are major research challenges to be faced if the uncertainties in climate prediction are to decrease. Recently, a group of climate scientists has compiled a list of recommended research areas, which are useful to paraphrase here [*Rial et al.*, 2004]:

(1) Explore the limits to climate predictability in view of the nonlinearities, feedbacks and critical thresholds in the climate system;

(2) Better understand the nonlinear response of climate to changes in solar forcing caused by Earth's orbital variations;
(3) Search for additional measures of past climate changes and use these to develop and test climate models;
(4) Develop three-dimensional climate models which incorporate the dynamics of the cryosphere, hydrosphere, atmosphere and pedosphere, and which are capable of addressing multi-millennial time scales;
(5) Better understand the connections between, and variability of, ocean-atmosphere interactions exemplified by the El Nino-Southern Oscillation and the North Atlantic Oscillation;
(6) Improve techniques for measuring or deducing the spectral variations of the solar output at 10 to 100 year time scales;
(7) Understand better the physics of the deep ocean (thermohaline) circulation and its role in major and rapid climate changes;
(8) Evaluate better the response of climate to biospheric and cloud microphysical variations including those caused by human activity (land-use change and aerosol emissions);
(9) Investigate the benefits and risks of deliberate large-scale interventions in the climate system exemplified by carbon sequestration and water management;
(10) Identify and further investigate those ocean and land areas (e.g. high latitudes) particularly sensitive to climate change;
(11) Investigate nonlinear interactions between atmospheric chemistry, climate and ecosystem fluxes of radiatively and chemically important trace gases.

To these challenges in the natural sciences, we should add the need for substantial research to better understand the economic, technical, and political drivers of human activity affecting, and affected by, climate change.

*Acknowledgements.* This research was supported by the U.S Department of Energy, U.S. National Science Foundation, and the Industry Sponsors of the MIT Joint Program on the Science and Policy of Global Change (Alstom Power (France), American Electric Power (USA), BP p.l.c. (UK/USA), ChevronTexaco Corporation (USA), DaimlerChrysler AG (Germany), Duke Energy (USA), J-Power (Electric Power Development Co., Ltd.) (Japan), Electric Power Research Institute (USA), Electricité de France, ExxonMobil Corporation (USA), Ford Motor Company (USA), General Motors (USA), Mirant (USA), Murphy Oil Corporation (USA), Oglethorpe Power Corporation (USA), RWE/Rheinbraun (Germany), Shell International Petroleum (Netherlands/UK), Statoil (Norway), Tennessee Valley Authority (USA), Tokyo Electric Power Company (Japan), TotalFinaElf (France), Vetlesen Foundation (USA), We Energies (USA)). I thank Drs. S. Wofsy and S. Sparks and an additional anonymous reviewer for comments which improved the manuscript.

## REFERENCES

Allen, M., Raper, S. and Mitchell, J., 2001. Uncertainty in the IPCC's Third Assessment Report. *Science* **293**: 430–433.

Ehhalt, D. H., 1999. Gas phase chemistry of the troposphere. *Topics in Physical Chemistry,* **6**: 21–109.

Forest, C. E., Allen, M.R., Sokolov, A. P. and Stone, P. H., 2001. Constraining climate model properties using optimal fingerprint detection methods. *Climate Dynamics,* **18**: 277–195.

Forest, C. E., Stone, P. H., Sokolov, A. P., Allen, M. R. and Webster, M., 2002. Quantifying uncertainties in climate system properties using recent climate observations. *Science*, **295**: 113–117.

Intergovernmental Panel on Climate Change (IPCC). 2001a. *Climate Change 2001: The Scientific Basis.* Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., and Xiaosu, D. (eds.). Cambridge University Press, U.K. 944 p.

Intergovernmental Panel on Climate Change (IPCC). 2001b. *Climate Change 2001: Impacts, Adaptation and Vulnerability.* McCarthy, J. J., Canzian, O. F., Leary, N. A., Dokken, D. J., and White, K. S. (eds.). Cambridge University Press, U.K. 1000 p.

Intergovernmental Panel on Climate Change (IPCC). 2001c. *Climate Change 2001: Mitigation.* Metz, B., Davidson, O., Swart, R. and Pan, J. (eds.). Cambridge University Press, U.K. 700 p.

Jacoby, H., 2004. Modeling Human-Climate Interaction. In *State of the Planet*, AGU Monograph, Eds. C. Hawksworth and S. Sparks, in press.

Jones, P. D., New, M., Parker, D. E., Martin, S. and Rigor, I. G., 1999. Surface air temperature and its changes over the past 150 years. *Rev. Geophysics*, **37**: 173–199.

Kamenkovich, I. V., Sokolov, A.P. and Stone, P., 2002. An efficient climate model with a 3D ocean and statistical-dynamical atmosphere. *Climate Dynamics*, **19**: 585–598.

Kamenkovich, I. V., Sokolov, A. P. and Stone, P., 2003. Feedbacks affecting the response of the thermohaline circulation to increasing $CO_2$: A study with a model of intermediate complexity. *Climate Dynamics*, **21**: 119–130.

Mayer, M., Wang, C. Webster, M., and Prinn, R. G., 2000. Linking local air pollution to global chemistry and climate. *J. Geophys. Res.*, **105**: 20,869–20,896.

MIT Joint Program on the Science and Policy of Global Change, 2004. Website: http://web.mit.edu/globalchange/www/.

Prinn, R. G., 2003. The cleansing capacity of the atmosphere. *Ann. Reviews Environ. and Resources,* **28:** 29–57.

Prinn, R. G., 1994. The interactive atmosphere: Global atmospheric-biospheric chemistry, *Ambio,* **23:** 50–61.

Prinn, R. G., Huang, J., Weiss,R., Cunnold, D., Fraser, P., Simmonds, P., McCulloch, A., Harth, C., Salameh, P., O'Doherty, S., Wang, R., Porter, L., and Miller, B., 2001. Evidence for substantial variations of atmospheric hydroxyl radicals in the past two decades. *Science,* **292:** 1882–1888.

Prinn, R. G., Jacoby, H., Sokolov, A., Wang, C., Xiao, X., Yang, Z., Eckaus, R., Stone, P., Ellerman, A. D., Melillo, J., Fitzmaurice, J., Kicklighter, D., Holian, G. and Liu, Y., 1999. Integrated global

system model for climate policy assessment: Feedbacks and sensitivity studies. *Climatic Change*, **41**: 469–546.

Reilly, J., Prinn, R., Harnisch, J., Fitzmaurice, J., Jacoby, H., Kicklighter, D., Melillo, J., Stone, P., Sokolov, A. and Wang, C., 1999. Multi-gas Assessment of the Kyoto Protocol. *Nature*, **401**: 549–555.

Reilly, J., Stone, P., Forest, C., Webster, M., Jacoby, H., and Prinn, R., 2001. Uncertainty and climate change assessments. *Science*, **291**: 430–433.

Rial, J. A., Pielke, R. A. Beniston, M., Claussen,M., Canadell, J., Cox, P., Held, H., Noblet-Ducoudre, N. de, Prinn, R. G., Reynolds, J. F. and Salas, J. D., 2004. Nonlinearities, feedbacks and critical thresholds within the Earth's climate system. *Climatic Change*, in press.

Schneider, S. H., 1992. Introduction to climate modeling, in: *Climate System Modeling*. Trenberth, K. (ed.), Cambridge University Press, Cambridge, U.K., pp. 3–26.

Sokolov, A., and Stone, P., 1998. A flexible climate model for use in integrated assessments. *Climate Dynamics*, **14**: 291–303.

Sokolov, A., Forest, C. E. and Stone, P., 2003. Comparing oceanic heat uptake in AOGCM transient climate change experiments. *J. Climate*, **16**: 1573–1582.

Wang, C., Prinn, R. and Sokolov, A., 1998. A global interactive chemistry and climate model: Formulation and testing. *J. Geophysical Research* **103**: 3399–3417.

Webster, M. D., Babiker, M., Mayer, M., Reilly, J. M., Harnisch, J., Sarofim, M. C., and Wang, C., 2002. Uncertainty in emissions projections for climate models. *Atmos. Environ.*, **36**: 3659–3670.

Webster, M. D., C. E. Forest, J. M. Reilly, M. Babiker, D. Kicklighter, M. Mayer, R. G. Prinn, M. Sarofim, A. Sokolov, P. H. Stone and C. Wang, 2003. Uncertainty analysis of climate change and policy response. *Climatic Change*, **61**: 295–320.

Xiao, X., Melillo, J., Kicklighter, D., McGuire, A., Prinn, R., Wang, C., Stone, P. and Sokolov, A., 1998. Transient climate change and net ecosystem production of the terrestrial biosphere. *Global Biogeochemical Cycles*, **12**: 345–360.

---

Ronald G. Prinn, Department of Earth Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307, USA.