Development and Application of Earth System Models

Citation: Prinn, R. G. “Fostering Advances in Interdisciplinary Climate Science Sackler Colloquium: Development and Application of Earth System Models.” Proceedings of the National Academy of Sciences (2012): 1-8. © 2012 National Academy of Sciences.

As Published: http://dx.doi.org/10.1073/pnas.1107470109

Publisher: National Academy of Sciences (U.S.)

Persistent URL: http://hdl.handle.net/1721.1/76724

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Development and application of earth system models

Ronald G. Prinn[1]

Center for Global Change Science and Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, MA 02139

Edited by Susan Solomon, Massachusetts Institute of Technology, Cambridge, MA, and approved May 4, 2012 (received for review October 24, 2011)

The global environment is a complex and dynamic system. Earth system modeling is needed to help understand changes in interacting subsystems, elucidate the influence of human activities, and explore possible future changes. Integrated assessment of environment and human development is arguably the most difficult and most important "systems" problem faced. To illustrate this approach, we present results from the integrated global system model (IGSM), which consists of coupled submodels addressing economic development, atmospheric chemistry, climate dynamics, and ecosystem processes. An uncertainty analysis implies that without mitigation policies, the global average surface temperature may rise between 3.5 °C and 7.4 °C from 1981–2000 to 2091–2100 (90% confidence limits). Polar temperatures, absent policy, are projected to rise from about 6.4 °C to 14 °C (90% confidence limits). Similar analysis of four increasingly stringent climate mitigation policy cases involving stabilization of greenhouse gases at various levels indicates that the greatest effect of these policies is to lower the probability of extreme changes. The IGSM is also used to elucidate potential unintended environmental consequences of renewable energy at large scales. There are significant reasons for attention to climate adaptation in addition to climate mitigation that earth system models can help inform. These models can also be applied to evaluate whether "climate engineering" is a viable option or a dangerous diversion. We must prepare young people to address this issue: The problem of preserving a habitable planet will engage present and future generations. Scientists must improve communication if research is to inform the public and policy makers better.

climate change | energy and environment | climate policy

A wide range of everyday human activity affects our environment: food production, transportation, manufacturing, urban development, population growth, supplying potable water, and waste disposal. The environmental effects include climate change, urban air pollution, lowered water quality, land degradation, ecosystem disruption, and human health. The climate issue exemplifies the challenge for sustaining a habitable earth. To forecast climate change and develop sound responses, we need to couple the human and natural components of the earth system. Such integrated assessments have many additional potential benefits: discovery of new interactions among natural and human climate system components, objective assessment of uncertainty in economic and climate projections, critical and quantitative analysis of policy proposals, and understanding connections to other science and policy issues (e.g., air pollution). Today, there are very significant policy debates regarding global climate change within most nations, contentious negotiations under the Framework Convention on Climate Change, and periodic assessments under the Intergovernmental Panel on Climate Change (IPCC) (1–3).

Over the past 2 centuries, the concentrations of carbon dioxide and many other long-lived gases (e.g., methane, nitrous oxide, chlorofluorocarbons, perfluorocarbons, hydrofluorocarbons, sulfur hexafluoride) have increased substantially, caused entirely or in part by human activity. When the concentration of a greenhouse gas (GHG) 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 is then temporarily receiving more energy than it radiates to space. This small imbalance, quantified by the concept of "radiative forcing," tends to raise temperatures at the surface and in the lower atmosphere and to lower them in the upper atmosphere. Uptake of heat by the world's oceans slows the rate of surface temperature rise significantly. The greenhouse effect, as quantified by this radiative forcing, is real, and the physics are well accepted and understood. What is more uncertain, and the cause of much of the scientific debate, is the magnitude of the response of the climate system to this radiative forcing. Interactive processes (feedbacks) in this system can either amplify or dampen the response in ways that are not fully understood at present (1–3).

The physical climate is determined to a significant degree on the strongly coupled circulations of the atmosphere and oceans that require simultaneous treatments of the laws of motion, material conservation, and thermodynamics in these media (4). Climate is also very dependent on the coupled physics of the land and atmosphere involving exchanges of heat, momentum, and water in all three of its phases. The models developed to provide solutions of the relevant interactive governing equations challenge the largest computers in the world. However, even so, the accuracy of these solutions is still dependent on approximations about the key processes occurring on space and time scales not resolved by the models, such as individual clouds and convective events.

Complex connections between air pollution, land-use change, and climate change also need to be taken into consideration (5). Environmentally significant chemical processes occurring in the atmosphere include those affecting urban air pollution, the ozone layer, and the levels of GHGs and reflecting or absorbing particles (aerosols; *SI Text 1*). The aerosols can also indirectly change the reflection properties and lifetimes of clouds. The levels of these GHGs and aerosols, and therefore the radiative forcing of climate, are closely linked to human industrial, urban, and land use activity, as well as to a complex set of natural chemical, physical, and biological processes.

Why do we need earth system models (ESMs)? First, such models are very valuable tools for improving understanding of the complex interactive processes involved in the system. However, there is another compelling reason for such models. In laboratory science, we have the luxury of running "control" experiments in which the outcomes are elucidated when the conditions that govern the processes of interest in the "main" experiment are omitted, with all else being equal. Because we do not have another earth without human influence to serve as a control, we often cannot directly calibrate the impacts of human development on the environment. Hence, we form computer models of the system, gain

---

This paper results from the Arthur M. Sackler Colloquium of the National Academy of Sciences, "Fostering Advances in Interdisciplinary Climate Science," held March 31–April 2, 2011, at the American Association for the Advancement of Science Auditorium in Washington, DC. The complete program and audio files of most presentations are available on the NAS Web site at www.nasonline.org/climate-science.html.

Author contributions: R.G.P. wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission.

[1] E-mail: rprinn@mit.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1107470109/-/DCSupplemental.

confidence in these models through comparison with observations, and then apply them as "numerical control" experiments. There is a growing demand for ESMs that integrate the diverse human and natural system components to enhance scientific understanding and inform policy decisions (*SI Text 2*).

Integrated Global System Model

Over the past 2 decades, an integrated global system model (IGSM) framework has been developed and improved at the Massachusetts Institute of Technology (MIT) both to address many of the scientific goals of earth system modeling and to help inform the policy-making process. We will use this specific model framework as an example of the utility of ESMs in general that integrate the natural and social sciences. The IGSM framework consists of a set of coupled submodels of global economic development and resultant emissions, as well as physical, dynamical, and chemical processes in the atmosphere, land, ocean, and ecosystems (natural and managed). Some of the submodels have both complex and simplified versions available, with the choice of which version to use being guided by the questions being addressed. Also, some of the questions of interest require only a subset of the submodels to be coupled and applied. First described and applied to sensitivity studies by Prinn et al. (6), the IGSM framework has subsequently evolved significantly in complexity to increase its realism and capabilities for integrated assessment and uncertainty analysis (7–10). The IGSM is designed specifically to address key questions in the natural and social sciences that are amenable to quantitative analysis and are relevant to policy. To answer such questions, address uncertainty of projections, and allow examination of a wide variety of proposed policies, the IGSM not only includes the major processes driving climate change (1–5) but its most computationally efficient version can be used in thousands of multicentury predictions. To ensure this efficiency, the most comprehensive existing versions of the component submodels could not be blindly coupled together; the resulting code would be computationally too demanding (*SI Text 3*). The current structure of the computationally efficient version of the IGSM is shown in Fig. 1.

A wide range of industrial, agricultural, and household activities lead to emissions of chemically and climatically important trace gases and aerosols. The emissions prediction and policy analysis (EPPA) model simulates the evolution of the major relevant economic, demographic, trade, and technological processes involved in the production of these emissions at the national and international levels (8, 9). The EPPA model is a general equilibrium model of the world economy (9) that has very detailed considerations of all relevant energy, industrial, agricultural, and transportation sectors and uses comprehensive regional data for production, consumption, and trade (*SI Text 4*). The EPPA model has been used in a wide variety of policy applications (e.g., 11–13).

The above anthropogenic emissions are input into the "natural" ESM that comprises coupled submodels of atmospheric and oceanic dynamics, circulation and chemistry, terrestrial and oceanic biogeochemistry, terrestrial biogeophysics, and oceanic and land cryospheric physics. The version of the model used for uncertainty and multiple policy applications includes computationally efficient, simplified, zonally averaged treatments of atmospheric and oceanic circulations, which resolve the land and ocean within each latitude band (14, 15) (*SI Text 5*). This IGSM reproduces many characteristics of the current zonally averaged climate, and its behavior and predictions are similar to those of coupled atmosphere-ocean 3D general circulation models. Specifically, through appropriate choices of its oceanic vertical diffusivity and climate sensitivity (altered by changing the cloud parameterization), this model can closely mimic the global mean temperature and sea level changes in transient runs of fully 3D models (14–16). By choosing this climate model, we are able to incorporate detailed atmospheric (17, 18) and oceanic chemistry (19) interactively with climate to allow study of key scientific and policy issues.

For other studies not requiring very large ensembles of runs, a version of the IGSM with a fully coupled 3D oceanic model (which replaces the 2D model) is used to allow simulations of changes in the rate of the oceanic meridional overturning (thermohaline) circulation (MOC) that are not treated in the simpler model (7, 10, 20). This 3D ocean model also enables

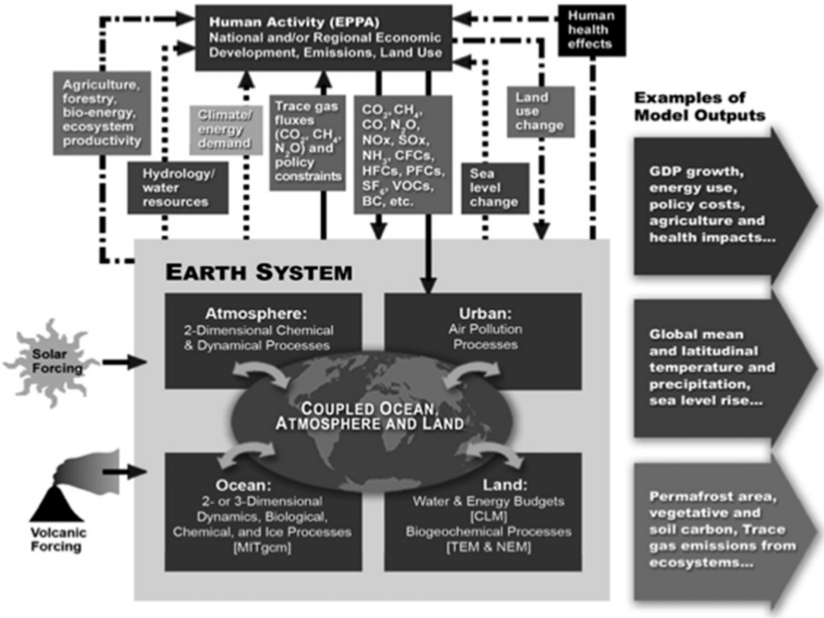

Fig. 1. Framework and processes of the MIT IGSM. Feedbacks between the component models that are currently included, or proposed for inclusion in the next generation of the model, are shown as solid and dashed lines, respectively. GDP, gross domestic product. (Reproduced with permission from Massachusetts Institute of Technology.)

more realistic studies of the interactions between oceanic biogeochemistry and phytoplankton dynamics (19). This enhanced IGSM model is nevertheless computationally efficient enough to be used in sensitivity and uncertainty studies with the IGSM (21). In addition, versions that partly couple a 3D atmospheric circulation and chemistry model into the IGSM framework are applied to specific issues (e.g., 22).

As a result of shared generating processes like combustion, which produces CO_2, CO, NO_x, black carbon aerosols, and SO_x, the emissions of chemicals important in air pollution and climate are often highly correlated. Also, the atmospheric life cycles of air pollutants, such as CO, NO_x, and volatile organic compounds, as well as some climatically important species (e.g., CH_4, sulfate aerosols) are closely linked (23, 24) (*SI Text 6*). To help unravel the interactions and assess the effects of air pollution on ecosystems and human health, emissions in urban areas are input into an urban-scale air chemistry module, whereas those outside urban areas are input into the global model (17, 18, 23, 24). Failure to simulate the chemical reactions occurring in large cities leads to significant overestimation of global aerosol levels (24) and tropospheric NO_x and ozone concentrations (23, 25).

Global land processes are simulated using dynamically coupled terrestrial biogeophysical (water and energy budgets) and biogeochemical (carbon and nitrogen budgets) submodels that are linked to the atmospheric model (26). The land processes can be run either with the latitude grid of the 2D IGSM atmospheric model or with the latitude-longitude grid of a 3D atmospheric model. The use of a mosaic scheme within each grid enables a simulation of multiple vegetation types without the need for a very fine-grid resolution. The land model employs three coupled submodels to represent the terrestrial water, energy, and ecosystem processes: the community land model (27) calculates the water and energy balances, including the roles of plants; the terrestrial ecosystems model (TEM) (22, 28, 29) simulates the carbon and nitrogen cycles in vegetation and soils; and the natural emissions model (6) embedded within the TEM simulates the natural emissions of CH_4 and N_2O, taking into account climate and ecosystem processes in wetlands and soils around the world.

Linking these complex submodels together leads to many challenges, which are illustrated well by the difficulty of almost all current coupled ocean-atmosphere models (including ours) to simulate current climate over the globe accurately and precisely without tuning the air-to-sea fluxes of heat, water, and (sometimes) momentum. In more recent models, these nonphysical adjustments are relatively small fractions of the annual mean fluxes but nevertheless indicate deficiencies in the model formulations of air-sea interactions (1). Also, the climate system contains a number of nonlinearities, feedbacks, and critical thresholds that are not present in the IGSM or in most other models (30). For example, the IGSM does not endogenously include irreversible conversions of ecosystems and the related releases of GHGs or the dynamics of the great 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. There are also several significant societal processes missing from current ESMs, including the IGSM. They include the substantial role of political and cultural forces on economic, technological, and policy decisions, as well as on population dynamics (*SI Text 7*). Despite these limitations, even the computationally efficient version of the IGSM has several capabilities that are either not present or are simplified in other integrated models of the global climate system that include economics (*SI Text 8*).

Testing and (if feasible) validation of ultracomplex models like the IGSM are essential elements in their development and application. To the extent possible, the natural system submodels in the IGSM have been individually developed and tested using available relevant physical, chemical, and biological measurements for the atmospheric, oceanic, and terrestrial systems. If these submodels do not agree statistically with these measurements, they have been modified or replaced where possible. Of course, such agreement is a necessary but not sufficient condition for validation. There must be confidence that the major processes are being simulated in the submodel, and this confidence may be limited by lack of knowledge and/or insufficient computational capability to include all the known dynamics. Similarly, the EPPA submodel encapsulates macroeconomic theory; extensive national reports for social accounting data on production, consumption, and trade; and detailed direct knowledge of all the sectors relevant to climate and air pollutant emissions, but it also contains many uncertain parameters. Where currently irreducible uncertainties exist in modeling these subsystems, our approach is to quantify these uncertainties (using observations and expert solicitation) for use in the probabilistic forecasts and policy applications discussed in the next two sections (*SI Text 9*).

Applications to Probabilistic Forecasts

Three key issues that ESMs can be applied to are as follows: the probabilities of various amounts of climate change if there is no explicit policy, the relationship between GHG stabilization targets and temperature change targets under uncertainty, and the uncertainty in the costs of stabilization policies. To provide an example of such an application, we refer to recent ensembles of forecasts using the computationally efficient IGSM, version 2.2 (7, 8). Each ensemble contains 400 forecasts, with different but comparably probable choices (using Latin Hypercube Monte Carlo sampling) for the many uncertain input parameters in both the economic and natural system submodels in the IGSM. This exercise is obviously dependent on the probability distributions assumed for the input parameters, and these distributions have evolved as more understanding has been gained.

The uncertain inputs into the EPPA submodel have changed from those used in the earlier EPPA-based study (31) (*SI Text 10*). Hence, the probability distributions of emissions used in the results presented here (7, 8) are higher compared with previous results (31, 32). These changes in projected emissions noticeably decreased the probability of low radiative forcing through reduction of the probability of very low emissions growth.

Estimates of uncertainties in the climate submodel parameters involving clouds and convection, oceanic overturn, and aerosol radiative forcing involved simulations of 20th century climate using both anthropogenic and natural forcing, as well as comparisons to observations of oceanic, surface, and atmospheric temperatures over the past century (33, 34). The inclusion of natural forcing attributable to volcanic eruptions led to significantly different probability distributions of these parameters than obtained in a similar earlier study that used only anthropogenic forcing (35). This led to significantly different climate forecasts (7, 8) than achieved in the earlier IGSM-based study (32), which used the earlier input distributions (35) (*SI Text 11*).

Climate Forecasts With and Without Stabilization. To elucidate the magnitudes and uncertainties of future climate change, five ensembles of IGSM forecasts have been carried out for a no-policy case [with a median 1,330 ppm-eq CO_2 in 2091–2100 (7)] and for four stabilization cases with a median 560, 660, 780, or 890 ppm-eq CO_2 in 2091–2100 (8). For the no-policy case, the median anthropogenic emissions in the MIT IGSM are similar to those for the IPCC Special Report on Emission Scenarios (SRES) A2 scenario (3); however, for several reasons (7, 8), the GHG concentrations simulated by the MIT IGSM are somewhat higher than those used in the simulations with the IPCC Assessment Report 4 (AR4) ensemble of climate forecasts (1). Also, the ensembles of IGSM simulations discussed here were carried out with climate input parameter distributions (34) that were based on specific estimates of trends in the deep-ocean temperatures (36). Alternative estimates of the ocean warming trends suggest somewhat smaller surface air warming than those presented here (7, 8).

Examination of the IGSM ensembles reveals that the effect of increasingly stringent policies is to reduce the probabilities of large, dangerous amounts of warming substantially rather than to lower the median warming dramatically (Fig. 2). For example, although the policy yielding stabilization at a median 890 ppm-eq reduces the median warming between the periods 1981–2000 and 2091–2100 by 1.7 °C relative to the no-policy case (i.e., from 5.1 °C to 3.4 °C), it reduces the upper 95% bound by 3.2 °C (i.e., from 8.2 ° to 5.0 °C) (8). This reduction is made even more significant if the damages increase superlinearly with the temperature increase (2). In addition, because the mitigating effects of the policy only appear very distinctly in the forecasts after 2050, there is significant risk in waiting for very large warming to occur before taking action (25) (Fig. 2 and *SI Text 12*).

When goals for climate policy are expressed in terms of temperature targets, it is important to clarify whether the target refers to the median temperature response or to a threshold temperature with a very low probability of exceeding it. Table 1 shows the odds of exceeding various targets of temperature increase. Although the dangers associated with these potential targets are subjective, the value of the policies is clearly expressed by their ability to avoid the presumed dangers. In this respect, the commonly discussed 2 °C target looks problematic even when referenced to the 1981–2000 period, let alone to the preindustrial period that effectively allows only about 1.2 °C warming after 1981–2000. With an 80% chance of exceeding 2 °C above preindustrial for the 560 ppm-eq case, it is clear that the median stabilization goal would need to be 450 ppm-eq or less [we are currently at around 475 ppm-eq for the Kyoto plus Montreal gases and 443 ppm-eq for the Kyoto gases alone (37), updated to end of 2011].

An important conclusion from these uncertainty analyses is that emissions policies yield much greater reductions in the probability of exceeding large warming thresholds than the smaller ones. For a very low temperature change target, such as 2 °C, the 890, 780, and 660 ppm-eq cases decrease the probability negligibly or only slightly. In contrast, the probability of exceeding higher temperature change targets, such as 6 °C, although 25% for the no-policy 1,330 ppm-eq case, is negligible for all four of the stabilization cases (*SI Text 13*). The reductions in risk as one proceeds from higher to lower stabilization levels is clearly not linear (Table 1).

Table 1. Probability of global average surface air warming (ΔT) from 1981–2000 to 2091–2100 exceeding 2 °C, 4 °C, and 6 °C, without a policy (leading to a 2091–2100 median 1,330 ppm-eq CO_2) and with a median 560, 660, 780, or 890 ppm-eq CO_2 GHG stabilization policy

Ensemble case and median level of GHGs in 2091–2100, ppm-eq CO_2	Global ΔT >2 °C (values to 1860 or preindustrial)	Global ΔT >4 °C	Global ΔT >6 °C
No policy: 1,330 ppm	100% (100%)	85%	25%
Stabilize at 890 ppm	100% (100%)	25%	0.25%
Stabilize at 780 ppm	97% (100%)	7%	<0.25%
Stabilize at 660 ppm	80% (97%)	0.25%	<0.25%
Stabilize at 560 ppm	25% (80%)	<0.25%	<0.25%

Data from Sokolov et al. (7) and Webster et al. (8).

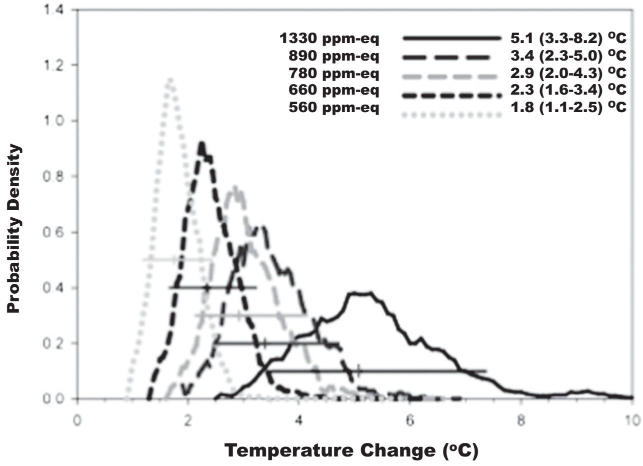

Fig. 2. Probability distributions (frequencies) for global mean temperature change between the 1981–2000 average and the 2091–2100 average without a policy (leading to a 2091–2100 median 1,330 ppm-eq CO_2) and with median 560, 660, 780, or 890 ppm-eq CO_2 GHG stabilization policies (7, 8). The median and 95% confidence (2.5–97.5%) probability ranges are given in the legend for each case. Horizontal lines show 90% ranges (5–95%), and vertical lines indicate medians adapted from Webster et al. (8).

To understand the risks better, it is also important to examine the latitudinal distribution of these projections. As evident in essentially all climate models (38), and in current observations (1), the computed or observed temperature increases in vulnerable polar regions are much greater than in equatorial regions. For example, the above ensembles of IGSM forecasts also provide the cumulative future probability of Arctic (60° N to 90° N) surface air warming from 1981–2000 to 2091–2100, without and with GHG stabilization policies (7, 8). From Table 2, the probability of exceeding polar warming of ∼4 °C (which was last reached during the Eemian) is unacceptably high for both the no-policy case and the median 890 and 780 ppm-eq stabilization policy cases (Table 2). Polar regions contain ecosystems with large carbon storage, as well as the Greenland and West Antarctic ice sheets with large water storage. The polar seas also play prominent roles in driving the oceanic MOC that is critical as a sink of heat and CO_2. Insights into the vulnerability of these polar systems can be provided using research on recent and past climates (*SI Text 14*) and also using ESM results (e.g., section on application to specific issues).

Policy Costs With and Without Stabilization. A central issue for policy making regards how much it will cost for stabilization at the various levels, and how this cost compares with the benefits accrued from the avoided damages. To address the first part of this question, the IGSM's economic module (EPPA) contains most of the key relevant economic sectors and technologies, albeit with some approximations (energy consumers, such as industry, households, and transportation; energy producers, such as fossil,

Table 2. Probability of the 60° N to 90° N average surface air warming (ΔT) from 1981–2000 to 2091–2100 exceeding 4 °C, 6 °C, and 8 °C without a policy (leading to a 2091–2100 median 1,330 ppm-eq CO_2) and with a 2091–2100 median 560, 660, 780, or 890 ppm-eq GHG stabilization policy

Ensemble case and median level of GHGs in 2091–2100, ppm-eq CO_2	Arctic ΔT >4 °C	Arctic ΔT >6 °C	Arctic ΔT >8 °C
No policy: 1,330 ppm	100%	95%	70%
Stabilize at 890 ppm	95%	30%	3%
Stabilize at 780 ppm	80%	9%	0.25%
Stabilize at 660 ppm	25%	0.25%	<0.25%
Stabilize at 560 ppm	0.5%	<0.25%	<0.25%

Data from Sokolov et al. (7) and Webster et al. (8).

nuclear, and renewables; and agricultural producers, such as food, livestock, forestry, and biofuels; *SI Text 15*).

Using the EPPA model, the probability for global mitigation costs (e.g., expressed as the percentage welfare losses in 2050) has been calculated for the four 400-member ensembles with median 560, 660, 780, and 890 ppm-eq CO_2 stabilization levels (8) (Table 3). Welfare is a measure of the total consumption of goods and services, which usually grows around 3% per year over the long term. Thus, a 3% welfare loss in 2050 can be interpreted as having to wait until 2051 to achieve the same total welfare that would have occurred in 2050 in the absence of policy. The policies are modeled as a "cap and trade" system with steadily increasing costs for permits to emit GHGs that are calibrated to achieve the above-median stabilization levels. For this purpose, the non-CO_2 GHG emissions are converted to their equivalent CO_2 emissions using global warming potentials (GWPs) with 100-y time horizons (1). From Table 3, we see that the chance of exceeding the 3% threshold for welfare loss is negligible for the 660, 780, and 890 ppm-eq stabilization levels and only 10% for the 560 ppm-eq level. This is a relatively low economic risk to take, given the value of the 560 ppm-eq level in substantially lowering the risk for dangerous amounts of global and Arctic warming (Tables 1 and 2). It should be emphasized, however, that these losses assume an economically efficient cap and trade policy; the losses may be substantially larger with less efficient policies, such as mandates, and with distortions introduced by preexisting policies (Table 3).

Application to Specific Issues

Future of the Oceanic Circulation and Stabilization Policy Targets. Overturn of the deep ocean, which is key to the oceanic carbon and heat sinks, is driven, in part, by sinking water in the polar seas (specifically the Norwegian, Greenland, Labrador, Weddell, and Ross Seas). This process is slowed by decreased sea ice and increased fresh water inputs into these seas. Indeed, increased rainfall, snowfall, and river flows, as well as decreased sea ice, are all expected with global warming. It is of significant interest to assess which GHG stabilization policy goals will substantially lower the probability of a massive slowdown. The 3D ocean circulation model that is a part of the MIT IGSM framework has been used to compute the response of the MOC of the world's oceans to increases in radiative forcing by GHGs (21). A variety of choices were made for the increases in CO_2 over various periods ranging from 0 to 1,000 y (with stabilization after that) and for the climate sensitivity within the climate model so as to gauge the importance of these two parameters. Following a general weakening of the MOC over the prestabilization period, the trend in the strength of the MOC after the stabilization of CO_2, namely, either a continued decrease or an increase back toward its initial strength (i.e., a collapse or a recovery of this circulation), depended on the final surface air temperature. This temperature was, in turn, related to the product of the radiative forcing and the climate sensitivity in each run. For the cases more relevant to typical policies, where the CO_2 increases occurred only over the first 100 y, three sets of runs with final CO_2 levels, climate sensitivities, and final temperatures of: 1,398 ppm-eq, 2.3 °C and 4.9 °C; 509 ppm-eq, 4.5 °C and 3.1 °C; and 856 ppm-eq, 1.9 °C and 2.7 °C, all collapsed. Seven other runs with final temperatures of 1.1 °C–2.7 °C all recovered. Studies of this type have obvious implications for answering the question of what the "danger" levels are that would lead to effectively irreversible detrimental future climate changes.

Table 3. Probability of the global welfare loss (relative to the no-policy case) in 2050 exceeding 1%, 2%, and 3% with a 2091–2100 median 560, 660, 780, or 890 ppm-eq GHG stabilization policy

Ensemble case and median level of GHGs in 2091–2100, ppm-eq CO_2	Welfare loss >1%	Welfare loss >2%	Welfare loss >3%
No policy: 1,330 ppm	—	—	—
Stabilize at 890 ppm	1%	0.25%	<0.25%
Stabilize at 780 ppm	3%	0.5%	<0.25%
Stabilize at 660 ppm	25%	2%	0.5%
Stabilize at 560 ppm	70%	30%	10%

Data from Sokolov et al. (7) and Webster et al. (8).

Assessment of the Kyoto Protocol. The IGSM can also be used to assess various aspects of specific existing or proposed policies in detail. For example, the Kyoto Protocol, which addressed the period from 2008 to 2012, allowed reductions in emissions of the non-CO_2 gases CH_4, N_2O, SF_6, hydrofluorocarbons (e.g., the refrigerant CH_2FCF_3), and perfluorocarbons (e.g., CF_4 from aluminum smelters) to be credited against a carbon-equivalent emissions cap. To achieve this crediting, the protocol adopted the GWP concept. The IGSM was used to evaluate the validity of this crediting process for the non-CO_2 gases (12) (*SI Text 16*). The results show that economic analyses that leave out GHGs other than CO_2 are deficient in several important ways: Emissions in a no-policy case are understated, allowable emissions in the period up to 2010 are too low, and opportunities to reduce emissions of other GHGs are not considered in abatement options. Although essentially the same computed reduction in warming was obtained either by control of sources and sinks of fossil CO_2 (plus CO) only or by equivalent control of fossil CO_2 (plus CO) and the other Kyoto gases, the fossil CO_2-only approach would cost over 60% more (12).

Transforming the Energy System. Meeting future world energy needs while addressing climate change requires large-scale deployment of low or zero GHG emission technologies, such as biofuels and wind energy, which, although renewable, require deployment over vast areas. To make a difference, each innovative renewable must operate at large scales [e.g., more than about 30 Exajoules (EJ)/y or 1 Terawatt (TW)]. It is prudent to examine the environmental and economic consequences of large-scale adoption of these renewable energy sources so as to ensure that they are developed in ways that minimize their potential impacts.

For example, a global biofuels program generating, for example, 300 EJ/y will lead to intense demands on water and arable land area and potentially to increased GHG emissions from land-use changes, such as deforestation. The EPPA and TEM modules in the IGSM have been used to examine the effects of a large new global cellulose-based bioenergy program on emissions over the 21st century (39). The study examined two cases: (*i*) one in which 365 EJ/y of biofuel is produced in 2100, using 16.2% (21.6 million km^2) of the total land area (natural forest area declines by 56% from 34.4 to 15.1 million km^2 and pasture area declines by 14% from 25.8 to 22.1 million km^2) and (*ii*) another in which 323 EJ/y of biofuels is produced in 2100, using 20.6 million km^2 of land (pasture areas decrease by 40% or 10.3 million km^2 and forest area declines by 24% or 8.4 million km^2). In addition to the "direct" emissions that occur when land is cleared or converted for biofuels, "indirect" emissions occur when biofuels production on agricultural land displaces agricultural production and causes additional (or indirect) land-use change (e.g., deforestation) that leads to an increase in net GHG emissions. The results, expressed as masses of CO_2 equivalents emitted per unit of biofuel energy produced, are summarized for cases 1 and 2 for the periods 2000–2030 and 2000–2100 in Table 4. Intensities are larger in the earlier period because of the direct and indirect emissions, and they are larger in case 1 than case 2 primarily because of the much greater deforestation in case 1.

Table 4. Carbon intensity (CO_2-eq grams emitted per megajoule of energy produced, with negative values indicating carbon accumulation) associated with cellulosic biofuel production

	Case 1	Case 1	Case 2	Case 2
Time period	2000–2030	2000–2100	2000–2030	2000–2100
Direct land C	11	0	−52	−7
Indirect land C	190	7	181	1
Fertilizer N_2O	29	20	30	19
Total	229	26	158	13

Data from Melillo et al. (39).

This modeling study implies that indirect land use and emissions will lead to substantially more carbon loss than that associated with direct emissions and land use. Also, because of predicted increases in fertilizer use, N_2O emissions (converted to carbon-equivalent losses in Table 4) will be very important as a result of the very large GWP of this gas. The study concludes that a GHG emissions policy that protects forests and encourages best practices for nitrogen fertilizer use can dramatically reduce emissions associated with biofuels production (Table 4).

As a second example, the widespread availability of wind power has fueled substantial interest in this renewable energy source. For very large-scale utilization of this resource, there are, however, potential environmental impacts (40). There are also problems arising from the inherent intermittency of wind power, in addition to the present need to lower unit costs. To address future potential multi-TW demand for renewable electrical power implied by runs of the IGSM EPPA model, a 3D land-ocean-atmosphere climate model has been used to simulate the potential future climate effects and reliability associated with installation of wind-powered generators over vast land or coastal areas (41, 42). Four runs of this climate model with global wind power generation over semiarid lands of 2.3–19 TW indicated that wind turbines could cause surface warming exceeding 1 °C–2 °C near the installations (41). Significant warming or cooling remote from the land installations and alterations of the global distributions of rainfall and clouds also occurred (*SI Text 17*). The computed intermittency of this land-based wind power by factors up to 6 on daily and longer time scales poses a demand for one or more options to ensure reliability, including backup generation capacity, very long-distance power transmission lines, and onsite energy storage, each with specific economic and/or technological challenges. To address coastal ocean deployment of wind turbines at similar large scales (1.7–11.9 TW globally in shelf regions up to 200, 400, and 600 m deep), a set of six additional model simulations was conducted using an improved climate model (42). In contrast to the land installation results, the offshore installations were found to cause a surface cooling over the installed offshore regions (*SI Text 17*). However, the intermittency (seasonal variations over factors of 2–4) for potential major offshore wind power sites over the globe requires measures to ensure the reliability of this resource.

Air Pollution and the Earth System. As emphasized earlier, there are very significant scientific, policy, economic, and human health connections between air pollution, ecosystems, and climate. By coupling the IGSM's EPPA with a health effects model and using results from a 3D global atmospheric model that computes the climate and air pollution effects of the future emissions, the human health and economic impacts (including mortality and morbidity) of changes in levels of the major air pollutant and GHG ozone (O_3) have been studied in 16 global regions (43). Using a high IPCC emissions scenario (3), the study compared the costs of ozone pollution for the 2000 and 2050 ozone precursor and GHG emissions. The study concludes that health costs incurred by the increase in global ozone pollution levels above their preindustrial values will be \$580 billion (year 2000 dollars) by 2050 and that there will be over 2 million mortalities from acute exposure to ozone. The economic effects of emissions changes that have an impact on both air pollution and climate far exceed the influence of climate alone (*SI Text 18*). In a related study, EPPA has been applied to the health impacts for 1970–2000 in the United States of particulates, NO_2, SO_2, and CO, as well as O_3, with and without the Clean Air Act. The results show the dominant role of particulate and ozone reductions in the computed benefits of the act (44).

When plants are exposed to ozone, it inhibits photosynthesis, and thus reduces net primary production and carbon sequestration by the vegetation. The reduced sequestration then forces the need for further reductions in emissions to meet a desired GHG concentration target, and thus increases the cost of attaining the target. The future effects of ozone on carbon sequestration and climate change policy have been estimated using the TEM component of the IGSM (22). Simulations for the period from 1860 to 1995 showed that the largest impacts occurred in the southeastern and midwestern states of the United States, Eastern Europe, and eastern China. For the more recent period from 1950 to 1995, Eastern Europe showed the largest reductions (41%) in carbon storage. Projections of ozone and ecosystem response through 2100 developed with the IGSM showed even greater expected reductions in carbon storage in the future (*SI Text 19*).

Conclusions

We have emphasized the importance of producing quantitative estimates of the uncertainty in outputs from ESMs. Future policy decisions will be better aided by environmental assessments that include formal and objective analyses of uncertainty for key projections, with explicit descriptions of the statistical approaches used (e.g., 1, 45, 46). The value of such probability analyses for policy decision making lies more in their ability to compare relative (as opposed to absolute) risks for various policies, which are less affected by the ESM uncertainties. Given the uncertainties in forecasts, it is also clear that we need to evaluate policies based on their ability to lower risk and to reevaluate decisions over time as new knowledge is gained (*SI Text 20*).

The same arguments about the value of integrated ESMs for informing policy making for climate mitigation also apply to decision making regarding adaptation. There are significant reasons for attention to climate adaptation. First, we are already committed to some unavoidable warming even at current GHG levels (about 0.6 °C) (1). Second, adaptation can help in the

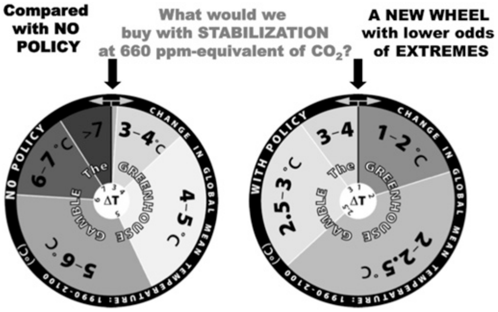

Fig. 3. Wheels depicting the probabilities of increases in global average surface air temperature between the 1981–2000 and 2091–2100 decadal averages using the MIT IGSM without and with a stabilization policy, yielding a median 660 ppm-eq CO_2 in 2091–2100 (7, 8). Spinning versions of these wheels are available at http://globalchange.mit.edu. (Reproduced with permission from Massachusetts Institute of Technology.)

short term, whereas mitigation helps in the long term (*SI Text 21*). ESMs can also inform studies of climate engineering (or geoengineering). For example, runs of the IGSM that linearly reduce the solar input between 2015 and 2100 by 1.5%, 2%, and 2.5% yield temperature trends that closely mimic those for stabilization of GHGs at 750, 650, and 550 ppm-eq CO_2, respectively. There is significant current debate about whether geoengineering is a viable option or a dangerous diversion from the need for lowering emissions (*SI Text 22*).

It is also very evident that scientists must improve communication if research is to inform the public and policy makers better. For example, how can we best express to the public the value of a climate policy under uncertainty? One useful approach has been to show the odds of various ESM outcomes on a "greenhouse gamble" wheel that people can imagine they are spinning to see what the future looks like if there is no deliberate policy (47). They can then compare this "no-policy" wheel with one they could choose instead, for example, one with stabilization at a median 660 ppm-eq CO_2 in 2091–2100. This new wheel obviously has significantly lower odds of dangerous extremes (Fig. 3).

Looking to the future, although there is continuing progress toward more comprehensive ESMs (*SI Text 23*), there are major research challenges to be faced for the natural and social sciences if the uncertainties in predictions are to decrease and ESMs are to become more powerful tools for decision making. Some time ago, a list of recommended research areas in climate science was compiled that remains relevant today regarding the following: (*i*) limits to predictability; (*ii*) role of the Earth's orbital variations; (*iii*) use of past climate changes to improve models; (*iv*) new generations of climate models and ultrafast computers; (*v*) ocean-atmosphere interactions; (*vi*) long-term spectral variations of the solar output; (*vii*) oceanic MOC and its role in climate; (*viii*) response of climate to biospheric and cloud processes; (*ix*) benefits and risks of climate engineering; (*x*) climate-sensitive ocean and land areas; and (*xi*) nonlinear interactions between atmospheric chemistry, climate, and ecosystem fluxes of GHGs (25, 30). These challenges for the natural sciences are matched by equally complex issues for the social sciences: (*i*) encapsulating the roles of political and cultural forces on development into ESMs, (*ii*) handling future technological innovations, (*iii*) including human population dynamics and political change in ESMs, and (*iv*) communication of climate risks to the public and policy makers, as well as the utility of ESMs in that communication.

In closing, I emphasize that recent research has solidified the need to foster collaborations better between the natural and social sciences. The research challenge is great: Integrated assessment of environment and development is arguably the most difficult, most interdisciplinary, yet most important systems problem facing the world today. There is also a major educational challenge. The problem of preserving a habitable planet will engage both present and future generations.

ACKNOWLEDGMENTS. I thank the two anonymous reviewers whose comments helped to improve the paper significantly. This research was supported by the US Department of Energy; US National Science Foundation; and the Federal, Industrial, and Foundation Sponsors of the MIT Joint Program on the Science and Policy of Global Change.

1. Intergovernmental Panel on Climate Change (IPCC) (2007) *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK).
2. Intergovernmental Panel on Climate Change (IPCC) (2007b) *Climate Change 2007: Impacts, Adaptation and Vulnerability*, eds Parry ML, et al. (Cambridge Univ Press, Cambridge, UK).
3. Intergovernmental Panel on Climate Change (IPCC) (2007c) *Climate Change 2007: Mitigation of Climate Change*, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK).
4. Schneider SH (1992) *Climate System Modeling*, ed Trenberth K (Cambridge Univ Press, Cambridge, UK), pp 3–26.
5. Prinn RG (1994) The interactive atmosphere: Global atmospheric-biospheric chemistry. *Ambio* 23:50–61.
6. Prinn RG, et al. (1999) Integrated global system model for climate policy assessment: Feedbacks and sensitivity studies. *Clim Change* 41:469–546.
7. Sokolov A, et al. (2009) Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *J Clim* 22:5175–5204.
8. Webster MD, et al. (2012) Analysis of climate policy targets under uncertainty. *Clim Change* 112:569–583.
9. Paltsev S, et al. (2005) The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. Report 125 (MIT Global Change Joint Program, Cambridge, MA). Available at http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf.
10. Sokolov AP, et al. (2005) The MIT Integrated Global System Model (IGSM): Version 2. Model Description and Baseline Evaluation. Report 124 (MIT Global Change Joint Program, Cambridge, MA). Available at http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt124.pdf.
11. Jacoby H, et al. (1997) CO_2 emissions limits: Economic adjustments and the distribution of burdens. *The Energy Journal* 18(3):31–58.
12. Reilly J, et al. (1999) Multi-gas assessment of the Kyoto protocol. *Nature* 401:549–555.
13. Paltsev S, et al. (2008) Assessment of US GHG cap-and-trade proposals. *Climate Policy* 8:395–420.
14. Sokolov A, Stone P (1998) A flexible climate model for use in integrated assessments. *Climate Dynamics* 14:291–303.
15. Sokolov A, Forest CE, Stone P (2003) Comparing oceanic heat uptake in AOGCM transient climate change experiments. *J Clim* 16:1573–1582.
16. Forest CE, Allen MR, Sokolov AP, Stone PH (2001) Constraining climate model properties using optimal fingerprint detection methods. *Climate Dynamics* 18:277–295.
17. Wang C, Prinn R, Sokolov A (1998) A global interactive chemistry and climate model: Formulation and testing. *J Geophys Res* 103(D3):3399–3417.
18. Cohen JB, Prinn RG (2011) Development of a fast, urban chemistry metamodel for inclusion in global models. *Atmos Chem Phys* 11:7629–7656.
19. Dutkiewicz S, Follows MJ, Bragg JG (2009) Modeling the coupling of ocean ecology and biogeochemistry. *Global Biogeochem Cycles*, 10.1029/2008GB003405.
20. Kamenkovich IV, Sokolov AP, Stone P (2002) An efficient climate model with a 3D ocean and statistical-dynamical atmosphere. *Climate Dynamics* 19:585–598.
21. Scott JR, Sokolov AP, Stone PH, Webster MD (2008) Relative roles of climate sensitivity and forcing in defining the ocean circulation response to climate change. *Climate Dynamics* 30:441–454.
22. Felzer B, et al. (2005) Future effects of ozone on carbon sequestration and climate policy using a global biogeochemical model. *Clim Change* 73:345–373.
23. Mayer M, Wang C, Webster M, Prinn RG (2000) Linking local air pollution to global chemistry and climate. *J Geophys Res* 105(D18):22869–22896.
24. Cohen JB, Prinn RG, Wang C (2011) The impact of detailed urban-scale processing on the composition, distribution, and radiative forcing of anthropogenic aerosols. *Geophys Res Lett*, 10.1029/2011GL047417.
25. Prinn RG (2004) *The State of the Planet: Frontiers and Challenges in Geophysics*, eds Hawksworth C, Sparks S (American Geophysical Union, Washington, DC), pp 297–305.
26. Schlosser CA, Kicklighter D, Sokolov A (2007) A Global Land System Framework for Integrated Climate-Change Assessments. Report No. 147 (MIT Joint Program on the Science and Policy of Global Change, Cambridge, MA).
27. Bonan GB, et al. (2002) The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model. *J Clim* 15:3123–3149.
28. Melillo JM, et al. (1993) Global climate change and terrestrial net primary production. *Nature* 363:234–240.
29. Xiao X, et al. (1997) Linking a global terrestrial biogeochemical model and a 2-dimensional climate model: Implications for the global carbon budget. *Tellus B Chem Phys Meterol* 49:18–37.
30. Rial JA, et al. (2004) Nonlinearities, feedbacks and critical thresholds within the Earth's climate system. *Clim Change* 65:11–38.
31. Webster MD, et al. (2002) Uncertainty in emissions projections for climate models. *Atmos Environ* 36:3659–3670.
32. Webster MD, et al. (2003) Uncertainty analysis of climate change and policy response. *Clim Change* 61:295–320.
33. Forest CE, Stone PH, Sokolov AP (2006) Estimated PDFs of climate system properties including natural and anthropogenic forcings. *Geophys Res Lett*, 10.1029/2005GL023977.
34. Forest CE, Stone PH, Sokolov AP (2008) Constraining climate model parameters from observed 20th century changes. *Tellus A Dyn Meterol Oceanogr* 60:911–920.
35. Forest CE, Stone PH, Sokolov AP, Allen MR, Webster MD (2002) Quantifying uncertainties in climate system properties with the use of recent climate observations. *Science* 295:113–117.
36. Levitus S, Antonov J, Boyer TP (2005) Warming of the world ocean, 1955–2003. *Geophys Res Lett*, 10.1029/2004GL021592.
37. Huang J, Wang R, Prinn R, Cunnold D (2009) *A Semi-Empirical Representation of the Temporal Variation of Total Greenhouse Gas Levels Expressed as Equivalent Levels of Carbon Dioxide. Report 174* (MIT Global Change Joint Program, Cambridge, MA).
38. Meehl GA, et al. (2007) Global climate projections. Chapter 10 in *Climate Change 2007: The Physical Science Basis*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK), pp 747–845.
39. Melillo JM, et al. (2009) Indirect emissions from biofuels: How important? *Science* 326: 1397–1399.

40. Keith DW, et al. (2004) The influence of large-scale wind-power on global climate. *Proc Natl Acad Sci USA* 101:16115–16120.
41. Wang C, Prinn RG (2010) Potential climatic impacts and reliability of very large-scale wind farms. *Atmos Chem Phys*, 10:2053–2061, Available at www.atmos-chem-phys.net/10/2053/2010/.
42. Wang C, Prinn R (2011) Potential climatic impacts and reliability of large-scale offshore wind farms. *Environ Res Lett*, 10.1088/1748-9326/6/2/025101.
43. Selin NE, et al. (2009) Global health and economic impacts of future ozone pollution. *Environ Res Lett*, 10.1088/1748-9326/4/4/044014.
44. Matus K, Yang T, Paltsev S, Reilly J, Nam K-M (2008) Toward integrated assessment of environmental change: Air pollution health effects in the USA. *Clim Change* 88:59–92.
45. Reilly J, et al. (2001) Climate change. Uncertainty and climate change assessments. *Science* 293:430–433.
46. Allen M, Raper S, Mitchell J (2001) Climate change. Uncertainty in the IPCC's Third Assessment Report. *Science* 293:430–433.
47. Prinn RG (2007) Climate Change: A Growing Scientific Impetus for Policy. Testimony to the Committee on Ways and Means, Hearing on Energy and Tax Policy, US House of Representatives, February 28, 2007. Available at http://globalchange.mit.edu/news/testimony.html.