Modeling Earth's future

Integrated assessments of linked human-natural systems

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Modeling Earth's future
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Engraving of Tycho Brahe's great brass globe ('Globus magnus orichalcicus'), in his Uraniborg observatory on the island of Hven. Illustration from *Astronomia instauratae mechanica*, by Tycho Brahe (Hamburg, 1598).

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Preface

In 2008 Raymond and Beverly Sackler established the USA-UK Scientific Forum to help the scientific leadership of the United Kingdom and the United States forge an enduring partnership on topics of worldwide scientific concern with benefit to all people. As presidents of the Royal Society and National Academy of Sciences, we are profoundly grateful to the Sacklers for this far-sighted act of generosity. In the modern world, science and technology have become engines that drive not only economic growth but also social change. By establishing the forum, the Sacklers have made it possible to examine forces that are creating our collective future.

The third forum, which was entitled Integrated Assessment Models and the Future Needs of Climate Change Research, took place on 19 – 20 September 2012 at the Kavli Royal Society International Centre in Buckinghamshire, UK. (Previous forums examined the worldwide food supply, and neuroscience and the law.) The forum was organized by a high-level steering group of distinguished researchers:

- Robert Dickinson (University of Texas)
- Inez Fung (University of California, Berkeley)
- Chris Hope (University of Cambridge)
- Brian Hoskins (Imperial College, London)
- Tim Palmer (University of Oxford)
- Ronald Prinn (Massachusetts Institute of Technology)
- Keith Shine (University of Reading)

The forum brought together a distinguished group of speakers and participants, resulting in a vigorous and eye-opening discussion. Participants included experts who take very different approaches to computer modeling of natural and human systems. Some work purely on natural systems. Others develop models involving economics, technology, agriculture, and other human systems. Each group had much to learn, and much to say, about the others' activities. The meeting was a great success. It helped to forge partnerships not only between US and UK researchers but also between distinct modeling communities and led to many recommendations for future action and collaboration.

This summary of the meeting, which was written by Steve Olson, an NAS science writer, in consultation with the steering group and staff from both academies, captures the main points from the presentations and many of the issues that arose during the discussions among forum participants. The final chapter contains observations and recommendations for future actions made by the steering committee after the forum concluded.

Raymond and Beverly Sackler created the USA-UK Scientific Forum to continue and enhance the partnership between the United States and the United Kingdom that proved so effective in World War II. In a very different venue, cooperation between the two countries continues to produce tremendous benefits today.

Paul Nurse
President, Royal Society

Ralph Cicerone
President, National Academy of Sciences

Summary

Just as climate models use numerical simulations of the atmosphere, oceans, and land to predict the future of the climate, integrated assessment models use numerical simulations of natural and human systems to explore the wider impacts of climate change and possible ways that human societies could mitigate and adapt to climate change. In addition to their necessarily simplified representation of the physical climate system, these models incorporate representations of economic activity, technological development, agriculture, and other human systems to predict the effects of a changing climate on food production, natural ecosystems, human health, population movements, water supplies, and many other issues of pressing importance. In many ways, integrated assessment modeling is still in its infancy, and current models make many simplifications beyond those in current climate models. Some are purposely very simplified and others are less simplified, allowing more complexity. Also, such models typically have to express attributes of the planet in monetary terms – a concept that many challenge. Nevertheless, integrated assessment models are the only way to gain rigorously derived, internally consistent, and quantitative insights into how the planet and human societies might change in the future.

Several kinds of integrated assessment models exist, and they have diverse goals. They reveal possible feedbacks within integrated systems and point to the influence of factors on less holistic models that are not included in those models. They indicate the strengths and weaknesses of alternative public policies, thereby providing policy makers with information they can use when making decisions. They also indicate where additional research is needed to reduce uncertainties.

Valuable policy insights derive from integrated assessment models. These models show that the limits on emissions imposed by current policies are not adequate to avoid potentially dire changes to natural and human systems. They demonstrate that greenhouse gas concentrations can be stabilized without producing major losses of human welfare, but also that such stabilization requires policies that may be difficult to implement. In addition, they reveal the consequences of changes that might be necessary to reduce climate change, such as pricing greenhouse gas emissions.

Understanding uncertainty and probabilities

The treatment of uncertainties by integrated assessment models is critically important. It can improve the policy advice generated by such models, reveal the influence of different inputs, and demonstrate the value of better information. Acknowledgment of uncertainty also provides common ground for discussion and further analyses when viewpoints become polarized.

Incorporating uncertainty can improve policy advice by allowing for a better accounting of the potential costs of climate change. For example, a calamitous outcome, such as the collapse of a crucial ecosystem or a substantial rise in sea level, may have a lower probability than other events but a very high cost. Thus, incorporating the full range of uncertainty (for both the probability and impact of an event) into a model provides a better estimate of possible future costs than using average probability and impact values for each future event.

Assessments of uncertainty also enable the influence of different inputs to a model to be determined. For example, one set of experiments with an integrated assessment model showed that the uncertainty in the climate sensitivity to greenhouse gas increases is the greatest influence on the estimated future costs of climate change, followed by inputs such as the discount rate used to adjust the costs of climate change in the future and the half life of greenhouse gases in the atmosphere. According to this analysis, improved understanding of these uncertain inputs could produce future savings of hundreds of billions of dollars.

Simplicity and complexity

More complex integrated assessment models are not necessarily superior to less complex models. Unless observations are available to underpin a more complex model, simpler models may be chosen on the basis that they are faster and easier to understand. Greater complexity in a model can make the uncertainties of the model more difficult to understand. More complex models also can contain hard-to-detect errors. However, the quantification of results from integrated assessment models generally cannot be relied upon if gross simplifications of component systems such as the atmosphere have been made.

Whether simple or complex, integrated assessment models, like climate models, have limitations that will not be overcome soon. They can yield an enormous variety of answers depending on their structure and the assumptions they incorporate. Detailed forecasts extending well into the future generally are not expected to be accurate. Complex integrated assessment models could be used to make short-term projections, where confidence in the model is higher, with simpler models being used to make more distant projections.

Future actions

Based on the presentations and discussions that occurred during the forum, the steering committee for the forum subsequently made several general observations and recommendations for future actions.

Top of the range climate models have some difficulty in explicitly simulating extreme spells of weather and extreme weather events. These have high impact, and any changes in them will be crucial. However, in general they must be represented implicitly in integrated assessment models. Climate models are starting to include uncertainties associated with motions on scales below their relatively very fine grid scale using stochastic techniques. Such techniques for representing extreme events in integrated assessment models should be explored. Model formulations must be transparent about the uncertainties of subgrid events, but building this transparency is challenging even within the modeling community, let alone for non-experts.

The simplified formulations of climate science used within integrated assessment models must be acceptable at some level to climate scientists, and the formulations of social science must be acceptable at some level to social scientists. These two groups will need to work together more intensively to improve integrated assessment models. Funding for exchanges between different communities of modelers could enhance collaboration.

One valuable research effort would be to develop a taxonomy of the goals and complexity of the spectrum of integrated assessment models, from very detailed and analytical models to simpler, more aggregated models. Such an inventory could reveal the questions asked, the physical climate information required, the lessons learned from past work, and the gaps to be filled. It also could enable future research on integrated assessment modeling to build on existing accomplishments.

The characteristics and goals of integrated assessment models

The future will be different than the present, but how will it differ?

To understand future changes in the world's climate, researchers have built computerized mathematical models that use the laws of physics and representations of chemical and biological systems to simulate the earth's atmosphere, land surfaces, and oceans. These models indicate that as humans release carbon dioxide and other greenhouse gases into the atmosphere by burning fossil fuels, converting forests to agricultural land, and other activities, the world will warm. This warming would be expected to change weather patterns, the distribution of ice on land and above the water, and global sea levels.

The uncertainties in processes represented in global climate models have been an ongoing focus of research, and many critical questions remain unanswered. What effect will changing weather patterns have on agriculture, human health, and natural ecosystems, and how costly will these impacts be? Will extreme weather events such as storms, droughts, or floods become more frequent and destructive? Can human populations change their sources and use of energy to slow the increase of greenhouse gases in the atmosphere, and how much will it cost to do so? How will societies adapt to the warming and other changes expected to occur in the future?

Researchers also have built computerized mathematical models to provide answers to these and many other questions. Known as integrated assessment models, these models link climate models of varying complexity to simulations of economic activity, technological development, agriculture, and other human activities to explore the possible evolution of linked human-natural systems. These models make many simplifications, but they are the only way to gain internally consistent and quantitative insights into how the planet and human societies might change in the future.

Quantification, although attractive, may in certain instances be rendered spurious by the simplifications in such models. Also, full integration in these models means that monetary values must be attached to many changing aspects of life on Earth – a concept that is widely challenged. Expert judgment together with less completely integrated models is a complementary and useful approach.

On 19 – 20 September 2012, the Royal Society and the U.S. National Academy of Sciences held the 2012 Raymond and Beverly Sackler USA-UK Scientific Forum to examine both integrated assessment models and the climate models on which they depend. About 80 participants gathered at the Kavli Royal Society International Centre, which is housed in Chicheley Hall, an 18th-century Georgian manor house northwest of London. Participants included researchers who work on integrated assessment models, climate modelers, other scientists, and research administrators who together engaged in a day and a half of animated discussion of the potential and pitfalls of building complex numerical models of natural and human systems. This summary of the forum draws from both the formal presentations that took place at the event and the discussions among forum participants, with a particular focus on the construction, value, and limitations of integrated assessment models.

The variety of integrated assessment models

Several types of integrated assessment models exist. Some are relatively simple – the Dynamic Integrated Climate Change (DICE) model[1] contains just 19 equations – while others contain many thousands of equations. Some are bottom-up models focused on the technologies that are available today or may become available in the future. Others are top-down models that emphasize economic markets. Different models may look at economic, physical, or ecological impacts, with simplified outputs or more detailed socioeconomic measures. Some models focus on the uncertainties associated with projections (as described in the next chapter), while others are designed to create scenarios or identify optimal policies. Similarly, the earth system models incorporated within integrated assessment models vary greatly, as do climate models in general (see Box 1.1). The earth system models used in integrated assessment models are necessarily much simpler than the climate models used in climate science, which require large computer resources to run the models and analyze data. Even in integrated assessment models, the

1 Information on the model is available at http://www.econ.yale.edu/~nordhaus/homepage/DICE2007.htm

representation of the climate system varies, the models may include different earth components, and they may be regionally or globally oriented. Many different questions can be asked about human and natural systems, and different questions require different kinds of models and approaches.

A common feature of integrated assessment models is that they are inherently interdisciplinary. Integrated assessment requires that people with different expertise work together to solve interdisciplinary problems. As Richard Tol, Professor of Economics at the University of Sussex and Professor of Climate Change at the Vrije Universiteit, Amsterdam, put it at the forum, in *multi*disciplinary research, different disciplines contribute to a problem, but they do so from their own disciplinary bases. In *inter*disciplinary research, collaborators go beyond multidisciplinary contributions to collaborate on methodological advances. In doing so, they take on problems that no one discipline could tackle on its own. The challenge, he said, is that "you want the economics to be acceptable to economists and the physics to be acceptable to physicists, and not the other way around."

Integrated assessment models differ from climate models in several ways. As Tol pointed out, natural scientists are most comfortable with "what if" questions. If circumstances change in a particular way, what are the consequences? But in the social sciences, two additional questions are pertinent. The first is, so what? If circumstances change, who is hurt and who is helped? The second is, what should be done? What is the best course of action given the consequences and the distribution of benefits and harms?

The goals of integrated assessment models

The goals of integrated assessment models are diverse. One goal is to provide information about feedbacks in an integrated system. For example, climate is clearly a factor in the economic decisions people make. As the climate changes, people will adjust by living in different places, growing different crops, and using energy differently. These actions will in turn have a feedback effect on climate. Other feedbacks occur throughout integrated assessment models, involving the use of land, water, energy, and the built environment, with further effects on population movements, health, and many other factors.

Integrated assessment models also point to interactions with other issues that may not be included in other, less holistic models. For example, urban air pollution typically occurs on a local and regional scale, not on the global scale of climate change. But the interaction and behavior of pollutants at the local and regional scale can affect atmospheric gases on a global scale. As a result, policies related to climate change are related to air pollution policies, so that a full consideration of climate change can benefit from considering urban air pollution (and perhaps incorporating such pollution into an expanded model). Other issues that may or may not be included in models include food production, transportation, manufacturing, urban development, biodiversity, population growth, water supply and quality, human health, land degradation, ecosystem disruption, and waste disposal.

Integrated assessment models provide information that policy makers can use in making decisions. Models can make transparent the trade-offs that are involved in complex policy decisions, create new policy options, compare alternate policies, and clarify the implications of following particular policies. For example, models can assess the effects of all countries limiting carbon emissions, some countries doing so, the pace at which emissions are limited, and so on. In this way, models can explore the implications of policies before potentially bad actions are taken. Also, as Tol observed, integrated assessments seek to reveal goals that are mutually contradictory or impossible to achieve. "Very few politicians ever stand up in Parliament or the Senate and propose to break the laws of physics. But on a daily basis they stand up and propose to break the laws of economics, and that is one of the things that policy-relevant research should point out."

Finally, work on integrated assessment models points toward areas where research is needed to improve understanding. Models reveal the structure of a problem, the dynamics of a problem, and which variables drive the problem. In this way, they guide future analysis and research by identifying important missing parts of the problem and identifying limits to existing analytical tools.

Building confidence in models

All models are only representations of reality and therefore inherently inaccurate. Researchers thus seek to "validate" models by comparing their performance against reality, using them to make predictions, or comparing one model against another. However, the idea of validation is quite different with models that involve social systems compared with natural systems. As Henry "Jake" Jacoby, Professor of Management in the MIT Sloan School of Management and former Co-Director of the MIT Joint Program on the Science and Policy of Global Change, pointed out, climate models can be validated through hindcasting – by establishing whether the models can account for climate change starting in the past and proceeding to the present. But the social science data needed to do extensive hindcasting for integrated assessment models generally do not exist for more than a few historical years. Also, climate has not yet changed much compared with the changes expected in the future, so the effects of climate change are still limited. Finally, human behavior can change over time, whereas the behavior of natural systems, as encapsulated in fundamental laws of physics and chemistry, does not change. Social scientists may sometimes engage in long-range or very detailed forecasts, but "to some degree it's an unnatural act," said Jacoby because of the uncertainties involved. For example, models cannot predict major social upheavals such as the dissolution of the Soviet Union or the rapid economic growth of China much in advance of the actual events.

Ronald Prinn, TEPCO Professor of Atmospheric Science at MIT, Director of the MIT Center for Global Change Science, and Co-Director of the MIT Joint Program on the Science and Policy of Global Change, suggested that a process of confidence building is more appropriate for integrated assessment models than validation. Comparison of model results with current conditions is one way to build confidence. Hindcasting is possible with some factors such as energy consumption or technological change. In addition, integrated assessment models can continually be improved through the addition of new processes and the improvement of model representations.

Supportive conditions for integrated assessment modeling

Jacoby laid out what he described as the supportive conditions for doing integrated assessment modeling.

First, the participants in a modeling effort need a common challenge for them to transcend their disciplinary boundaries and work together. They also need the promise of results that will benefit their own disciplinary work. "It's very hard to have interdisciplinary work where one discipline is the servant of the other and is just providing inputs and doesn't get anything out of it," Jacoby said.

Institutions need to facilitate integrated assessment modeling by bringing together researchers and by providing them with the financial support needed to engage in interdisciplinary work. In an academic setting, departments may differ over the allocation of funding, and institutions may need to negotiate how funding will be allocated. More than one source of financial support can keep an interdisciplinary effort going even when one source of support is lost.

Continuity of effort and personal leadership can create the inter-personal chemistry needed for successful interdisciplinary efforts. People in different departments need to not only talk with each other but also respect each other, and building this respect takes time.

National and international policies have been calling for enhanced integrative activity. In March 2011 the Belmont Forum, which is a subgroup of the International Group of Funding Agencies for Environmental Change Research, issued a challenge to governments and researchers "to deliver knowledge needed for action to mitigate and adapt to detrimental environmental change."[2] Doing so will require "inter- and trans-disciplinary research which takes account of coupled natural, social, and economic systems." Similarly, the U.S. Global Change Research Plan, which coordinates the work of federal agencies that fund climate research, has established the goal of providing "the scientific basis to inform and enable timely decisions on adaptation and mitigation."[3] Achieving this goal will require a deeper "understanding of individual natural and human earth system components," with an

2 A white paper describing the Belmont Challenge is available at www.igfagcr.org/images/documents/belmont_challenge_white_paper.pdf.

3 U.S. Global Change Research Program. 2012. *The National Global Change Research Plan: 2012 – 2021*. Washington, DC: Office of Science and Technology Policy, Executive Office of the President.

emphasis on "fuller integration of social, behavioral, and economic sciences" and "fuller integration of the biological, biogeochemical, and ecological sciences."

Finally, as Jacoby pointed out, the amount of money spent on integrated assessment modeling at present is small compared with the amount spent on climate modeling, owing in part to the relatively small size of the integrated assessment modeling community and the state of development of the discipline. Especially if research funding becomes more constrained, tension may surround how to allocate research funds among different modeling activities.

Examples of integrated assessment modeling

Several models were discussed extensively at the forum as examples of what can be done through integrated assessment modeling. One was the Integrated Global Systems Model that has been developed at MIT over the past two decades.[4] As Prinn observed in his description of the model, it has a modular framework, in that components of the model can be added or changed depending on the questions being explored and the goals of the analyses. The model includes an energy sector, an agricultural sector, and an economics model that resolves all of the world's large economies, including many consumer and producer sectors within those economics. The earth system within the model includes the atmosphere, a two- or three-dimensional ocean, biogeochemical processes on the land and in the ocean, and air pollution processes in cities. Human activities include agriculture, forestry, bioenergy production, water use, and energy demand. Examples of model outputs include GDP growth, energy use, policy costs, agriculture and health impacts, global mean and latitudinal temperatures, precipitation, sea level rise, permafrost area, vegetative and soil carbon, and trace gas emissions from ecosystems.

It is a complex model compared with some that have been developed, but one unforeseen benefit of this complexity, Prinn explained, is that it has served to attract experts who have participated in building and improving the model. By enabling them to work on complex representations of linked human-natural systems, they have been able to publish in their own fields of disciplinary expertise as well as contributing to the interdisciplinary task of integrated assessment modeling.

Many measures of uncertainties have been incorporated into the model. (The next chapter discusses the issue of uncertainty in detail.) Examples range from key aspects of the climate system such as oceanic circulation to economic factors such as the rate of penetration of new technologies into the economy. These uncertainties limit the predictions that can be made with the model, but they also indicate where the model is most usefully applied.

One topic studied with the model has been the cost of transforming the global energy system to stabilize greenhouse gases in the atmosphere. For example, an Emissions Predictions and Policy Analysis economic model within the overall model has been used to calculate the probability of global losses of welfare (approximately the total consumption of goods and services) in the year 2050 given the use of optimal policies to stabilize greenhouse gas concentrations (Figure 1.1). Stabilizing greenhouse gases at 560 parts per million (ppm) of carbon dioxide equivalents (where the level is already approximately 475 ppm today) would entail a 70 percent chance of a welfare loss greater than 1 percent, but only a 10 percent chance of a welfare loss greater than 3 percent. Even a 3 percent loss of welfare is not a major impact, Prinn noted, since it is approximately equivalent to the long-term average annual growth rate of the economy measured by welfare (essentially waiting until 2051 to reach what would have been the level of welfare in 2050). And this welfare impact should be compared to the value of the substantial damages, both monetary and non-monetary, avoided by the stabilization. However, this result depends on implementing an optimal policy on all sources of greenhouse gases, which will be difficult to achieve in the real world.

As another example, Prinn described the issues that would arise through large-scale conversion of land to the production of biofuels. The use of biofuels could reduce the need for fossil fuels. However, the necessary land conversion would entail an increase in greenhouse gases emissions. In one model run, for example, global forested area decreased by about 40 percent as biofuel production increased.

4 More information about the model is available at http://globalchange.mit.edu.

Figure 1.1
With an optimal greenhouse gas stabilization policy, losses of welfare (WL) by 2050 could be relatively limited. For example, if policies were to stabilize greenhouse gases at 560 ppm, the chance that welfare losses from those policies would exceed 3 percent is only 10 percent. Probabilities for each policy case come from ensembles of 400 projections. Source: Webster, M. D., A. P. Sokolov, J. M. Reilly, C. Forest, S. Paltsev, C. A. Schlosser, C. Wang, D. W. Kicklighter, M. Sarofim, J. M. Melillo, R. G. Prinn, and H. D. Jacoby. 2012. Analysis of climate target policies under uncertainty. *Climatic Change*: 112(3-4) 569–583.

	ΔWL>1%	ΔWL>2%	ΔWL>3%
No policy	–	–	–
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 560ppm	70%	30%	10%

This deforestation released carbon dioxide and disrupted the nitrogen cycle as forests were replaced with crops. As a result, greenhouse gas emissions increased temporarily before the benefits of using biofuels began to accrue. An interesting result of this model, Prinn noted, is that Africa could become an economic powerhouse because of the large amounts of biofuels it could produce.

Finally, Prinn discussed an analysis of the mitigation commitments made at the 2009 UN Framework Convention on Climate Change's Conference of the Parties in Copenhagen which looked at the world's current development path and the associated energy and climate implications. The MIT model indicates that energy use will stabilize in developed countries and grow in the rest of the world to about what is used presently in the developed world. With just the pledges made in Copenhagen, the projected temperature rise from 1990 to 2100 is 3.5 to 6.7 degrees Celsius (Figure 1.2). Such an increase would risk major changes to oceanic circulation and critical ecosystems. "We need to do a lot, lot more than Copenhagen," said Prinn.

The MIT program has done considerable work on how to communicate to policy makers the value of a climate policy in the face of uncertainty. One way is through a graphic Prinn and his colleagues have labeled "The Greenhouse Gamble" (Figure 1.3). It demonstrates the reduction of risk that a stabilization policy would achieve. People "get the idea," said Prinn. "They say, 'I can see what you're doing. You're lowering the risk. You haven't ruled it out totally. But you're lowering the risk of the very dangerous outcomes'."

Another modeling effort discussed extensively at the forum has been conducted by Tol and his colleagues. One way of overcoming the biases inherent in computer models is to compare the results of multiple models to see where they agree and disagree. Thus, Tol has compared the outputs of 13 models that seek to measure the tax that would need to be imposed on carbon emissions to stabilize greenhouse gases in the atmosphere by the year 2100. The assumptions surrounding these 13 estimates are obviously simplified. All forms and sources of emissions are taxed uniformly around the world, and the tax on carbon rises at a uniform rate over the course of the century, but these simplifications make comparisons possible.

If the results of these models are combined through a technique called kernel density estimation, the models imply that imposing a carbon tax of between $25 and $125 per ton of carbon in the year 2015, with a steady rise after that, is most likely to produce stabilization of greenhouse gases by the year 2100 at about twice the preindustrial concentration (Figure 1.4). The lower bound of this amount is comparable to recent prices of

Figure 1.2
Under the agreements made at the Copenhagen Conference of the Parties to the UN Framework Convention on Climate Change, annual energy use (EJ = exajoules) and resultant emissions will continue to rise through 2050.

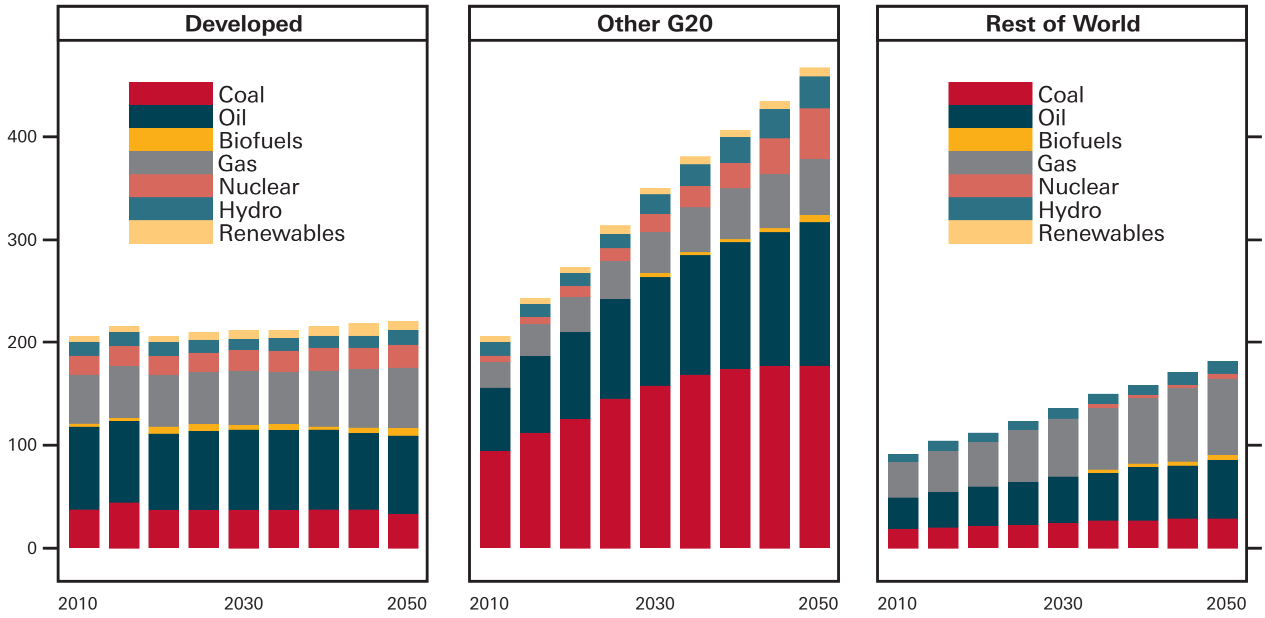
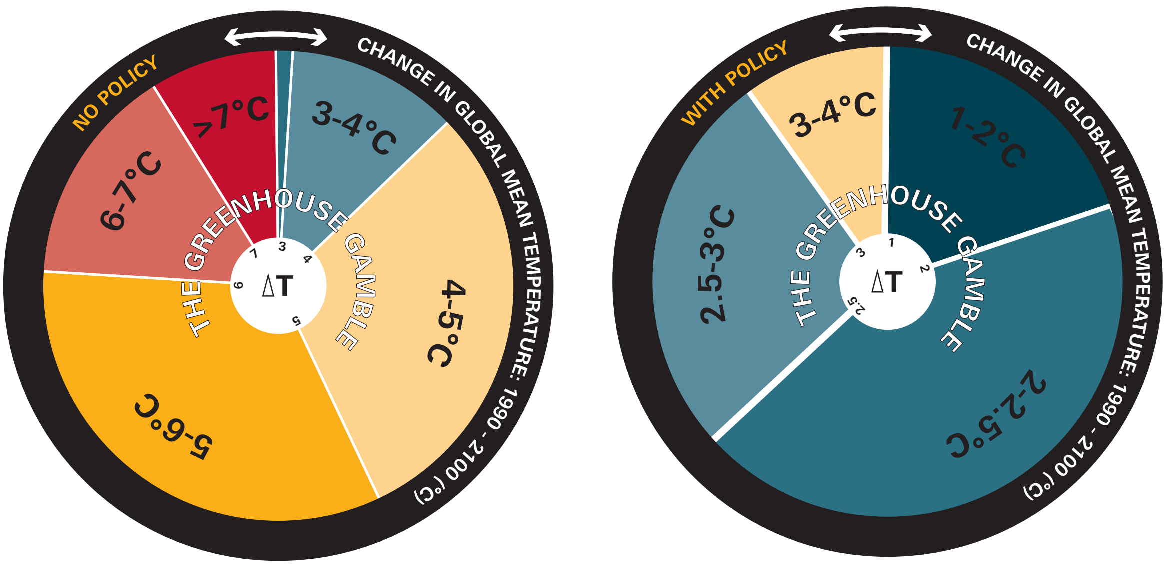


Figure 1.3
Stabilizing greenhouse gases at 660 ppm CO2 equivalents in the atmosphere (right circle) would greatly reduce the risk of extreme climate change compared with the no policy scenario (left circle). Probabilities in each of these wheels come from ensembles of 400 projections. Source: R. Prinn, Development and Application of Earth System Models, *Proceedings of National Academy of Sciences*, 2012, www.pnas.org/cgi/doi/10.1073/pnas.1107470109



emission permits in the European Union's Emission Trading System, Tol observed, which currently applies to about half the emissions in the European Union. To stabilize emissions at a lower level will require a higher tax, given the assumptions of the models. For example, to stabilize greenhouse gas concentrations at 100 ppm less than a doubling of greenhouse gases would require a high tax of $600 to $700 per ton of carbon in the year 2015, with steady increases thereafter.

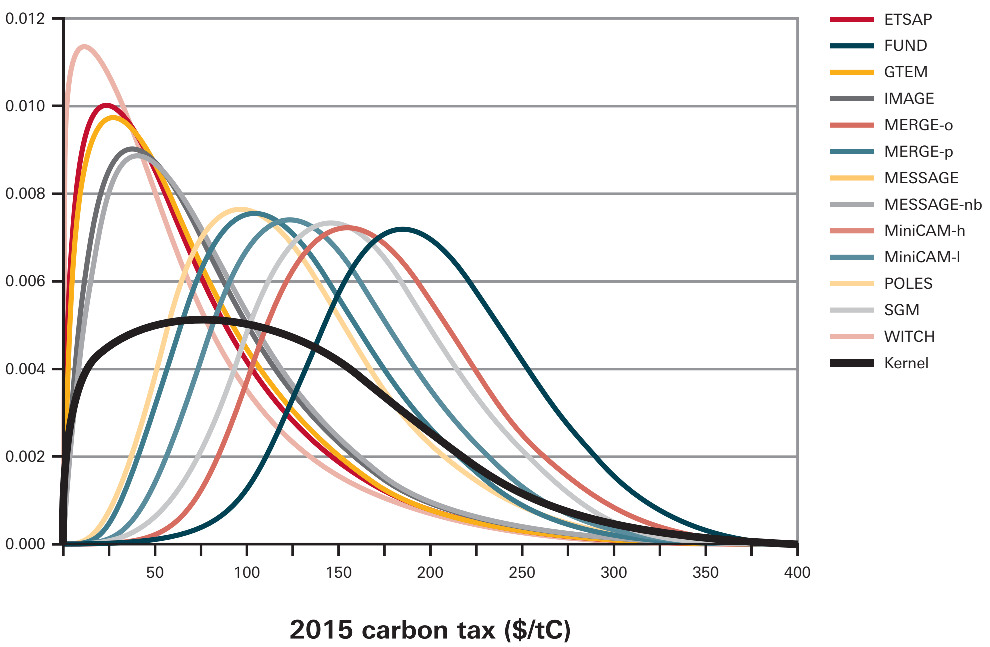
In a similar exercise, Tol used 17 published estimates in the peer-reviewed literature to assess the impacts of climate change. He estimated that the overall impact on personal welfare, as measured solely by gain or loss of income, would be positive through about 2.25 degrees Celsius of warming because of such effects as carbon dioxide fertilization of plants, reduced heating costs in winter, and fewer cold-related deaths. The results then turn negative, so that 2.5 degrees Celsius of warming would produce an estimated loss of welfare of 0.9 percent. However, this loss of income represents the equivalent of less than one year of economic growth.

Estimates of the impacts of climate change vary widely, Tol acknowledged, with some turning negative after just a half degree of warming. Moreover, the estimated average loss of welfare is strongly negative after warming of 3.5 degrees centrigrade. The reliability of such an important analysis could be greatly improved by consideration of more estimates.

A comparison of the net benefits to the net costs of reducing greenhouse gas emissions suggests that raising the tax on carbon emissions by about 2 percent per year would maximize global welfare over time, Tol said. In contrast to much higher rates of increase, a 2 percent rate would suggest that the decarbonization of the economy – an essential step in the long run to prevent continued warming – will not occur until sometime after the year 2100.

The conclusions Tol drew are that cost-benefit analysis supports some energy saving and some fuel switching, but it does not support the stringent targets recommended in current policy documents.

Figure 1.4
Combining separate probability analyses (colored lines) of the carbon tax required to stabilize atmospheric greenhouse gas concentrations at twice the preindustrial level by 2100 yields an estimate (black line) of between $25 and $125 dollars per ton of carbon.



For example, the objective of the UN Framework Convention on Climate Change is "to achieve... stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." The definitions of *dangerous*, *naturally*, *threatened*, and *sustainable* are not specified in this statement, but "stabilization of greenhouse gas concentrations" implies an almost complete elimination of carbon emissions, Tol said. Either cost-benefit analysis needs to be abandoned for climate change, which logically would require changing many other public policies, or the standard rhetoric of climate policy needs to be abandoned, he concluded.

These were controversial statements that drew considerable comment at the workshop. Forum participants disagreed with the discount rate Tol used in his model, which makes the costs of climate change in the more distant future less significant than the costs of mitigation in the near-term future. They objected to ascribing a monetary cost to such drastic impacts as the loss of entire ecosystems, where it may be more appropriate to apply a rights-based analysis to the protection of irreplaceable assets. They pointed out that the harmful effects of a warming climate can come largely from extreme events or unforeseen outcomes, which are very difficult to predict from models that simply project global average warming, and this would imply that policies should be more cautious than models suggest. They also observed that many other models lead to the conclusion that higher taxes on carbon will be needed to avoid unacceptable losses.

Tol agreed with many of these observations. For example, he observed that integrated assessment models tend to foresee a peaceful future but that conflict, whether between nations or within nations, can drastically alter emissions scenarios. He also pointed out that a major limitation of integrated assessment models is that some end in the year 2100, whereas some of the most drastic effects of climate change are not likely to occur until after that date. Though the differences were not resolved at the workshop, the discussion revealed the power of integrated assessment models to foster comparisons of policies and alternative futures.

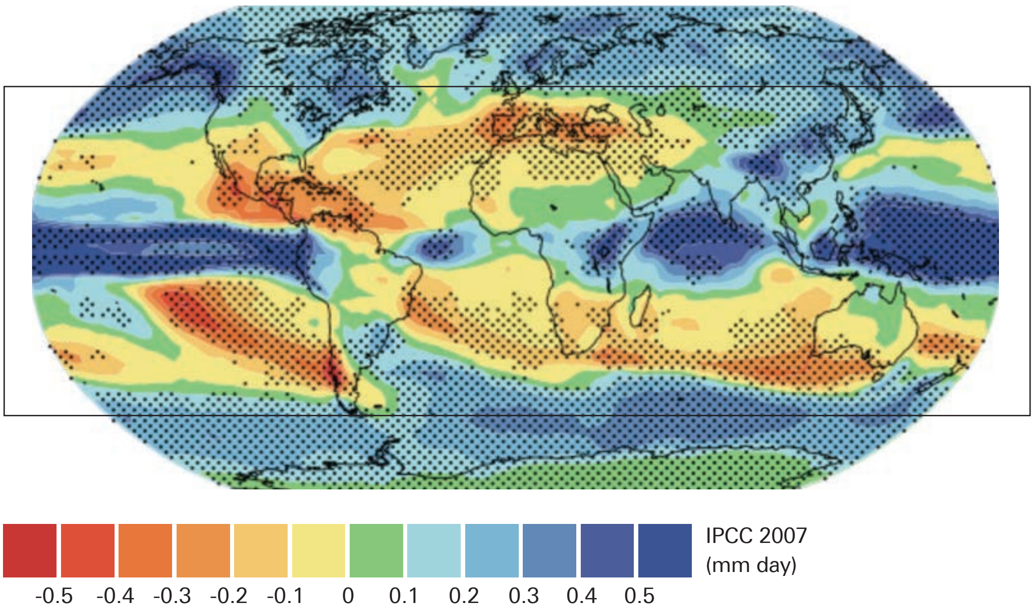
Box 1.1: a strategy for advancing climate modeling

The broad conclusions that can be drawn from simulations of the global climate are robust, said Chris Bretherton, Professor in the University of Washington Departments of Atmospheric Science and Applied Mathematics. However, at a detailed level, a Pandora's Box of complexity emerges. Climate modeling is driven both by the scientific goals of understanding and by the societal goals of applying model results. Many different groups use the results of climate models, including all levels of government, nonprofit organizations, and the private sector, and their demands are becoming more local, specific, sophisticated, and probabilistic. Also, the results of climate models are critical inputs to integrated assessment models.

Many kinds of climate models have been developed to meet these demands. However, knowledge gaps and variability at the subgrid levels in existing models create critical uncertainties, such as the effects of clouds or aerosols, that will not be eliminated soon, even at global scales. Furthermore, local trends and extreme events often are driven by processes occurring at multiple scales or in distant locations, which complicates the assessment of uncertainties. For example, regional subtropical rainfall trends are hard to predict, yet these trends could have dramatic impacts on ecosystems, agriculture, and water resources for cities and towns.

Bretherton recently chaired a National Research Council committee that proposed a strategy for U.S. climate modeling over the next decade[5] The committee identified three prominent drivers for such a strategy: decision makers' needs for climate information, the transition to radically new computing hardware, and increasing understanding of the earth system. It then developed a vision for the next generation of climate models that looks toward a hierarchy of models, high-resolution modeling, comprehensive representation of the earth system, an advanced climate observation system, and improved access, archiving, and synthesis of data.

Precipitation A1B 2080 – 2099 minus 1980 – 1999



Many climate models predict that subtropical regions of the world will become drier as greenhouse gases increase, but not all models are in agreement at a regional level.

5 National Research Council. 2012. *A National Strategy for Advancing Climate Modeling*. Washington, DC: The National Academies Press.

Box 1.1 continued

To achieve this vision, the committee called for improvements in climate models through multi-institution efforts. The transition to massively parallel computing will require the adaptation of both hardware and software. A common software and data infrastructure would help coordinate the development of global and regional climate models and promote a hierarchy of models.

The committee also called for an annual U.S. climate modeling forum that would bring together climate modelers and users and provide a mechanism for different climate modeling communities to work together. In addition, the users of climate models would have opportunities for continuing education and strategic discussion.

A U.S. modeling effort that spans weather to climate time scales could test advances in climate models at weather time scales, reduce weather forecast errors, and provide a powerful tool for synthesizing observations into climate reanalyses.

Finally, developing a training program for climate model "interpreters" could facilitate two-way communication between climate model developers and users. These individuals could translate findings and output from climate models for a diverse range of private and public sector applications and channel user feedback to the climate modeling enterprise.

Using models to understand uncertainty

All models of linked human-natural systems have uncertainties. But these uncertainties are not necessarily a weakness of integrated assessment models. Indeed, models may be focused as much on identifying and quantifying uncertainties as on making projections. Especially when discussions of climate change become polarized, an acknowledgment of uncertainty provides a common ground from which to move forward.

Uncertainties also do not imply that nothing should be done. As an example, Granger Morgan, Professor and Head of the Department of Engineering and Public Policy at Carnegie Mellon University, described the experience in the 1980s with acid rain. In the United States, the Reagan Administration argued that the uncertainties were so great that it made sense only to do research until better understanding could be obtained. A large multi-laboratory study known as the National Acid Precipitation Assessment Program, which was based on the development of submodels that would later be connected, did not yield clear-cut policy guidance. But a smaller scale effort at Carnegie Mellon University, which used a simple integrated model that focused on key choices in regulatory policy and incorporated uncertainties, quickly showed that some controls on the emissions of sulfur dioxide and nitrogen oxides were warranted even with significant uncertainties.

Policy makers tend to want a single number that they can use to make decisions, but the uncertainties inherent in models make it impossible to derive such a number. Instead, these uncertainties point to the need for decisions to be robust despite uncertainty. As several forum participants observed, policy analyses sometimes have a tendency to minimize uncertainty, which can reduce the value of policy guidance. A better approach for policy analyses is to specify known uncertainties at the beginning of a project and maintain awareness of those uncertainties while exploring possible ways of reducing them.

The PAGE model

Chris Hope, Reader in Policy Modeling at Judge Business School, University of Cambridge, pointed to three benefits obtained through a better understanding of uncertainty:

- Changing the policy advice generated by integrated assessment models
- Revealing the influence of different inputs
- Demonstrating the value of better information

Hope works with a 'classic' integrated assessment model known as PAGE that broadly considers the impacts of climate change and the costs of both abatement and adaptation. It divides the world into eight regions and can make assessments to the year 2200. The model can be run to analyze the total impact of climate change, the impact at some date in the future, the cost of taking a particular action, or the net benefit of that action. In this way, it allows policies to be compared – for example, a more aggressive abatement policy, requiring greater changes in energy systems, versus a business as usual policy that will have higher impact costs of climate change.

The model has 112 inputs, each of which has an associated uncertainty characterized as a probability distribution. These inputs range from earth system factors such as the sensitivity of climate to greenhouse gas levels to economic parameters such as the discount rate or the vulnerability of the economy to climate change. The model's impacts are divided into four categories – sea level rise, economic effects, non-economic effects such as ecosystem losses, and "discontinuities," which include catastrophic events such as the melting of the Greenland or West Antarctic icesheets – with all of the impacts converted into costs based on the value that people attach to avoiding those impacts. Both the probability distributions and the impact valuations are based on evaluations done by experts in those particular areas.

Better policy advice

The first benefit of understanding uncertainty is that it can change policy advice. As an example, Hope cited a comparison of a business as usual emissions scenario with a low emissions scenario. If the mean value is used for each input to the model, the low emissions scenario produces total discounted benefits, compared with the business as usual scenario, of $150 trillion in constant dollars. However, it also has total discounted abatement costs of $162 trillion, yielding a negative net value of benefits for the low emissions scenario. This analysis would point to the business as usual scenario as preferable.

However, if the whole range of probability distributions is used for the inputs, the results are quite different. In this case, the discounted benefits of the low emission scenario are $314 trillion, while the discounted abatement costs are $184 trillion, yielding a positive mean net benefit of $130 trillion. In this more detailed analysis, the low emissions scenario is clearly advantageous.

The reason for the difference is that the impacts, and thus the valuation, of climate change have a very long right tail. Bad outcomes, such as high climate sensitivity or catastrophic events, may not be very likely, but if they occur they have drastic consequences. The low emissions scenario largely avoids the small chance of a very bad outcome. Thus, a full consideration of uncertainty reveals that action is warranted today to avoid relatively low probability events that could have calamitous effects.

The influence of inputs

The second benefit of understanding uncertainty is that it can demonstrate the relative influence of different inputs to the model. Thus, the PAGE model can be used to calculate the relative effects of increasing each input to the model by one standard deviation of the uncertainty distribution (Figure 2.1). The largest influence on the model's output is one component of the climate sensitivity, the transient climate response, followed by the elasticity of utility (which involves the distribution of costs and benefits around the world), a measure of the discount rate known as the pure time preference (ptp) rate, and the half life of global warming.

The transient climate response is the amount by which the temperature will have risen if greenhouse gas concentrations double over a period of 70 years. An increase of one standard deviation in transient climate response increases the overall net benefits of the low emission scenario by about $200 trillion. In contrast, the effects of a higher pure time preference (ptp) rate are negative because the major benefits of a low emission scenario come later in this century or in the next century while the costs start accruing immediately.

The value of better information

The third benefit of a better consideration of uncertainty is that it demonstrates the value of better information. Suppose that researchers were able to develop new information revealing that climate sensitivity is most likely toward the high end of the range now thought possible. This would narrow the probability distribution of climate sensitivity, which would allow emissions pathways to be re-optimized. The PAGE model then can calculate the net economic benefits of having this more detailed information.

At the forum, Hope presented an analysis of the benefits of research that would improve our knowledge of the climate sensitivity, revealing whether it is toward the low, middle, or high end of the range predicted today. If research could generate this new knowledge, its benefits could be approximately $400 billion in constant dollars. "This is a big number," Hope said. Such an analysis can "justify quite large research programs to try and get better information." Furthermore, the number is large today but decays over time as society has to pursue hedging strategies to avoid severe impacts in the face of uncertainty before the better information is received, emphasizing the importance of getting better knowledge sooner rather than later.

The costs of incorporating uncertainty

Understanding uncertainty does have costs, Hope acknowledged. Developing probability distributions for the 112 inputs is difficult and requires considerable time. Because the inputs are probability distributions, the model has to be run typically 10,000 to 100,000 times to calculate the outputs of interest. However, the model is simple enough that even 100,000 runs take under an hour. Only when calculating optimum values of inputs – which can require tens of millions of model runs – does the strain on computer resources become significant.

Perhaps the most significant cost of incorporating uncertainty into integrated assessment models, Hope suggested, is that a full account of uncertainty requires reduced complexity in models. The next chapter discusses the advantages and disadvantages of simplicity in integrated assessment models.

Remaining uncertainties

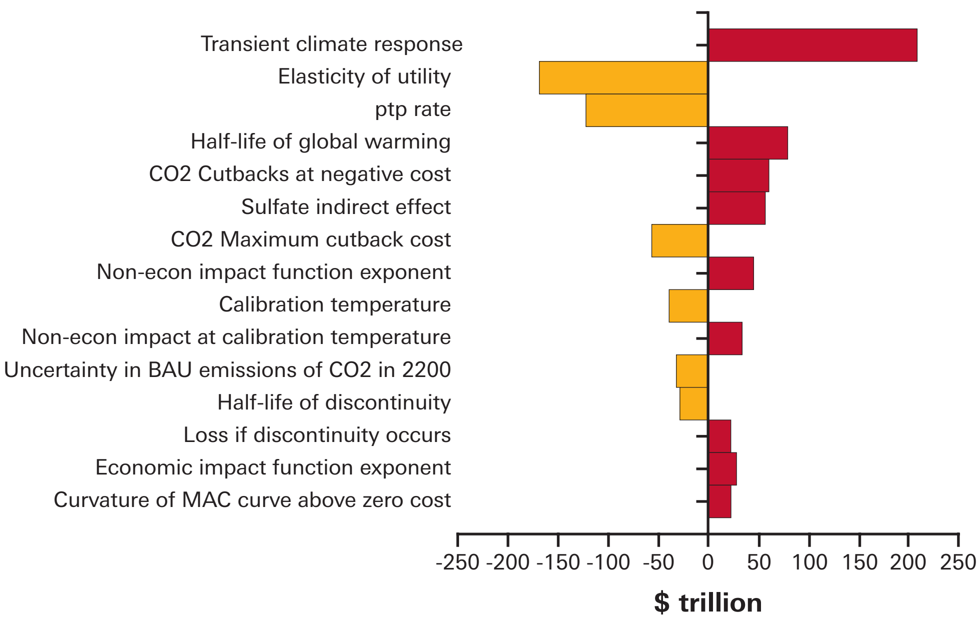
Integrated assessment models continue to have many uncertainties that can limit the policy guidance that they are able to provide. For instance, one uncertainty much discussed at the meeting was the difficulty of predicting runoff at the level of individual river basins. This is a complicated problem involving climate, land use, agriculture, and other factors. Climate models themselves have uncertainty in generating regional precipitation forecasts (see Box 2.1), and additional uncertainties arise through the factors typically considered in integrated assessment models.

Another uncertainty involves extreme events, both in natural systems and human systems. Climate models are not good at describing these extreme events, often because they occur at a level of geographical resolution smaller than that of the model. Similarly, integrated assessment models typically cannot predict major disruptions such as wars or economic collapses. Both climatic models and integrated assessment models may assume that extreme events will not change an overall long-term trend. But because these extreme events will be a major source of human impacts, their absence from current models is a serious flaw and an important challenge for the future.

Finally, a much broader constraint on models is that they assume the ongoing existence of a particular economic structure and set of climatic boundary conditions. But the economic system may change over time as the factors of production shift or the relative importance of services, agriculture, and manufacturing evolves. Similarly, as the climate enters a new regime, climatic boundary conditions may change in ways not foreseen by current models. Both climate models and integrated assessment models will need to be continually updated to incorporate newly recognized processes and new information.

Figure 2.1

Increasing the transient response of the climate to greenhouse gas loading by one standard deviation of the associated uncertainty in this measure has the greatest influence on calculations of the net benefits of the low emissions scenario. A similar increase in the pure time preference (ptp) rate has a somewhat lesser influence and causes the economic effects of the low emissions scenario to be negative rather than positive.



Box 2.1: dealing with uncertainty in climate models

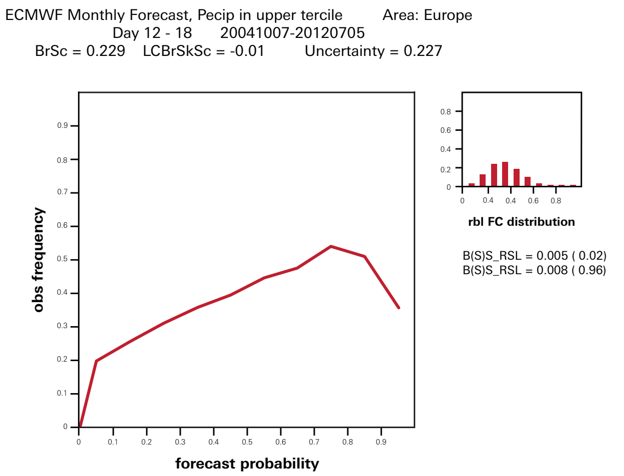
Climate models are becoming important tools for decision makers across a wide variety of sectors, including agriculture, water resources, construction, and humanitarian relief. But for these tools to be useful, climate models must be reliable.

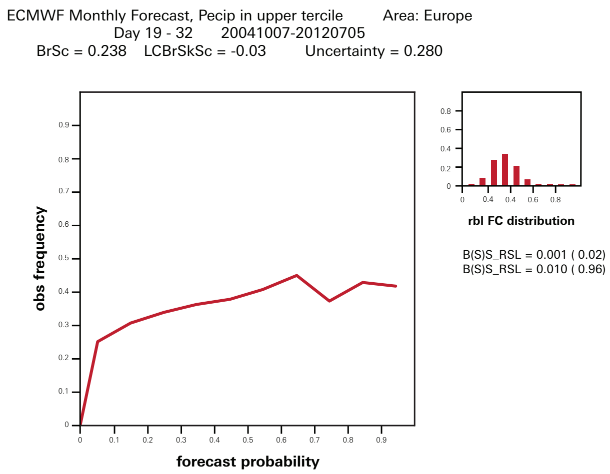
Tim Palmer, Royal Society Research Professor at the University of Oxford, examined the reliability of climate models by analyzing the reliability of closely related models designed to forecast weather a few days or weeks in advance. Deterministic weather models are generally unreliable, so weather forecasters have moved toward ensemble-based forecast methods that indicate the probability of future weather events through combinations of multiple model runs. However, the current levels of statistical reliability from these ensembles are far from satisfactory. Weather models designed to predict the probability of rainfall are fairly reliable four to five days in advance, but their reliability drops dramatically more than a couple of weeks after the prediction (see figure).

On a seasonal timescale, multi-model ensemble forecasts for some regions are fairly reliable. Thus, climate models are fairly good at predicting rainfall anomalies in the Amazon basin and southeast Asia, where climatic factors such as El Niño exert a strong effect. But they are poor at predicting differences from climatology in regions such as India or Europe. Furthermore, climate forecasts made for these regions tend to be overconfident, in that they underestimate the uncertainties associated with the forecast. This observation suggests that current models may be overconfident about climate change over longer periods, especially on a regional scale.

Improving reliability may require a culture change in the development of comprehensive models of weather and climate, Palmer said. Uncertainty will need to be embraced at all levels of model development, both in the parameterization of subgrid processes and in the core dynamics of models. For example, clouds in a model may need to be treated not as a uniform process at the subgrid level but as a spectrum of stochastic processes.

According to this modeling philosophy, the boundary between the dynamic core of models and subgrid parameterizations will become increasingly blurred in the future. These developments can in turn inform computer manufacturers about the types of computational architecture needed to improve the reliability of climate predictions. For example, it may be possible to run climate models on superefficient computer chips that do not always calculate exact answers yet still produce better overall simulations of climate.





If forecasts of precipitation probabilities were perfect, the forecast probability (the horizontal axis) would match the observed frequency (the vertical axis), resulting in a 45-degree line from the origin. But forecasts are already fairly unreliable 12 to 18 days after the forecast (above left) and are even less reliable 19 to 32 days after the forecast (above right).

Simplicity and complexity in integrated assessment models

As noted in Chapter 1, integrated assessment models can range in size from a handful to thousands of equations. They can use simplified representations of individual processes or much more elaborate formulations of those processes. They can be run a single time or hundreds of thousands of times with varying inputs. Some integrated assessment models can be used by single researchers, while others require large teams to run.

The desired complexity of a model depends on the questions being asked, said Simon Dietz, Co-Director of the Grantham Research Institute on Climate Change and the Environment at the London School of Economics and Political Science. Is a model being used to predict the future or to understand a system? Is a model designed to produce alternate simulations or to search for optimal policies? Is the purpose of a model to measure the cost effectiveness of policy options against established goals or to do cost-benefit analyses of climate policies to control emissions? Answers to these questions will go a long way toward dictating the appropriate complexity of an integrated assessment model.

Factors determining complexity

Stochastic models that are being used to assess the effects of uncertain inputs typically have to be simpler than deterministic models that are calculating outputs from a single choice of inputs. Also, looking at a specific component of a system often requires a more complex description of the component of interest and less complex descriptions elsewhere. If a model incorporates relatively simple equations, those equations may need to be validated against more complicated renditions of the subsystems in a model. All else being equal, the more components a model includes, the more complex the model will be.

A phrase used at the forum was "horses for courses" – referring to the idea that different horses run better on different tracks. A distinction also was made between models that are primarily diagnostic, meaning they are directed toward understanding a system, and models that are largely prognostic, meaning that they seek to predict the future. In practice, most models combine these tasks in different proportions. For example, some integrated assessment models initially were built primarily for understanding but have over time become used more as models for prediction.

A basic problem of integrated assessment models is that they often seek to model events for which there are few data points. For example, a damage function in such a model may be based on very few observations, which means that it can be difficult to distinguish between different formulations of the data function. Also, as mentioned in the previous chapter, the model may be trying to predict a system governed by boundary conditions that have never existed in the past, which means that no observations exist to calibrate the model. (Box 3.1 provides an example of an earth system model that seeks to predict unprecedented conditions, with counterintuitive results.)

As a result of the lack of observations, more complex models tend to be compared with less complex models rather than against observations. This makes it difficult to determine the proper balance between simplicity and complexity, Dietz observed. For example, the lack of data on damages as temperatures increase represents a lack of guidance for model builders when incorporating damage functions into their models. A thorough study of the consequences of substantial climate change would make it possible to interpolate damages rather than extrapolate them from marginal climatic changes, which would be helpful, but any such assessment also would have large uncertainties. In addition, because of the lack of observations, differences in modeling philosophy become more prominent. For example, some modelers are very cautious in modeling phenomena that are poorly understood, while others include such phenomena in part to understand them better. (Box 3-1 provides an example of a modeling system that adds complexity but can also add uncertainty.)

Finally, more complex models are more likely to have errors in the underlying computer code, and these errors can have subtle effects on outcomes. Though modelers try through various means to minimize or eliminate these errors, they cannot be sure that errors do not exist.

"The presumption should be that small is beautiful," Dietz concluded. "I don't think that complexity is intrinsically valuable. Indeed, there is a sense in which complexity makes things harder to understand, not only for decision makers but, as is evidenced in error rates in model code, for modelers themselves." A single integrated assessment model should never attempt to do everything. There should be a division of labor among numerous simple models, and modelers should resist the temptation to increase complexity even where more data exist. More complexity is valuable where greater process understanding is sought or where simple models do not match either the data or the results of other models. However, greater complexity should be introduced only where needed, with simpler formulations sufficing where greater complexity does not matter.

The limitations of integrated assessment models

As an example of the limitations of integrated assessment models, Morgan described the series of Integrated Climate Assessment Models developed at Carnegie Mellon University over the past two decades. The models have been based on influence diagrams developed by Morgan and his colleagues to describe key functional relationships. These relationships are then converted into a model through a software package now known as "Analytica" that makes it straightforward to build, test, and refine probabilistic models. Various sub-elements of the models could be altered and the implications explored. The models also include switches that allow for the exploration of alternate model structures.

From the outset the Carnegie Mellon University group was persuaded that various uncertainties would be the central issue (see Chapter 2). It therefore sought to represent uncertain quantities as probability distributions, propagate probabilistic values through the models, and perform deterministic and stochastic sensitivity and uncertainty analyses. This approach has made it possible to explore alternative assumptions about such factors as energy system changes, rates of discovery of new resources, diffusion of new technologies, ecological responses, demographic models, air pollution and aerosols, changes in the discount rate, and even whether or not "tax revolts" occur. In addition, the models have made it possible to explore different decision rules such as minimizing ecological impacts, minimizing economic impacts, or various combinations of the two.

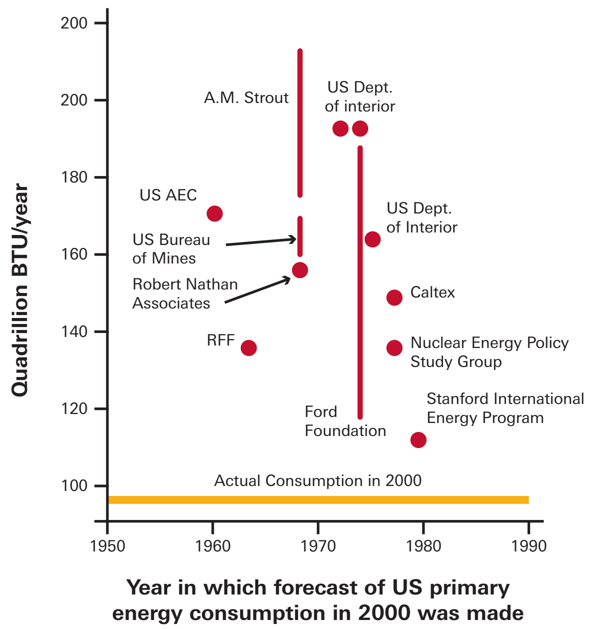
Morgan and his colleagues have found that the models yield an enormous variety of answers depending on the range of plausible assumptions made about the structure of the model, the decision rules used in the model, and which regional decision makers are considered. This range of answers can make it difficult or impossible to differentiate between the outcomes of alternative policies. Rarely is any policy optimal for all regions, and rarely are any results stochastically dominant.

Based on these conclusions, Morgan has concluded that it is a mistake to think in terms of a single utility-maximizing decision maker for the entire planet. Instead, at least a dozen different nations will make choices that could have significant implications for climate, and many of those choices will be made not by single national decision making authorities but rather through the individual choices of millions of individual citizens driven by local interests and conditions.

Morgan and his colleagues have concluded that the most useful results from integrated assessment models are not answers to specific policy questions but insights into the nature and structure of the climate problem and into what more needs to be learned to address that problem. Morgan also has come to the somewhat pessimistic conclusion that many of the standard analytical tools used in such modeling are not appropriate for the problem. Most conventional tools make such assumptions that values are known, a single decision maker can maximize expected utility, that impacts are of manageable size and can be valued at the margin, and that uncertainty is modest and manageable. For many climate problems, these assumptions are clearly unrealistic. Instead, the resources required to make changes are large compared with those of nations and cultures, the problems involve long time scales, and the cultural or political differences among groups are large. For these problems, non-conventional analytical methods need to be adapted or developed.

Retrospective analyses suggest that the ability to make good predictions about key variables such as future energy consumption is extremely limited. Forecasts of U.S. primary energy consumption for the year 2000 made in the early 1980s were uniformly too high (see Figure 3-1). Forecasts of coal prices, natural gas prices, and electricity sales have all been seriously mistaken. For this reason, said Morgan, it does not make much sense to run integrated assessment models for 50 or 100 years into the future. Doing so would be like projecting population, labor productivity, and technical performance from the American Civil War to today.

Figure 3.1
Forecasts of U.S. primary energy consumption for the year 2000 made in the 1960s and 1970s all exceeded the actual consumption. Source: Smil, V. 2003. *Energy at the Crossroads: Global Perspectives and Uncertainties*. Cambridge, MA: MIT Press.



Morgan also pointed to problems with conventional scenario building. The more detail that is added to a story line, the more probable it appears, and the greater the difficulty people have in imagining equally or more likely ways in which the same outcome could be reached. As a result, the construction of scenarios often leads to systematic overconfidence and underestimation of the range of possible future outcomes. A better approach would be to describe a trajectory over time through a multidimensional space of future possible conditions, with intervals of that space ascribed discrete probabilities.

Finally, Morgan said that he personally is not persuaded that integrated assessment modeling has had much impact on the broader science community or on public or policy discourse. On the other hand, he acknowledged that others have pointed to greater impacts, including a report from a Department of Energy workshop that concluded that integrated assessment models "have delivered tremendous value to date" and "are being used by regional, national, and global decision-makers in both the public and private sector".[6] One challenge for the community is to show that its work is being used and is affecting public policy, Morgan stated.

Based on their experiences, Morgan and his colleagues have identified seven attributes that any good integrated assessment – not necessarily in the form of a model – should exhibit:

1. The characterization and analysis of uncertainty should be a central focus of all assessments.
2. The approach should be iterative. The focus of attention should be permitted to shift over time depending on what has been learned and which parts of the problem are found to be critical to answer the questions being asked.
3. Parts of the problem about which little knowledge exists must not be ignored. Order-of-magnitude analysis, bounding analysis, and carefully elicited expert judgment should be used when formal models are not possible.
4. Treatment of values should be explicit, and when possible parametric, so that many different actors can all make use of results from the same assessment.
5. To provide proper perspective, climate impacts should be placed in the context of other natural and human background stochastic variation and secular trends. Where possible, relevant historical data should be used.
6. A successful assessment is likely to consist of a set of coordinated analyses that span the problem, not a single model. Different parts of this set will probably need to adopt different analytical strategies.
7. There should be multiple assessments. Different actors and problems will require different formulations, and no one project will get everything right. Nor are results from any one project likely to be persuasive on their own.

6 A. C. Janetos et al. 2009. *Climate Change Integrated Assessment Research*. Washington, DC: U.S. Department of Energy, Office of Science.

Simpler approaches

In addition, Morgan advocated the use of simpler approaches rather than complex integrated assessment models. One involves model switching. Different approaches to the climate problem are believable for different periods of time into the future. For example, a general equilibrium model of the world's economy would not be expected to be reliable for more than a decade or two. Therefore, running such a model out for a century is not informative and may be misleading. One approach to this problem would be to start with complex models about which modelers are fairly confident and switch to simpler order-of-magnitude models where confidence is reduced.

Morgan also argued for the use of bounding analysis. Rather than developing a few very detailed storylines that lead to a particular outcome with a high value, build a list of all the developments that might lead to the high value of that outcome along with all the developments that might lead to that outcome having a low value. The resulting lists and analyses then could be subjected to repeated critical review and revision.

Finally, he made a plea for working a problem backwards. Modelers have a strong tendency to work in the direction of causal influences, from greenhouse gas emissions, to changes in climate, to impacts, to the valuation of impacts. The problem is that the earlier steps have so much uncertainty that the probability distributions for the latter stages are very broad. An alternative strategy is to ask what outcomes are most important and then work backwards to what things would have to happen to lead to those outcomes. Many people find it very hard to approach the problem in this way, but it deserves serious consideration, Morgan said.

In the Center for Climate and Energy Decision Making at Carnegie Mellon University,[7] Morgan and his colleagues have chosen to stop doing integrated assessment work. Instead, they are focusing on three tasks:

1. Addressing technical, economic, and behavioral issues that arise on the critical path to decarbonizing the world's energy system. The climate problem is basically the energy problem, and any success the world has in reducing greenhouse gas emissions will be the emergent consequence of a large number of distributed decisions (which might later be merged to a global regime).

2. Understanding the impacts of climate change and strategies for adapting or mitigating their consequences, because the earth is already committed to a large amount of climate change.

3. Focusing on the scientific, policy, and regulatory aspects of solar radiation management, because such steps will prove to be tempting (being fast and cheap) as the impacts of climate change become more apparent.

In all the work Morgan does, he also continues to focus on characterizing, analyzing, and communicating uncertainty.

Box 3.1: afforestation as a climate management strategy

Simulating the movement of water through the earth system has been a major challenge of weather and climate modeling. In particular, the amount of moisture in the soil has been one of the weakest links in climate modeling. Soil moisture depends on precipitation, evaporation, vegetation, landforms, soil characteristics, and other factors, producing a complex system that is difficult to model. Yet soil moisture determines whether an ecosystem will provide food, fiber, and other services or whether it will wither and increase the amount of carbon dioxide in the atmosphere as organic matter decomposes.

As an example of the benefits to be gained through greater understanding of one component of the earth system, Inez Fung, Professor in the Department of Earth and Planetary Science at the University of California, Berkeley, presented the results of three planetary experiments using the climate model developed at the National Center for Atmospheric Research. In the first

7 Information about the center is available at http://cedm.epp.cmu.edu/index.php

Box 3.1 continued

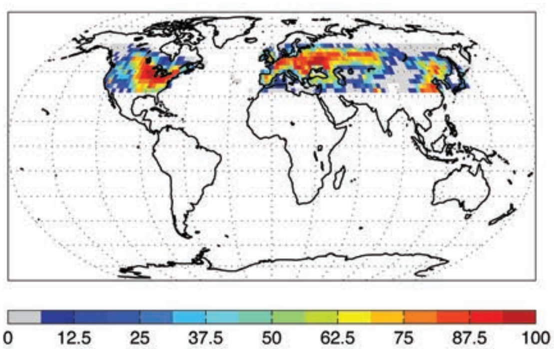
experiment, bare ground in the Arctic was replaced in the model with deciduous trees. The trees absorb carbon dioxide from the atmosphere, thus reducing greenhouse warming. However, transpiration from the trees increases water vapor in the atmosphere, which enhances the greenhouse effect and warms the atmosphere. This warming in turn furthers the melting of sea ice and increases evaporation, leading to amplification of the warming.

In the second experiment, croplands and grasslands in the middle latitudes were replaced in the model with deciduous trees. At these latitudes, the reservoir of moisture in the soil is limited, which limits transpiration from plants. The atmosphere then warms up from sensible heat emitted from the earth's surface into the atmosphere. The absorption of solar radiation by the darker trees also increases warming. The resultant warming of the northern hemisphere shifts the rain belt in the tropics, drying the southern edges of the Amazon. As a result, plant growth diminishes in regions distant from the afforested area.

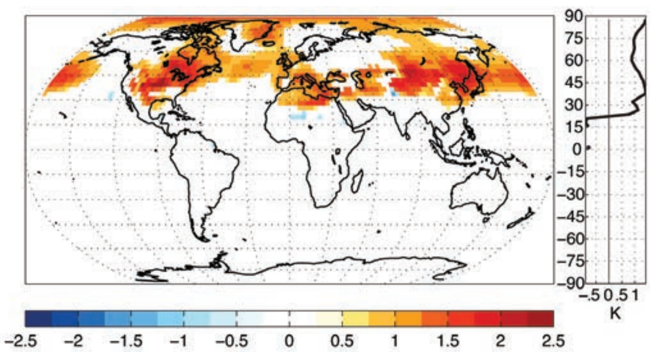
In the third experiment, the photosynthetic season is extended into the dry season in the tropics. Because soil moisture is plentiful, the enhanced transpiration contributes to cooling. Thus, the effects of growing trees in lower latitudes are positive both because the trees remove carbon dioxide from the atmosphere and contribute to atmospheric cooling.

Based on these results, Fung observed that large-scale afforestation in middle and high latitudes may not be effective carbon management strategies in the long term because the reduction in atmosphere carbon dioxide due to afforestation leads to reduced air-sea differences in carbon dioxide partial pressures and a reduced ocean carbon sink. As a result, changes in globally averaged temperature and carbon dioxide levels are minimal at equilibrium. She noted that there are many good reasons for growing trees other than climate management. But she also observed that a comprehensive analysis would be needed for afforestation to be considered as a major climate management strategy.

a) Map of the area of new trees (%)



b) Δ Temperature (Kelvin)



Replacing mid-latitude croplands and grasslands with deciduous forests, as shown in the left-hand figure, produces heating of those regions by greater absorption of solar radiation and increased heating of the atmosphere where transpiration is constrained by finite soil moisture, as shown in the right-hand figure. Source: Swann, A. L. S., I. Y. Fung, and J. C. H. Chiang. 2012. Mid-latitude afforestation shifts general circulation and tropical precipitation. *Proceedings of the National Academy of Sciences* 109(3):712-716.

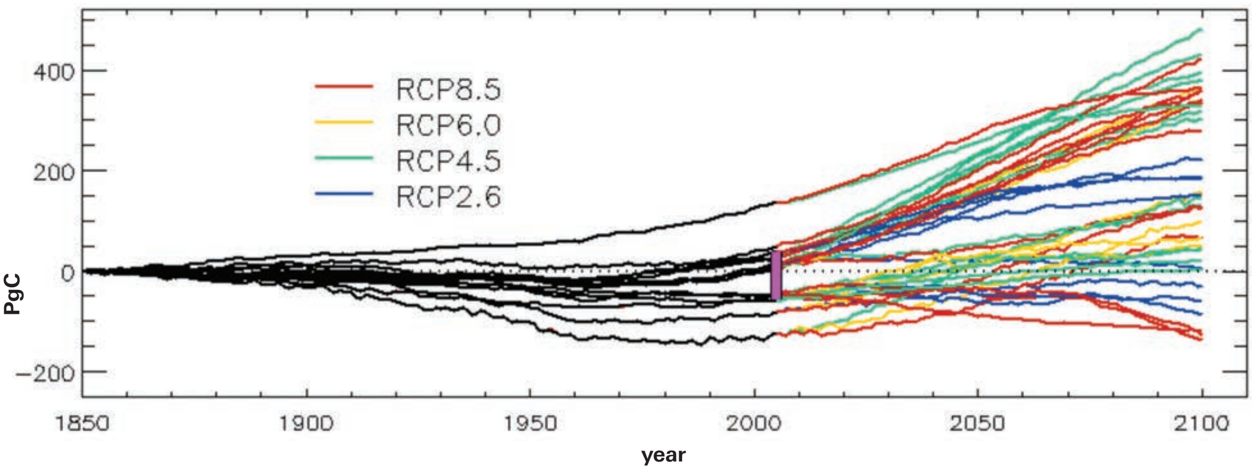
Box 3.2: complexity in carbon cycle models

Climate models have become more complex over time as more physical components have been added to the models and as atmospheric chemistry and land and ocean biogeochemistry have been modeled in greater detail. One major advance has been to simulate the changing levels of carbon dioxide in the atmosphere. Only about half of the current human emissions of carbon dioxide remain in the atmosphere. The remainder is being absorbed by the oceans and by vegetation on land. However, these carbon sinks are sensitive to climate. For example, if warming temperatures cause vegetation to take up less carbon from the atmosphere, warming will be greater than expected – an example of positive feedback.

Carbon cycle models take emissions of carbon dioxide as given and then simulate the movements of carbon among the atmosphere, land, and ocean. In an effort to be more realistic, these simulations are more complex than previous representations – the obvious question is whether they also are more accurate.

Pierre Friedlingstein, Chair in Mathematical Modeling of the Climate System at the University of Exeter, has been participating in an effort to compare models of the carbon cycle and their implications for climate models in general. This comparison has shown that as carbon cycle models have become more complex, they have created larger uncertainty in the output of climate models. This greater uncertainty in climate models in turn contributes to greater uncertainty in integrated assessment models, which some of the models can easily handle. However, greater complexity in integrated assessment models can complicate their provision of guidance for policy makers. For example, models that predict the uptake of atmospheric carbon by the soil and vegetation do not always agree even on the sign of the change for various emissions scenarios (as shown in the figure), and the model spread is larger than the spread associated with different scenarios. Land use is partly responsible for this, and it is unclear how models differ in their estimate of land use changes. More validation is needed in the model development phase, Friedlingstein said, and integrated assessment models need to keep the uncertainties of carbon cycle models in mind.

Total land carbon



Carbon cycle models that predict the uptake of atmospheric carbon by the soil and vegetation for various emissions scenarios (representative concentration pathways, or RCPs) make a greater range of predictions than the range of the emissions scenarios.

Recommendations

For several weeks after the forum concluded, the steering committee carried on a lively e-mail exchange about the major observations that emerged from the meeting and the recommendations that follow from them. This final chapter of the forum summary highlights those observations and recommendations.

Current integrated assessment models sometimes overlook events with low probabilities but high impacts. More work is needed to understand the tail of the probability distributions for these events, as well as the occurrence of extremes and thresholds in climate-related systems. The uncertainties associated with events occurring on small geographical scales also need increased attention in integrated assessment models. Climate models have attempted to capture extreme events that occur below their relatively fine grid scale through stochastic approaches; perhaps integrated assessment models can do the same to attempt to represent extreme events and thresholds. Model formulations must be transparent about the uncertainties of subgrid events, but building this transparency is challenging even within the modeling community, let alone for non-experts. Easily understood subjective sensitivity tests need to be associated with the factors contributing to uncertainties, even if these uncertainties cannot be quantified.

The simplified formulations of climate science used within integrated assessment models must be acceptable at some level to climate scientists, and the formulations of social science must be acceptable at some level to social scientists. These two groups will need to work together more intensively to improve integrated assessment models. In particular, the linkages between state-of the-art climate models and integrated assessment models (with simplified climate models) need to be studied to maximize the benefits from both types of models. Also, the purposes of integrated assessment models need more attention, particularly as work on regional impacts increasingly involves different sets of decision makers than are involved in national or international issues. Funding for exchanges between different communities of modelers could enhance collaboration.

Decision making can and should be served by a range of models, not just the most complex integrated assessment models. Increased complexity in a model can obscure crucial system interactions. Integrated assessment models can be very useful for investigating the coupling of systems. Do strong feedbacks exist, or are systems loosely coupled? Do new modes of behavior arise from the coupling? Exploration of these interactions can lead to greater understanding and to more focused research by the modeling community.

A major limitation of integrated assessment models is the difficulty encountered in testing them. Model comparisons, though necessary and useful, cannot substitute for testing with real data. Given the simplifications and assumptions that such models inevitably make, sweeping policy decisions based on such models must be made with caution. Quantitative measures of uncertainty should be developed wherever possible.

One valuable research effort would be to develop an overview of the goals and complexity of the spectrum of integrated assessment models, from very detailed and analytical models to more aggregated models. Such an inventory could reveal the questions asked, the physical climate information required, the lessons learned from past work, and the gaps to be filled. It also could enable future research on integrated assessment modeling to build on existing accomplishments.

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