

Climate Models: A User's Guide

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I. Introduction

Use of models has become increasingly central to the regulatory process. Modeling is sometimes even explicitly mandated by Congress.² The potential benefits are manifold. “Computer modeling,” according to a leading environmental law scholar, “narrows the range of uncertainties related to pollution impacts and causal pathways that have plagued environmental policymaking on all levels.”³ In turn, “[b]etter forecasting allows potential problems to be spotted before they emerge and helps to target policy interventions.”⁴ As a result of improved forecasting, he says, the “evolutionary process of policy evaluation and refinement through trial and error thus can be sped up dramatically.”⁵

But not everyone would agree with this optimism about modeling. Environmental modeling is hardly foolproof,⁶ and we are still learning how it can best be used in environmental protection.⁷ There are some basic questions to be addressed about environmental modeling.

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² For example, one section of the Clean Air Act requires the use of “photochemical grid modeling” unless EPA certifies some other techniques to be “at least as effective.” 41 U.S.C. § 7511a©(2)(A).

³ Daniel C. Esty, *Environmental Protection in the Information Age*, 79 NYU L. REV. 115 (2004).

⁴ *Id.*

⁵ *Id.*

⁶ Modeling defects are the subject of Orrin H. Pilkey and Linda Piley-Jarvis, *Useless Arithmetic: Why Environmental Scientists Can't Predict the Future* (2007). Although their skepticism of modeling is somewhat extreme, they do effectively point out the risks of relying on models as infallible forecasts.

⁷ *Id.* For another perspective on the use of modeling in environmental law, see James D. Fine and Dave Owen, *Technocracy and Democracy: Conflicts Between Models and Participation in Environmental Law and Planning*, 56 Hastings L.J. 901 (2005). According to Fine and Owen:

Models can process reams of data and represent mathematically complex chemical, physical and social relationships, allowing modelers to make predictions and test assumptions in ways that otherwise would not

How much of the potential of modeling has already been realized? What are the potential pitfalls of modeling? How can the regulatory and legal systems best make use of models? Climate modeling provides an ideal setting for exploring the larger issues related to modeling. These models are both important in their own right and paradigms of sophisticated scientific models.⁸

This article has two goals: providing legal and policy analysts with a basic understanding of the types of computer models that are used in studying climate change, and thinking through the uses and limitations of these models for courts and agencies. The article proceeds in four stages. Part I analyzes the models used by climate scientists to understand climate change. Some of the models are mind-bogglingly complex, requires weeks to run on the most powerful supercomputers. Even the simplest models may be challenging to understanding for scientific novices. As we will see, we have good reason to rely on these models, but we must also recognize that considerable areas of residual uncertainty remain.

Another kind of computer modeling is helpful in bridging the gap between the models of climate change and the people who must apply their results. Part II discusses the role of geographic information systems (GIS) in understanding climate impacts. These modeling systems convert data to interactive maps. Given the complexities of climate change such models are especially important in making information accessible to policymakers and members of the

be possible. Not surprisingly, models have become essential and ubiquitous planning tools, our dependence upon them making their abandonment all but unthinkable.

Nevertheless, models are incomplete representations of reality and suffer from many sources of uncertainty. Every model, strictly speaking, is an approximation, for no model can be an exact representation of the real world. Air quality planning models, like any physically based simulation, also are unverifiable, limiting modelers' ability to assess their reliability. Approximations, subjective choices, and errors in both design and application are common in any modeling effort, but the complexity of current state-of-the-science models hinders assessment of their certainty.

Id. at 904-905.

⁸ For an overview of climate modeling, see David Randall et al., *Climate Models and Their Evaluation*, in CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (2007). A good discussion of uncertainties in models can be found in Gerald A. Meehl, et al., *Global Climate Projection*, in CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS. CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL REPORT ON CLIMATE CHANGE 747, 754-760, 797-810 (S. Solomon, et al. eds. 2007). A more detailed introduction to modeling can be found in KENDAL MCGUFFIE AND ANN HENDERSON-SELLERS, A CLIMATE MODELLING PRIMER (3d ed. 2005), although it should be noted that the authors' statement that the book requires "basic high school mathematics", *id.* at xiv, is true only for those readers whose basic high school courses included vector calculus, and some details of the discussion presume some post-high school exposure to physics. Among other useful features, Appendix B of the book contains a useful glossary of technical vocabulary, most helpful for those of us whose daily conversation does not include terms like "advection" or "adiabatic." The basic concepts underlying climate modeling are explained in John Harte, *Consider a Spherical Cow: A Course in Environmental Problem Solving* (1988). For an overview of the current state of knowledge about climate issues generally, see Peter J. Robinson and Ann Henderson-Sellers, *Contemporary Climatology* (2d ed. 1999).

public. For many users, GIS models will be the interface between them and the climate scientists' work.

In Part III, we consider the probable response of courts to computer modeling, an issue that can arise in judicial review of administrative proceedings and in ordinary civil litigation. Courts are just beginning to confront the use of climate models, but it seems likely that they will find these models reliable enough for use in litigation and in administrative decisions. The distinctive processes that climate scientists have designed for testing and improving models should provide additional assurance to courts. The main pitfall may be over-reliance on any single model without acknowledging model limitations or recognizing the importance of confirmation from other models and observations.

Part IV considers the implication of model uncertainty – the risk that a model has failed to capture the dynamics of the process it is simulating.⁹ Model uncertainty should diminish as our modeling efforts improve. Nevertheless, the models now provide considerable confidence about the existence of human-originated harmful climate change, but they leave uncertainty about regional effects and downside risks. Economic models are particularly subject to uncertainty. Climate policy must be designed with these uncertainties in mind.

Because this article covers a good deal of fairly diverse terrain, it may be helpful to identify four key “take away” points:

- Climate models establish a lower end estimate for global temperature impacts, but the distribution is less clearly bounded on the high side – or in simpler terms, the high-end risk may be considerable. The models are better at predicting temperature patterns than precipitation patterns, and global predictions are considerably firmer than more localized ones.
- Economic models are much less advanced, and their conclusions should be used with caution. Unfortunately, economists are not always careful about incorporating uncertainty into their policy recommendations.
- Climate scientists have created a unique institutional system for assessing and improving models, going well beyond the usual system of peer review. Consequently, their conclusions should be entitled to considerable credence by courts and agencies.

⁹ This paper focuses on the uncertainties in predicting the degree of harm from climate change. There are also large uncertainties about the costs of mitigation measures. Oddly, those who view uncertainties about harm as a basis for ignoring the impact of climate change tend to place a great deal of credence in economic models of mitigation cost – in their minds, uncertainty apparently is relevant when considering scientific models but not economic models. See Philippe Tulkens and Henry Tulkens, *The White House and the Kyoto Protocol: Double Standards on Uncertainties and Their Consequence* (June 2006), <http://ssrn.com/abstract=910811>.

- Model predictions cannot be taken as gospel. There is considerable residual uncertainty about climate change impacts that cannot be fully quantified. The uncertainties on the whole make climate change a more serious problem rather than providing a source of comfort. The policy process should be designed with this uncertainty in mind. For instance, rather than focusing on a single cost-benefit analysis for proposed regulatory actions, the Office of Management and Budget (OMB), which oversees federal regulatory policy, might do better to require the development of standardized scenarios for agencies to use.

II. Models and Climate Change Policy

Climate scientists rely heavily on very complex, sophisticated computer models of the climate system. Decision makers need to be aware of the strengths and weaknesses of these models, lest they either exaggerate the degree of uncertainty about climate change – often an excuse for inaction – or act with a misguided confidence that the situation is fully understood.

A. *An Overview of Climate Modeling*

A popular science writer gives a particularly clear explanation of the basics, discussing a particular model called GISS:

Like all climate models, GISS's divides the world into a series of boxes. Thirty-three hundred and twelve boxes cover the earth's surface, and this pattern is repeated twenty times moving up through the atmosphere. . . . [I]n the world of the model, features such as lakes and forests and, indeed, whole mountain ranges are reduced to a limited set of properties, which are then expressed as numerical approximations. Time in this grid-world moves ahead for the most part in discrete, half-hour intervals, meaning that a new set of calculations is performed for each box for every thirty minutes that is supposed to have elapsed in actuality. Depending on what part of the globe a box represents, these calculations may involve dozens of different algorithms, so a model run [may involve] more than a quadrillion separate operations. A single run of the GISS model, done on a supercomputer, usually takes about a month.¹⁰

The model calculates changes in each block based on fundamental laws and on “parameterizations.” These parameterizations approximate complex physical processes with simpler equations that capture the physical results but without all the details of the process.

¹⁰ ELIZABETH KOLBERT, *FIELD NOTES FROM A CATASTROPHE: MAN, NATURE, AND CLIMATE CHANGE* 99-101 (2006).

Climate modeling has developed quickly over the past few decades.¹¹ The publications on climate research have doubled approximately every eleven years since the middle of the last century.¹² Supercomputer speed has increased by a million-fold in the past three decades.¹³ There has been a shift from traditional supercomputers (in which all processors use the same memory space) to massively parallel machines in which each processor has its own memory.¹⁴ As everyone knows, chip speeds have also grown exponentially. These technological advances allow models to be more fine-grained (smaller cells providing more detail on processes) and enable the incorporation of ocean currents and other factors too complex for the early models.¹⁵ Faster computer speeds also allowed ensemble runs in which model parameters are varied in order to study their effect on climate.¹⁶

Initially, “climate modeling was dominated by atmospheric physicists and no one without a sound training in fluid dynamics, radiative transfer or numerical analysis could hope or expect to make a contribution”¹⁷ Early models were derived from weather prediction models.¹⁸ These early models approximated some processes such as ocean/atmosphere interactions. The approximations produced problems due to gaps in the ocean data; the problems in turn had to be compensated by adding “fluxes” to keep the models from drifting off course.¹⁹ Some models continue to use fluxes, while others have been able to model the physical processes more directly.²⁰ The ozone hole over Antarctica provided the impetus for including atmospheric chemistry in models.²¹ (The chemicals that caused the ozone problem are potent greenhouse gases.²²)

¹¹ A detailed discussion can be found in Herve Le Treut et al., *Historical Overview of Climate Change Science*, in CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS, CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (2007).

¹² *Id.* at 98.

¹³ *Id.* at 112.

¹⁴ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 177.

¹⁵ *Id.* at 113.

¹⁶ *Id.* at 48. Early models turned out to be much too sensitive to perturbations. *Id.* at 53.

¹⁷ *Id.* at xv.

¹⁸ *Id.* at 6.

¹⁹ *Id.* at 117. Perhaps ironically in light of the origin of the models, there is now some tension between the views of climate scientists and those of meteorologists about matters such as the relationship of climate change to hurricane intensity. This topic is explored in depth in CHRIS MOONEY, *STORM WORLD: HURRICANES, POLITICS, AND THE BATTLE OVER GLOBAL WARMING* (2007).

²⁰ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 7.

²¹ *Id.*

Today, Atmospheric-Ocean General Circulation Models (AOGCMs) are able to include consideration of aerosols (such as sulfur dioxide plumes caused by industrial sources), river and estuary water mixing (affecting ocean salinity), sea ice, and terrestrial processes.²³ Instead of using rough approximations (like average levels of cloudiness in a given locale), models are increasingly able to “represent such processes as cloud particles and raindrop formation” to “predict the distributions of liquid and ice clouds.”²⁴ Models also increasingly incorporate the terrestrial biosphere, including vegetation and soil carbon cycles.²⁵ Many factors turn out to be relevant: snow-vegetations interactions, evaporation from forest canopies, and soil moisture.²⁶ Vegetation and land use may be held fixed, however, rather than responding to climate change.²⁷

As one scientist succinctly put it, “first-class modeling requires first class data.”²⁸ The data used as input for climate modeling has also improved, with more sophisticated measurements for surface sea temperature (SST),²⁹ satellite data, and more careful and comprehensive data sets of ground-based measures.³⁰ Because of the improved monitoring network when Mount Pinotuba erupted, scientists were able to make great advances in understanding the climate impacts of volcanic eruptions.³¹ Nevertheless, gaps in the data remain. We still need better data about such matters as ocean surface heat content and evaporation.³² We still lack hydrological data needed to initialize and validate models.³³ Thus, a great deal remains to be done to provide the raw material for AOGCMs.

²² *Id.*

²³ *Id.* at 592.

²⁴ *Id.* at 602.

²⁵ RANDALL, *supra* note , at 604.

²⁶ RANDALL, *supra* note , at 605.

²⁷ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 72. For discussion of efforts to model land use, *see* van der Werf, Edwin and Peterson, Sonja M., "Modeling Linkages between Climate Policy and Land Use: An Overview" (May 2007). FEEM Working Paper No. 56.2007, *available at* SSRN: <http://ssrn.com/abstract=989968>.

²⁸ M. Bruce Beck, *How Best to Look Forward?*, 316 *Science* 202 (2007).

²⁹ Truet, *supra* note, at 102.

³⁰ *Id.* at 116.

³¹ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 32.

³² RANDALL, *supra* note , at 613.

³³ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 199.

AOGCMs are very powerful, even without the full data that we would ideally like to have, but their power comes at a price. AOGCMs are complex and correspondingly expensive and slow. These models take roughly twenty-five or thirty person-years to code.³⁴ (Yet even these models are “far removed in complexity from the full climate system.”³⁵) They typically divide use grid points two to five degrees apart,³⁶ using about twenty layers to model the atmosphere and tracking changes over twenty minute intervals.³⁷ Because of their computational demands, it is not feasible to use them for long-term projections or to large numbers of runs to provide a probability distribution of outputs.

To allow longer-term trend analysis, climate scientists also use Earth Models of Intermediate Complexity (EMIC).³⁸ There is no such thing as a typical EMIC; what they have in common is simply that “one or more aspects of the full climate system is neglected or parameterized with the goal of including a process or time-frame that could not otherwise be resolved with the available resources.”³⁹ EMIC outputs hold up well against direct observations and AOGCM results. Using ensembles of EMIC runs also allows a fuller exploration of uncertainties in long-term projections.⁴⁰ Essentially, EMICs offer a way to simulate the more complex models (which themselves simulate the real world.)⁴¹ EMICs include realistic representations of basic geographic features like the shape of continents and ocean basins.⁴² EMICs are “not suitable for quantifying uncertainties in regional climate change or extreme events,” but they can be used for large assemblies (i.e., running many simulations) or for simulations extending over long time periods. Thus, some EMICs can be used for systematic sampling of possible parameter values in order to develop probability distributions of outcomes.⁴³ EMICs also allow in-depth exploration of the impact of specific processes, such as very detailed consideration of atmospheric chemistry.⁴⁴

³⁴ *Id.* at 4.

³⁵ *Id.* at 9

³⁶ *Id.* at 56. Since there are 360 degrees of latitude and longitude, this means means dividing the earth’s service into roughly 2500- 20,000 pieces.

³⁷ *Id.* at 56.

³⁸ For a detailed discussion of EMICs, *see id.*, at 117-153.

³⁹ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 150.

⁴⁰ RANDALL, *supra* note , at 592.

⁴¹ *Id.* at 643.

⁴² *Id.* at 644.

⁴³ Meehl and Stocker, *supra* note , at 797.

⁴⁴ *Id.* at 54.

Even more stripped down are Simple Climate Models (SCMs). They represent the major components of the global system as boxes, predicting global surface temperature changes using “an energy balance equation, a prescribed value of climate sensitivity and a basic representation of ocean heat uptake.” They can be used to extrapolate results from AOGCMs or study interactions between global variables.⁴⁵ Even simple models seem to have predictive validity: for example, they do well at modeling the impact of volcanic eruptions on climate.⁴⁶

B. The Place of GCMs in Climate Policy

First, how sure can we be that climate change is a genuine threat? The most reliable source is the 2007 report of the International Panel on Climate Change (IPCC), which explains the scientific consensus. According to the IPCC’s report:

Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years. The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change, while those of methane and nitrous oxide are primarily due to agriculture.⁴⁷

The IPCC report is the result of an exhaustive review process:

Forty governments nominated the 150 lead authors and 450 authors of *Climate Change 2007: The Physical Science Basis*. Authors had their draft chapters reviewed by all comers. More than 600 volunteered, submitting 30,000 comments. Authors responded to every comment, and reviewers certified each response. With their final draft of the science in hand, authors gathered in Paris, France with 300 representatives of 113 nations for 4 days to hash out the wording of a scientist –written Summary for Policymakers.⁴⁸

⁴⁵ *Id.* at 797.

⁴⁶ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 12

⁴⁷ S. SOLOMON, ET AL., CONTRIBUTION OF WORKING GROUP I TO THE FOURTH ASSESSMENT INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE SUMMARY FOR POLICYMAKERS 1 (2007). The IPCC explains that “the understanding of anthropogenic warming and cooling influences on climate has improved since the Third Assessment Report (TAR), leading to *very high confidence* that the globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing of +1.6 [+0.6 to +2.4] W m².” *Id.* at 4.

⁴⁸ *Scientists Tell Policymakers We’re All Warming the World*, 315 SCIENCE 754 (2007).

Because of improvements in modeling and data, the 2007 Report was able to eliminate some concerns that had previously been raised about climate change. In particular, four key issues were resolved. First, could evidence of warming be skewed because previously rural measurement sites have been swept into urban areas, which are warmer than their surroundings? The answer is no. While the urban heat-island effect, caused by the tendency of urban concrete and asphalt to absorb heat, is real, it is “a negligible influence” on overall temperature. Second, do satellite measurements show that the world is not really warming (unlike the ground level measurements)? Again, the answer is no. The previous discrepancy between earth-based and satellite-based temperature measurements has been resolved by improved satellite measurements, which are more in line with the earth-based results. Third, could warming be due to natural forces? Again, no. While natural forces such as volcanoes and variations in solar intensity can influence climate and have done so in the past, these natural variations cannot produce the currently observed patterns of climate change. And fourth, is it plausible to think that small changes in the gas composition of the atmosphere could cause significant climate change? Yes, the evidence does show that the climate system is sufficiently sensitive to atmospheric composition to produce the observed climate change, as shown by the response to other disturbances such as the Mount Pinatubo eruption of 1990.⁴⁹ Resolving these issues eliminates some of the residual uncertainty that had still clouded discussions of climate change, leaving little room for doubt that human-caused climate change is real and serious.

Of course, complete scientific certainty is never possible, and the IPCC claims only that its conclusions are highly likely (over 90%). But social policy can never be based on complete certainty. We make major governmental decisions based on social science evidence such as economic theories that are subject to much less intensive scrutiny. Climate change models are imperfect, but highly credible. Overall, according to the IPCC,

There is considerable confidence that AOGCMs provide credible quantitative estimates of future climate change, particularly at continental and larger scales. Confidence in these estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation).⁵⁰

In short, the evidence for climate change is imperfect, but probably stronger than much of the evidence society uses to make life-or-death decisions.

C. Limitations and Critiques

Even today’s most sophisticated models have their limits. For example, clouds are responsible for up to two-thirds of the light reflected by our planet, but they contain complex dynamics and have only been partially modeled.⁵¹ This limitation can make a substantial

⁴⁹ *Id.* at 755.

⁵⁰ RANDALL, *supra* note , at 591.

⁵¹ Truet, *supra* note , at 114.

difference. Experiments with a model in the early 1990s showed that global average temperature increases could increase from two degree Celsius up to five, depending on what approximations were used for cloud behavior.⁵² As an IPCC report says, “[i]t is somewhat unsettling that the results of a complex climate model can be so drastically altered by substituting one reasonable cloud parametrization for another. . . .”⁵³

Also, like predictions of weather, predictions of climate may be inherently probabilistic. Efforts using the same model to predict the climate for a particular time in the future may differ in different model runs.⁵⁴ In comparison, predictions of average, long-term climate properties are the goal of most modelers, and these predictions are more stable.⁵⁵ As a recent article explains:

. . . . On lead times of less than 10 years, the signal of anthropogenic climate change is relatively small compared to natural decadal climate variability, and uncertainties in initial conditions dominate the overall uncertainty of the prediction.

By contrast, climate predictions on time scales of a century are much less sensitive to initial conditions, because the signal of anthropogenic climate change is much larger at longer time scales and because more elements of the climate system have a “memory” of past climate-forcing factors that is shorter than a few decades. The major source of uncertainty here lies in the future anthropogenic emissions of greenhouse gases and aerosols.⁵⁶

Another source of uncertainty in longer-term projections relates to the parameters covering some features of atmospheric behavior, which are not known precisely.⁵⁷ It is possible, however, that there are multiple equilibria, making it difficult to be confident of outcomes given the limitations of measurement for the initial condition and other variables.⁵⁸ Another advance in modeling is to give more explicit attention to uncertainty by providing confidence intervals for predictions.⁵⁹

⁵² *Id.* at 114.

⁵³ *Id.*

⁵⁴ Truet, *supra* note , at 117.

⁵⁵ *Id.* at 117, 118.

⁵⁶ Peter Cox and David Stephenson, *A Changing Climate for Prediction*, 317 *SCIENCE* 207, 208 (2007).

⁵⁷ *Id.* As a result, the most reliable forecasts are for lead times between thirty and fifty years. The authors suggest that better data about current conditions could help pin down the parameters. *Id.*

⁵⁸ Truet, *supra* note . at 117.

⁵⁹ *Id.* at 121.

Models differ significantly in their predictions. Disagreement about climate sensitivity is one indication of model differences. Climate sensitivity means the equilibrium average temperature change resulting from a doubling of carbon dioxide concentrations – thus, climate sensitivity indicates what the temperature will be in the very long run, after transitional effects have damped down. It is “largely determined by internal feedback processes that amplify or dampen the influence of radiative forcing on climate.”⁶⁰ As it turns out, the biggest source of differences between models relates to cloud formation and effects on heat radiation.⁶¹ Clouds reflect light back into space, but also trap heat emitted from below; the balance between these processes is complex.⁶²

Given that the models are necessarily imperfect, what reasons do we have for crediting their results? Perhaps the most basic reason is that the cores of the models are based on well-understood laws of physics relating to fluid behavior, thermodynamics, radiation absorption, and other processes.⁶³

In addition, models have undergone three important “reality checks.” First, some models have been successfully tested for short-term and season weather forecasting, with good results. This provides some grounds for confidence that major weather factors have not been omitted.⁶⁴

Second, models have been tested at the component level. Standardized tests are applied to the components through organized activities, such as regularly held Workshops on Partial Differential Equations on the Sphere.⁶⁵ The physical parameters in the models are tested through case studies, run by programs specializing in cloud systems, atmospheric radiation, and other topics.⁶⁶

⁶⁰ RANDALL, *supra* note , at 629.

⁶¹ *Id.* at 633.

⁶² *Id.* at 635. The IPCC’s summary on clouds is as follows:

Despite some advances in the understanding of the physical processes that control the cloud response to climate change and in the evaluation of some components of cloud feedbacks in current models, it is not yet possible to assess which of the model estimates of cloud feedback is the most reliable. However, progress has been made in the identification of the cloud types, the dynamical regimes and the regions of the globe responsible for the large spread of cloud feedback estimates among current models.

Id. at 638.

⁶³ See RANDALL, *supra* note , at 600.

⁶⁴ *Id.* at 593.

⁶⁵ *Id.* at 594.

⁶⁶ *Id.* at 594.

Third, models are tested against past and present climate. They have been extensively used to simulated Twentieth Century climate changes.⁶⁷ The results are encouraging:

Models show significant and increasing skill in representing many important mean climate features, such as the large-scale distributions of atmospheric temperature, precipitation, radiation and wind, and of oceanic temperatures, currents and sea ice cover. Models can also simulate essential aspects of many of the patterns of climate variability observed across a range of time scales. Examples include the advance and retreat of the major monsoon systems, the seasonal shifts of temperatures, storm tracks and rain belts, and the hemispheric-scale seesawing of extratropical surface pressures (the Northern and Southern “annular modes.”)⁶⁸

For example, there has been “steady progress” in simulating and predicting El Niño events.⁶⁹ Models have also been successful in simulating global statistics of extreme events, especially head and cold waves.⁷⁰ It is difficult to check models against pre-industrial history because the weather data from those periods is spotty and its interpretation is controversial.⁷¹ In addition, we do not have completely firm evidence about the magnitude of other climate drivers such as solar and volcanic activity.⁷²

Notably, the models collectively outperform any individual model. Researchers have found that “averages across structurally different models empirically show better large-scale agreement with observations, because individual model biases tend to cancel.”⁷³ We can also get some sense of the extent of uncertainty through running models with variations in parameters, since parametrization is a key aspect of model uncertainty. One such effort found a 90% percent probability that climate sensitivity (the response to doubling pre-industrial CO₂ levels) was

⁶⁷ *Id.* at 595.

⁶⁸ *Id.* at 600. “Skill” is an indication of a model’s ability to predict patterns of events rather than averages.

⁶⁹ RANDALL, *supra* note , at 623.

⁷⁰ *Id.* *supra* note , at 627.

⁷¹ Mayles Allen et al., *Scientific Challenges in the Attribution of Harm to Human Influences on Climate*, 155 U. Pa. L. REV. 1353, 1364 (2007).

⁷² *Id.* at 1366.

⁷³ Meehl and Stocker, *supra* note , at 754. *See also* MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 230 (“the model group mean (after excluding unreasonable results/outliers) outperforms any one model, where performance is measured against observational data.”)

between 2.4 and 5.4 °C.⁷⁴ The study found essentially no chance that climate sensitivity is below 1 °C, but a high-side range extending (with low probability) past 8 °C.⁷⁵

It should be noted that modeling issues do not necessarily mean that we are overestimating the harm of climate change. The models may well be underestimating the threat. For example, for reasons that are still poorly understood, sea level rise has been about twice as fast as the models predict.⁷⁶ It is also important to note that the economic models used to calculate the costs of climate mitigation are less developed than the climate models,⁷⁷ and as we will see in the next subsection, they contain considerable uncertainties and may well underestimate the economic impact of climate change.

For those of us who are not experts in climate science, there are limits to the degree with which we can confidently form independent judgments about the validity of the models now being used. Having done what we can to understand the basis for their judgments, at some point we must also give weight to consensus among climate scientists regarding climate change projections. Given the convergence of available models and observational evidence and the large degree of agreement among the experts in projecting at least two to three degrees of warming and its attendant effects such as sea-level rise, current scientific findings are the best guide we can find to action.⁷⁸

D. Integrated Assessment Models: Adding Economics to Climate Models

For policymaking purposes, we would like to know not only how much climate change to expect, but how what costs these changes will impose on society and what it would cost to ameliorate climate change. Unfortunately, our knowledge of these economic issues is still quite crude.

There are now about a dozen models that couple climate change predictions to economic analysis.⁷⁹ These models differ in a number of dimensions: their focus on the energy sector or

⁷⁴ James M. Murphy, *Quantification of Modelling Uncertainties in a Large Ensemble of Climate Change Simulations*, 430 NATURE 768 (2004).

⁷⁵ *Id.* at 770 (Figure 3).

⁷⁶ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 16.

⁷⁷ *See id.* at 240 (“integrated assessment models” have only been under development for about ten years, as opposed to forty years for climate models).

⁷⁸ *See* Stephen H. Schneider and Kristin Kuntz-Durseti, *Uncertainty and Climate Change Policy*, in STEPHEN H. SCHNEIDER, ARMIN ROSENCRANZ, AND JOHN O. NILES, CLIMATE CHANGE POLICY: A SURVEY 44-47 (2002) (“the basis of climate science . . . is firmly rooted in solidly proven scientific theories”; much of science is less certain than its fundamental theories, but that uncertainty can be quantified and may temper but not destroy our confidence in scientific projections.”)

⁷⁹ For a list, *see* MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 242.

reliance on a broad macroeconomic analysis, the degree to which they analyze localized versus average global impacts, and their treatment of uncertainty.⁸⁰ Model results differ correspondingly.

For example, the Mendelsohn model estimates impacts for five market sectors and find positive economic effects for temperature increases up to about 4 °C, whereas the Toll model finds small net economic losses at all levels in terms of global output but estimates the losses to be twice as high when measured in terms of individual welfare rather than dollars (because many of the costs fall on poorer populations).⁸¹

The Nordhaus model included a broader range of impacts (market and non-market) and also made the first effort to take into account the economic costs of potential catastrophic impacts.⁸² The Nordhaus model found nonlinear effects of climate change, so that a 6 °C change produces about twice as much harm as a 4 °C change.⁸³ Despite these attractive features, the Nordhaus model also has significant limitations where modeling had to be based on assumptions rather than data or theory. To take a few examples:

- The calculations of the impact of sea level rise exclude storms, impacts on undeveloped lands, and storm damage, which the authors attempt to compensate for with what they consider a conservative estimate.⁸⁴
- The shift away from carbon intensive energy sources is assumed to follow historical trends, rather than reflecting incentives for new technologies.⁸⁵
- The cost of catastrophic harm was roughly estimated via a survey of experts followed by some “assumptions” about the degree of harm.⁸⁶

⁸⁰ *Id.* at 240-243 (treatment of uncertainty is tabulated on p. 242).

⁸¹ Stern Report, *supra* note , at 166-167.

⁸² *Id.* at 167.

⁸³ *Id.* at 167.

⁸⁴ Nordhaus, *supra* note , at 76.

⁸⁵ *Id.* at 51. Compare Richard S.J. Tol, *Carbon Dioxide Emissions for the USA*, www.ssrn.com/abstract=932508 (noting that the “model cannot anticipate structural breaks. This is a humbling conclusion for a 100 year forecast.” And “history-based projections are not robust to radically new technologies.”)

⁸⁶ Nordhaus. at 87-88.

In contrast to Nordhaus, the Stern Report uses a model called PAGE2002IAM and finds considerably higher levels of harm.⁸⁷

Models also differ in their assessments of the costs of complying with the Kyoto Protocol, with the range running from negligible losses to at least one to two percent of GDP, annually.⁸⁸ The models differ in terms of three critical assumptions about the timing of abatement efforts, the types of policy instruments used, and the likelihood of technological innovation.⁸⁹ Other relevant factors include the willingness of economic actors to substitute away from high carbon technologies and trends in energy efficiency.⁹⁰

There are similar difficulties in modeling the costs of mitigating and adapting to climate change. Most of the model results are in the range of two to five percent of GDP in 2050. However, the range spans from a four percent *gain* in GDP due to reduced use of carbon to a fifteen percent *loss* of GDP.⁹¹ A meta-analysis shows that key factors in explaining these differences include the following: whether revenue from carbon taxes is recycled; what kinds of technological changes are assumed; whether shifts in energy sources have non-climate benefits; and whether the model includes international carbon trading.⁹² Hopefully, economists will be able to narrow the uncertainty, but it is discouraging that at this point they cannot even agree on the sign of the economic effect.

Many of the individual elements of the economic impact analysis are the subjects of serious debate. For instance, economists hotly dispute the net effect of climate change on agriculture, with some finding an overall positive effect on U.S. agriculture (but with very large regional variations),⁹³ while others find substantial negative effects.⁹⁴ If we do not even know the sign of important elements of the economic impact, predicting overall impact (taking into account all of the feedback loops of the economy) is obviously going to be difficult.

⁸⁷ Stern, *supra* note , at 186.

⁸⁸ Jason F. Shogren and Michael A. Toman, *How Much Climate Change is Too Much?*, in *CLIMATE CHANGE ECONOMICS AND POLICY: AN RFF ANTHOLOGY* 42 (Michael A. Toman ed. 2001).

⁸⁹ *Id.*

⁹⁰ *Id.* at 43.

⁹¹ Stern Report, *supra* note , at 269.

⁹² *Id.* at 271.

⁹³ See Oliveir Deschenes & Michael Greenstone, *The Economic Impacts of Climate Change: Evidence from Agricultural Output and Random Fluctuations in Weather*, 96 *AMER. ECON. REV.* 354 (2007) (but note that this study excludes possible impacts of increased in extreme events such as storms and droughts).

⁹⁴ Wolfram Schlenker, W. Michael Hanemann & Anthony C. Fisher, *The Impact of Global Warming on U.S. Agriculture: An Econometric Analysis of Optimal Growing Conditions*, 88 *REV. ECON. AND STATISTICS* 113 (2006).

Modeling the systemic economic impact of climate change as well as the costs of adaptation and mitigation involves tremendous challenges, particularly if the projection goes out more than a few years.⁹⁵ As Nordhaus and Boyer say, it “must be emphasized that attempts to estimate the impacts of climate change continue to be highly speculative.”⁹⁶ To begin with the model, the economic model must build on the outputs of climate models, which are themselves uncertain. Then there is the difficulty of forecasting the future trajectory of the economy over future decades. This clearly cannot be done in detail – for example, no forecaster in 1970 would have predicted the explosive growth of personal computers, let alone the Internet, neither of which existed at the time.

Even efforts to forecast at a cruder level must rely heavily on the assumption that the future will on average be much like the recent past – for example, that technological progress will continue at something like its current pace and that some unforeseen catastrophe will not cause an economic crash. Even predictions for specific economic sectors are difficult. Past experience with model projecting energy use do not lend much confidence to these predictions: the projections have generally been too high, by as much as a factor of two.⁹⁷ Projecting adaptation is made more difficult by the institutional barriers that may prevent its optimal use.⁹⁸ The uncertainties go both ways: to the extent that climate change scenarios are based on projections of future emissions, they implicitly make assumptions about future political and economic developments.

One of the oddities of the economic models is the occasional disconnect between the description of the model and the conclusions. For example, in terms of the Nordhaus model, the description of the model and the policy recommendations seem to be written by different people.⁹⁹ The description of the model is replete with qualifications: “a major uncertainty in the

⁹⁵ A good overview of modeling issues can be found in J.C. Huracade, *et al.*, *Estimating the Costs of Mitigating Greenhouse Gases*, in CLIMATE CHANGE 1995: ECONOMIC AND SOCIAL DIMENSIONS OF CLIMATE CHANGE: CONTRIBUTION OF WORKING GROUP III TO THE SECOND ASSESSMENT REPORT OF THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (James P. Bruce, Hoesung Lee & Erik F. Haites eds. 1996). Of course, in the decade since this report, models have improved in their capacity to handle these issues.

⁹⁶ Nordhaus and Boyer, *supra* note , at 86. This does not, however, impede them from issuing confident policy pronouncements.

⁹⁷ Stephen J. DeCanio, *Economic Models of Climate Change: A Critique* 138-143 (2003).

⁹⁸ See Matthew D. Zinn, *Adapting to Climate Change: Environmental Law in a Warmer World*, 34 Ecology L.Q. 61 (2007) (adaptation may not be successfully managed to minimize ecological or other impacts).

⁹⁹ As indeed they may have been, since the book describing the model is coauthored. William D. Nordhaus and Joseph Boyer, *Warming the World: Economic Models of Global Warming* (2000). The level of sophistication of the economic models can be gauged from the fact that the Nordhaus model is designed to run on a PC, *id.* at 56, while the most advanced climate models require weeks to run on a supercomputer.

model involves projecting the growth of total factor productivity”¹⁰⁰; “there are no well-established empirical regularities and very little history can be drawn upon” regarding the link between climate change and the economy¹⁰¹; there are “major uncertainties about the long-run trajectories of economic growth in different regions”¹⁰²; regional growth models “are difficult to validate or estimate and are subject to large and growing projection errors as they run further into the future”¹⁰³; and so forth.¹⁰⁴ Yet, the policy implications are precise and unqualified: damages “for the United States, Japan, Russia, and China are essentially zero” until 2100 (assuming no catastrophe materializes)¹⁰⁵; a delay of ten years in implementing mitigation “leads to a trivially small net loss”¹⁰⁶; limiting global emissions to 1990 levels causes a net “discounted loss of \$3 trillion”¹⁰⁷; “an efficient climate-change policy would be relatively inexpensive and would slow climate change surprisingly little”¹⁰⁸; and the “Kyoto protocol has no economic or environmental rationale.”¹⁰⁹ These policy prescriptions would be more accurate if each of them were prefaced with “Our best informed guess is that”, or perhaps even better, “In one plausible scenario,” And indeed, other economists seem to have informed guesses that are quite different or different plausible scenarios in mind.

Outputs of various economic models are so far apart as to make it perilous to rely on any one model or even a small subset. According to a recent review, “cost estimates of Kyoto emissions reductions diverge by a factor of about 500 (and not all estimates shown an economic

¹⁰⁰ Nordhaus and Boyer, *supra* note , at 17.

¹⁰¹ *Id.* at 20.

¹⁰² *Id.* at 47.

¹⁰³ *Id.* at 53.

¹⁰⁴ Some additional examples:

(1) “[T]here are no established methodologies for valuing catastrophic risk.” *Id.* at 71.

(2) Findings regarding climate impacts are “highly conjectural” and it is difficult “to make solid estimates of the impacts of climate change.” *Id.*

(3) “Given the lack of any comprehensive estimates, the authors have made rough estimates here of the extent to which the economy and other institutions are vulnerable to climate change.” *Id.* at 86.

¹⁰⁵ *Id.* at 96.

¹⁰⁶ *Id.* at 127.

¹⁰⁷ *Id.* at 129.

¹⁰⁸ *Id.* at 174.

¹⁰⁹ *Id.* at 177.

loss.)”¹¹⁰ There is also evidence of a systematic bias in ex ante economic studies to overestimate the cost of complying with environmental regulations.¹¹¹ We can only speculate about the reasons for this finding, but the following possibilities come to mind: (1) estimates rely on industry supplied data, which is biased because of the industry’s interest in projecting high compliance costs to defeat regulations; (2) estimates rely on existing technology or ignore other potential compliance measures such as process changes, thereby underestimating the ability of innovations to reduce costs; or (3) the studies of cost projections themselves have flaws, such as some unknown selection biases in the cases studied. In any event, estimates of mitigation costs must be taken with a large grain of salt.

Rather than making “best guess” predictions about future economic impacts, it might be better for economic modelers to also present a range of scenarios relating to future economic factors, leaving it to policymakers to sort out how these potential economic effects should figure into the determination of policy. This would leave the uncertainties closer to the surface, which makes decision-making more difficult, but also more realistic.

In any event, it is clear that courts and agencies should approach cost-benefit analyses of climate change with some caution. Given the high degree of uncertainty and disagreement between models, it would be a mistake to view any particular economic analysis as definitive. This is entirely apart from other vexing issues in cost-benefit analysis, such as the difficult issue of what discount rate should be applied once costs and benefits have been determined.

III. Geographic Information Systems as a Tool for Adaptation Decisions

For the results of climate models to be useful to decision makers, their output needs to be presented in understandable form. This especially in terms of mitigation, where decision makers are likely to have expertise in other areas and to be interested in climate change only as it affects their own agendas. Decisionmakers also need to be able to link climate impacts with demographic, economic, and other factors, in order to think about the local impacts of and responses to climate change. A different form of computer modeling may be most relevant for these decisions. Geographic information systems may provide the ideal method of informing decisionmakers.

A. The Scope of the Adaptation Problem

Adaptation – steps taken in ameliorate the effects of unavoidable climate change -- has not received nearly as much attention as mitigation, but we can already begin to see the outlines of adaptation needs.¹¹² Of course, the scale adaptation required relates to the degree of

¹¹⁰ Tulkens and Tulkens, *supra* note , at 8.

¹¹¹ *Id.* at 15-16.

¹¹² For a good overview of adaptation issues, see Matthew D. Zinn, *Adapting to Climate Change: Environmental Law in a Warmer World*, 34 ELQ 61 (2007).

mitigation: if we do nothing to limit emissions, climate change will be more drastic and the costs of adaptation will be correspondingly higher. The IPCC notes that adaptation covers a wide spectrum of responses:

The array of potential adaptive responses available to human societies is very large, ranging from purely technological (e.g., sea defences), through behavioural (e.g., altered food and recreational choices) to managerial (e.g., altered farm practices), to policy (e.g., planning regulations). While most technologies and strategies are known and developed in some countries, the assessed literature does not indicate how effective various options are in fully reducing risks, particularly at higher levels of warming and for vulnerable groups. In addition, there are formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation. For developing countries, availability of resources and building adaptive capacity are particularly important.¹¹³

Few of these measures are costless, and some may turn out to be quite expensive.

The Pew Foundation collected much of the available information about adaptation strategies in a 2004 report.¹¹⁴ One conclusion is that we will need to develop new agricultural plant varieties to deal with changing temperatures, rainfall, and pests. Since 1980, federal expenditures for agricultural research have been flat, but substantial increases will probably now be needed.¹¹⁵ Farmers will have to make risky decisions about when the climate has changed to a point that justifies switching to new varieties and growing methods.¹¹⁶ Agricultural production is likely to shift northward,¹¹⁷ perhaps to the disadvantage of agricultural southern states such as Florida. Other areas where adaptation may be required include forestry, health hazards from heat stress, and conservation management.¹¹⁸

The Stern Report contains the most extensive discussion of adaptation costs. The Report estimates that:

¹¹³ IPCC Adaptation Report, *supra* note , at 18.

¹¹⁴ William E. Easterling III, Brian H. Hurd & Joel B. Smith, COPING WITH GLOBAL CLIMATE CHANGE: THE ROLE OF ADAPTATION IN THE UNITED STATES (Pew Center on Global Climate Change 2004).

¹¹⁵ *Id.* at 20.

¹¹⁶ *Id.*

¹¹⁷ *Id.* at 21.

¹¹⁸ *Id.* at 3, Table 1.

Infrastructure is particularly vulnerable to heavier floods and storms, in part because OECD economies invest around 20% of GDP or roughly \$5.5 trillion in fixed capital each year, of which just over one-quarter typically goes into construction (\$1.5 trillion - mostly for infrastructure and buildings). The additional costs of adapting this investment to a higher-risk future could be \$15 – 150 billion each year (0.05 – 0.5% of GDP), with one-third of the costs borne by the US and one-fifth by Japan. This preliminary cost calculation assumes that adaptation requires an extra investment of 1 – 10% to limit future damages from climate change.¹¹⁹

In Britain alone, one “study estimated that a cumulative increase in investment of \$18 – 56 million (£10 – 30 million) each and every year for the next 80 years would be required to prevent the costs of flood damages escalating in the UK.”¹²⁰ The risks to London exemplify the scope of infrastructure needs:

Flooding would cause immense disruption to London’s commercial activities, and could cause direct damage equivalent to around £50 billion (plus wider financial disruption). Climate change could increase the maintenance costs of flood defences in the Thames over 100 years from £3.8 billion without climate change (£1.1 billion, Green Book discounted) to £5.3 – £6.8 billion (£1.9 - £2.8 billion, Green Book discounted) with climate change . . . The design of the [Thames] Barrier allowed for sea level rise but did not make any specific allowance for changes in river flows or the height of North Sea storm surges. . . . [After 2030], the risk increases, potentially reaching 1-in-50 years by the end of the century without any active intervention to upgrade capital.¹²¹

B. An Introduction to GIS

GIS is not yet a term in common usage, but it may be on its way. One of the most popular and accessible forms of GIS has been provided by Google:

The idea is simple. It's a globe that sits inside your PC. You point and zoom to anyplace on the planet that you want to explore. Satellite images and local facts zoom into view. Tap into Google search to show local points of interest and facts. Zoom to a specific address to check out an apartment or hotel. View driving directions and even fly along your route.¹²²

¹¹⁹ Stern, *supra* note , at 417.

¹²⁰ *Id.*

¹²¹ *Id.* at 423.

¹²² <http://earth.google.com/earth.html>

Viewers can also superimpose other layers, such as road maps, shopping locations, parks, and other facilities. Microsoft has a similar, though as of yet less elaborate site.¹²³ All of this is fun and moderately useful, but it only scratches the surface of GIS.¹²⁴

A couple of examples may help illustrate the environmental applications of GIS. In the U.K., the Nuclear Industry Radioactive Waste Executive (NIREX) has used GIS to help identify suitable radioactive waste disposal sites. The first step was to establish digitalized “data layers” based on maps showing geology, transport networks, conservation areas, and population statistics. These layers were refined, for example, by identifying which geological conditions were suitable for waste disposal sites. Finally, GIS software was used to combine the layers, producing a map that showed all of the relevant factors. One advantage of this technique, as opposed to the use of paper maps and documents, is that the map can be modified in order to identify the effects of changes in citing criteria or to include updated information.¹²⁵

Another example comes from the Czech Republic. There, GIS was used to integrate information about the Zdarke Vrchy region as a basis for planning. The GIS integrated data from maps, aerial and satellite images, field studies, pollution monitoring, and socioeconomic data. To help identify conservation sites, scientists were asked to identify the soil types, topography, land uses, and drainage systems that were relevant for water retention and flow control. An iterative process then took place where the scientists used the GIS to study existing water retention zones, the results were used to develop a model, and the model was used to identify additional sites suitable for water flow control.¹²⁶

GIS is still under development. Two of the biggest challenges are to move from two to three-dimensional mapping and to include a temporal dimension so that changes over time can be easily tracked. Moreover, better modeling of the ways that different features interact is needed.¹²⁷ Even today, however, GIS is beginning to find important uses in environmental assessment.

For example, in one use of GIS for environmental assessment, the area was broken into cells of areas with similar vegetation, climate and soils. Then a model was used to predict, on a cell-by-cell basis, the growth and aging of a forest, including the size and distribution of each

¹²³ See <http://local.live.com>

¹²⁴ For further discussion of the application of GIS to environmental issues, see Robert Goldstein, *Putting Environmental Law on the Map: A Spatial Approach to Environmental Law Using GIS in LAW AND GEOGRAPHY* (Jane Holder and Carolyn Harrison eds. 2003).

¹²⁵ Ian Heywood, Sarah Cornelium, and Steve Carver, AN INTRODUCTION TO GEOGRAPHIC INFORMATION SYSTEMS 5-6 (1998).

¹²⁶ *Id.* at 7.

¹²⁷ Heywood, Cornelius, and Carver, *supra* note , at 246-247, 250.

forest type. Those calculations in turn were used together with a habitat suitability model to predict impacts on wildlife.¹²⁸

In another instance, the Bureau of Reclamation made good use of GIS in performing an assessment of the operations of the Glen Canyon Dam. Public interest was very high, with more than thirty thousand people commenting on the draft of the environmental impact statement.¹²⁹ As CEQ has explained,

GIS provides the analyst with management of large data sets, data overlay and analysis of development and natural resource patterns, trends analysis, mathematical impact modeling with locational data, habitat analysis, aesthetic analysis, and improved public consultation. Using GIS has the potential to facilitate the efficient completion of projects while building confidence in the NEPA process.¹³⁰

Besides the Glen Canyon project, GIS has also been used for the Pacific Northwest Forest Plan and for the Upper Columbia River Basin Study.¹³¹

GIS has received enthusiastic reviews because of its ability to catalyze public input:

According to the Western Governors' Association, GIS is a vital component of successful NEPA processes that address land management decisions because the decisions are spatial and stakeholders relate to location; therefore, location is often the focus of stakeholder comments and concerns. The U.S. Air Force commented that a website developed by Eglin Air Force Base to accomplish interdisciplinary reviews of environmental impact analyses uses GIS to illustrate proposals. Their GIS also provides simultaneous access to operational and environmental information, thereby increasing awareness of environmental issues.¹³²

GIS technology is not a panacea. There are some subtle pitfalls. Source maps often do not contain good-quality information. Errors may be compounded when translating existing maps into digital format.¹³³ There are also additional technical problems:

¹²⁸ William Eady, *The Use of GIS in Environmental Assessment*, 13 *IMPACT ASSESSMENT* 199, 202 (1995). For a brief discussion of possible uses of GIS under NEPA, including linkages with remotely sensed data, see Kenneth Markowitz, *Using 21st Century Technologies to Implement NEPA* (SGO026 ALI-ABA 155) (Dec. 2001).

¹²⁹ CEQ, NEPA Study, *supra* note , at 26.

¹³⁰ *Id.* at 28.

¹³¹ *Id.* at 28.

¹³² The NEPA Task Force, *Report to the Council on Environmental Quality: Modernizing NEPA Implementation* §1.4.1 (Sept. 2003).

¹³³ JOHN FELLEMAN, *DEEP INFORMATION: THE ROLE OF INFORMATION POLICY IN ENVIRONMENTAL SUSTAINABILITY* 69 (1997).

[G]eospatial data holdings are widely dispersed. Compiling available data across jurisdictional boundaries is often difficult due to differences in data element definitions, sampling methodologies, spatial and temporal resolution, technology, and standards. Lack of adequate metadata and documentation also inhibits the use of non-Federal information.¹³⁴

In an effort to combat this problem, the Office of Management and Budget (OMB) established the National Spatial Data Infrastructure and the Federal Geographic Data Committee as the coordinating body for geospatial data.¹³⁵

C. Using GIS in Adaptation Decisions

Adaptation presents great challenges to our governance systems. As one commentator observes:

Complexity and coordination problems are likely to be even more troublesome where climate change requires large-scale and widely distributed adaptations. Experience suggests that we lack the capacity to plan for and choose among the numerous necessary adaptations in order to minimize their massively cumulative and synergistic environmental effects. While we have had some success in reducing emissions of individual air or water pollutants, for example, nothing in the history of environmental law suggests that we can carry out the kind of large-scale, panoptic planning *65 needed to manage the host of impacts that would be caused by adaptation to unchecked climate change.¹³⁶

It is clear that our governance system struggles to deal with complex, multidimensional ecosystem problems, particularly those involving multiple governmental bodies.¹³⁷

Although far from being a panacea, GIS can help decisionmakers and the public understand systemic relationships by displacing them graphically. For example, if climate change increases flood risks in a particular area, a GIS system can display the areas of increased risk, superimposed on demographic and economic data, making the information much easier to grasp. More sophisticated systems might allow users to experiment with how changes in wetlands buffer flood risks or how increased upstream development increases these risks.

The biggest issue with GIS mapping may be its very accessibility and clarity, which may cause users to underestimate the amount of uncertainty associated with projections. As we have

¹³⁴ The NEPA Task Force, *supra* note , at § 1.3.2.

¹³⁵ *Id.* at § 1.3.3.

¹³⁶ Zinn, *supra* note , at 63.

¹³⁷ See Jody Freeman and Farber, *Modular Environmental Regulation*, 54 DUKE L.J.795 (2005).

seen, uncertainty is a pervasive aspect of climate modeling. For instance, a map showing flood impacts may cause users to overlook the possibility that floods may be greater than projected. Also, mapping decisions may truncate the levels of risks considered. For instance, a decision to portray the 100-year floodzone is useful but may lead users to neglect the serious impacts of possible two or three hundred year flood events, which may also deserve consideration in the planning process.

Despite these potential pitfalls, GIS has great potential for helping to bridge gaps between the experts and decisionmakers as well as members of the public. Climate change will require large-scale decisions on mitigation strategies as well as very localized decisions about planning for oncoming changes in climate. Neither kind of decisions (nor those in between), can be simply left in the hands of experts. GIS can help make the democratic process work better in terms of these complex issues.

IV. Legal Acceptance of Models

Courts do not have much familiarity with complex computer models, and nothing in the professional training of judges prepares them to understand these models in any depth.¹³⁸ For some judges, models may seem disconnected from the real world, as well as being inscrutable in their operation. This section considers the question of how courts should respond to evidence based on computer models of climate change.

A. Admissibility of Model Results in Litigation

It is easy to see ammunition for cross-examination in some of the limitations of climate models. Consider some of the caveats of leading climate scientists about their own findings. For example, the IPCC states that the “magnitude of cryospheric feedbacks remains uncertain, contributing to the range of model climate responses at mid- to high latitude”; that “biases and long-term trends remain in AOGCM control simulations,” that “simulation of the Madden-Julian Oscillation (MJO) remains unsatisfactory; and that “[s]ystematic biases have been found in most models’ simulation of the Southern Ocean.”¹³⁹ Also, we are told, “important deficiencies remain in the simulation of clouds and tropical precipitation (with their important regional and global impacts).”¹⁴⁰ Words like *uncertainty*, *systematic biases*, and *important deficiencies* are music in the ears of cross-examiners.

¹³⁸ On the general problem of educating judges and juries about scientific issues, see Elaine Spencer, *Use and Misuse of Technical Data: Telling the Scientific Story to Scientific Virgins*, SM092 ALI-ABA 131 (American Law Institute - American Bar Association Continuing Legal Education ALI-ABA Course of Study June 27 - 30, 2007).

¹³⁹ RANDALL, *supra* note ,at 591.

¹⁴⁰ *Id.*

These questions could also be raised in an effort to block expert witnesses who might testify about model results. Current restrictions on expert testimony stem from a trilogy of Supreme Court cases.

The foundational case, *Daubert v. Merrell Dow Pharmaceuticals, Inc.*,¹⁴¹ involved a claim that birth defects had been caused because the plaintiffs' mothers had used Bendectin, an anti-nausea medication. The plaintiffs' experts believed that Bendectin caused birth defects. These experts based their conclusions on test tube and animal studies, structural similarities with other chemicals known to cause birth defects, and reanalysis of published epidemiological studies. The question before the Court was whether this expert testimony was admissible. Rejecting the previous requirement that scientific findings be "generally accepted" in the scientific community in order to be admissible,¹⁴² the Supreme Court used the occasion to announce a new approach to the admission of expert testimony. The Court emphasized the need to determine the reliability of the expert testimony. Although it said the inquiry was a flexible one, it emphasized certain key factors:

Ordinarily, a key question to be answered in determining whether a theory or technique is scientific knowledge that will assist the trier of fact will be whether it can be (and has been) tested.

Another pertinent consideration is whether the theory or technique has been subjected to peer review and publication. . . . The fact of publication (or lack thereof) in a peer reviewed journal thus will be a relevant, though not dispositive, consideration in assessing the scientific validity of a particular technique or methodology on which an opinion is premised.

Additionally, in the case of a particular scientific technique, the court ordinarily should consider the known or potential rate of error.

Finally, "general acceptance" can yet have a bearing on the inquiry. . . . Widespread acceptance can be an important factor in ruling particular evidence admissible, and "a known technique which has been able to attract only minimal support within the community," may properly be viewed with skepticism.¹⁴³

Two follow-up cases clarified the application of the *Daubert* rule. In *General Electric v. Joiner*,¹⁴⁴ the Court held that a trial court's decision about the admissibility of expert testimony

¹⁴¹ 509 U.S. 579 (1993).

¹⁴² *Id.* at 587.

¹⁴³ *Id.* at 593-595.

¹⁴⁴ 522 U.S. 136 (1997).

can only be reversed on appeal if the trial court abused its discretion. In a final case, *Kumho Tire v. Carmichael*,¹⁴⁵ the Court considered testimony by an engineer who claimed to be able to determine whether a tire that had caused an accident by whether shredding had been defective. The Court held that *Daubert* and *Joiner* apply to all expert testimony, not merely testimony relying on novel scientific theories.

After this trilogy of decisions, Federal Rules of Evidence was amended to codify the changes. It currently reads:

If scientific, technical, or other specialized knowledge will assist the trier of fact to understand the evidence or to determine a fact in issue, a witness qualified as an expert by knowledge, skill, experience, training, or education, may testify thereto in the form of an opinion or otherwise, if (1) the testimony is based upon sufficient facts or data, (2) the testimony is the product of reliable principles and methods, and (3) the witness has applied the principles and methods reliably to the facts of the case.

The Advisory Committee Comments explain that “the standards set forth in the amendment are broad enough to require consideration of any or all of the specific *Daubert* factors where appropriate.” The Comments stress that these factors may not always be appropriate, and that other factors may be relevant in particular cases.¹⁴⁶

¹⁴⁵ 526 U.S. 137 (1999). For general discussion of these opinions and their implications, see David L. Faigman, et al, *Modern Scientific Evidence* (2005). These decisions have not been without their critics. For instance, a well-known environmental scholars contends that they have prompted lower courts to reject sound cases:

It is now clear after more than a decade's experience with *Daubert* that the lower courts have applied it quite vigorously to screen out not only “junk science” but also a good deal of “sound science” as well. Since the plaintiff ordinarily has the burden of proof in tort litigation, this aggressive invocation of the judge's new role as guardian of the purity of scientific evidence has clearly had a disproportionate impact on plaintiffs. A plaintiff's attorney must come to court prepared not only to establish the expert's qualifications, but also to demonstrate to a skeptical trial judge that the testimony forms scientifically reliable conclusions based upon reliable data and that those conclusions “fit” the legal requirements for establishing cause-in-fact.

Thomas O. McGarity, *Our Science is Sound Science and Their Science is Junk Science: Science-Based Strategies for Avoiding Accountability and Responsibility for Risk-Producing Products and Activities*, 52 KAN. L. REV. 897, 910 (2004).

¹⁴⁶ The Advisory Committee comments explain some of these other factors that may be relevant to admissibility:

(1) Whether experts are "proposing to testify about matters growing naturally and directly out of research they have conducted independent of the litigation, or whether they have developed their opinions expressly for purposes of testifying." *Daubert v. Merrell Dow Pharmaceuticals, Inc.*, 43 F.3d 1311, 1317 (9th Cir. 1995).

(2) Whether the expert has unjustifiably extrapolated from an accepted premise to an unfounded conclusion. *See General Elec. Co. v. Joiner*, 522 U.S. 136, 146 (1997) (noting that in some cases a trial

Climate models are produced under a process that is designed to address the reliability concerns of Rule 702. As noted earlier, the refereed publications supporting these models are voluminous. Moreover, additional procedures have been put in place to assure reliability. According to the IPCC,

Enhanced scrutiny of models and expanded diagnostic analysis of model behavior have been increasingly facilitated by internationally coordinated efforts to collect and disseminate output from model experiments performed under common conditions. This has encouraged a more comprehensive and open evaluation of models. The expanded evaluation effort, encompassing a diversity of perspectives, makes it less likely that significant model errors are being overlooked.¹⁴⁷

Eighteen modeling groups have combined their efforts in order to perform standardized experiments, and the output has been intensively analyzed. According to the IPCC, the “benefits of model intercomparison include increased communication among modeling groups, more rapid identification and correction of errors, the creation of standardized benchmark calculations and a more complete and systematic record of modeling progress.”¹⁴⁸ An archive of model outputs is held at the Program for Climate Model Diagnosis and Intercomparison; this archive is used by

court "may conclude that there is simply too great an analytical gap between the data and the opinion proffered").

(3) Whether the expert has adequately accounted for obvious alternative explanations. *See* *Clair v. Burlington N.R.R.*, 29 F.3d 499 (9th Cir. 1994) (testimony excluded where the expert failed to consider other obvious causes for the plaintiff's condition). Compare *Ambrosini v. Labarraque*, 101 F.3d 129 (D.C. Cir. 1996) (the possibility of some uneliminated causes presents a question of weight, so long as the most obvious causes have been considered and reasonably ruled out by the expert).

(4) Whether the expert "is being as careful as he would be in his regular professional work outside his paid litigation consulting." *Sheehan v. Daily Racing Form, Inc.*, 104 F.3d 940, 942 (7th Cir. 1997). *See* *Kumho Tire Co. v. Carmichael*, 119 S.Ct. 1167, 1176 (1999) (Daubert requires the trial court to assure itself that the expert "employs in the courtroom the same level of intellectual rigor that characterizes the practice of an expert in the relevant field").

(5) Whether the field of expertise claimed by the expert is known to reach reliable results for the type of opinion the expert would give. *See* *Kumho*, 119 S.Ct. at 1175 (1999) (Daubert's general acceptance factor does not "help show that an expert's testimony is reliable where the discipline itself lacks reliability, as for example, do theories grounded in any so-called generally accepted principles of astrology or necromancy."), *Moore*, 151 F.3d 269 (5th Cir. 1998) (en banc) (clinical doctor was properly precluded from testifying to the toxicological cause of the plaintiff's respiratory problem, where the opinion was not sufficiently grounded in scientific methodology); *Sterling*, 855 F.2d 1188 (6th Cir. 1988) (rejecting testimony based on "clinical ecology" as unfounded and unreliable).

¹⁴⁷ RANDALL, *supra* note , at 591.

¹⁴⁸ *Id.* at 593.

large numbers of researchers outside of modeling groups to study the models.¹⁴⁹ There are now nearly forty model intercomparison projects, each with its own mysterious acronym like SMIP-2/HFP (Seasonal Prediction Model Intercomparison Project-2/Historical Forecast).¹⁵⁰

Despite the efforts made to assure reliability, admissibility decisions are subject to some degree of uncertainty. Trial judges have leeway in making admissibility decisions because of the “abuse of discretion” standard for judicial review. Observers have found considerable variability in admissibility decisions, even when precisely the same evidence has been before different courts.¹⁵¹

In particular, witnesses who use climate modeling results may encounter two obstacles. First, some courts have required that experts rely only on evidence that individually satisfied the *Daubert* standard, rather than allowing experts to form judgments based on the weight of the evidence.¹⁵² This would be a problem for climate change experts, since no one model or set of observations may be sufficient to generate a firm judgment. Second, some courts have required proof of a doubling of the probability of harm from the baseline level in toxic torts cases, based on epidemiological studies.¹⁵³ As discussed earlier, because the existing ensemble of models may not reflect the full range of possibilities, it is difficult to provide clear-cut numerical estimates of probabilities, although multiple runs of individual models with parameter changes are at least suggestive.

These artificial restrictions on admissibility do not find support in the current Federal Rules of Evidence. The Advisory Committee’s note to the current version of Rule 702 recites a variety of factors as a “non-exclusive checklist” and does not make any one factor decisive. It also observes that “the rejection of expert testimony is the exception rather than the rule.”

Efforts to use climate models in litigation may have received an indirect boost from the Court’s decision in *Massachusetts v. EPA*.¹⁵⁴ In *Massachusetts v. EPA*, states, local governments, and environmental organizations petitioned for review of EPA’s denial of their petition. They had petitioned the EPA to begin a rulemaking to regulate greenhouse gas

¹⁴⁹ *Id.* at 594.

¹⁵⁰ MCGUFFIE AND HENDERSON-SELLERS, *supra* note , at 229.

¹⁵¹ See CARL F. CRANOR, TOXIC TORTS: SCIENCE, LAW AND THE POSSIBILITY OF JUSTICE 18-25, 328-330 (2006).

¹⁵² See *Allen v. Pennsylvania Engineering*, 102 F.3d 194, 198 (5th Cir. 1996); *Wright v. Willamette Indus.*, 92 F.3d 1105, 1107 (8th Cir. 1996).

¹⁵³ See Russel S. Carruth and Bernard D. Goldstein, *Relative Risk Greater than Two in Proof of Causation in Toxic Tort Litigation*, 41 JURISMETRICS J. 195, 200-201 (2001).

¹⁵⁴ 127 S. Ct. 1438 (2007).

emissions from motor vehicles under the Clean Air Act.¹⁵⁵ A divided panel of the D.C. Circuit ruled in favor of the EPA, in part on the basis of questions about the petitioners' standing.¹⁵⁶ Justice Stevens, writing for the Court, held that the plaintiffs did have standing and in particular that they had presented adequate evidence that they would suffer harm from climate change. Regarding these harms, the Court said:

The harms associated with climate change are serious and well recognized. Indeed, the NRC Report itself--which EPA regards as an "objective and independent assessment of the relevant science,"--identifies a number of environmental changes that have already inflicted significant harms, including "the global retreat of mountain glaciers, reduction in snow-cover extent, the earlier spring melting of rivers and lakes, [and] the accelerated rate of rise of sea levels during the 20th century relative to the past few thousand years . . ."¹⁵⁷

The Court noted that these effects posed a particular threat to the state's interests: "If sea levels continue to rise as predicted, one Massachusetts official believes that a significant fraction of coastal property will be 'either permanently lost through inundation or temporarily lost through periodic storm surge and flooding events.'" ¹⁵⁸ "Remediation costs alone, petitioners allege, could run well into the hundreds of millions of dollars."¹⁵⁹ Evidence of these harms derives in large part from climate modeling; in other words, the Court apparently finds such evidence credible.

In the first trial court decision to deal with the expert trial testimony on climate change, the judge dealt carefully with the issue of admissibility.¹⁶⁰ For example, the court admitted the testimony of the Director of the Goddard Institute, who testified about the basic reality of climate change and its likely effects, as well as stating that the climate could reach a tipping point at which even a small increase in CO2 levels would have a drastic effect.¹⁶¹ The court found that the testimony was based on sufficiently reliable information, despite the testimony of a rebuttal witness (the Arizona state climatologist) who argued that there was insufficient evidence of sea level rise.¹⁶² Although the court conceded that no existing model fully covered the potential for sea level rise from ice sheet disintegration, the witnesses "use of his expertise to make a

¹⁵⁵ 127 S. Ct. at 1449-1451.

¹⁵⁶ *Massachusetts v. EPA*, 415 F.3d 50 (D.C. Cir. 2005).

¹⁵⁷ *Id.* at 1455.

¹⁵⁸ *Id.* at 1456.

¹⁵⁹ *Id.*

¹⁶⁰ *Green Mountain Chrysler Plymouth Dodge Jeep v. Crombie*, No.2:05-cv-302 (Sept. 12, 2007).

¹⁶¹ *Id.* at 32.

¹⁶² *Id.* at 40.

prediction based on climate history is not an unreasonable choice of methodology. [His] predictions need not be certainties to be admissible under Rule 702, nor need his estimates of the timing and amount of sea level rise be exact to be admissible.”¹⁶³ Admitting that the predictions “do not have a known error rate and cannot be tested, at least not in a laboratory,”¹⁶⁴ a “prediction on this enormous scale must necessarily be tested by the extent to which it is confirmed by evidence such as the historical record and model results.”¹⁶⁵

Similarly, the *Green Mountain* court admitted testimony by a distinguished climatologist at the University of New Hampshire, who testified about the impact of climate change on the local environment.¹⁶⁶ The plaintiffs challenged his testimony on the basis that he had relied on flawed models.¹⁶⁷ A rebuttal witness challenged the Canadian and Hadley models, claiming they were “extreme and were downscaled unreliably.”¹⁶⁸ The court rejected this criticism, finding that the rebuttal witness’s views were outside the scientific mainstream and that the models had been selected for use by the U.S. government in studying regional impacts.¹⁶⁹

What about other kinds of computer models?¹⁷⁰ GIS models should pose relatively straightforward issues, since they are primarily ways of summarizing and presenting other information, and the main question is whether they do so accurately (along with the validity of the underlying data).¹⁷¹ Economic models of climate change should be viewed with caution in

¹⁶³ *Id.* at 40.

¹⁶⁴ *Id.* at 41.

¹⁶⁵ *Id.* at 43.

¹⁶⁶ *Green Mountain*, No.2:05-cv-302 at 49.

¹⁶⁷ *Id.* at 51.

¹⁶⁸ *Id.* 53.

¹⁶⁹ *Id.* at 53-54.

¹⁷⁰ Climate skeptics may also attempt to present their own modeling results in court. Given the lack of peer review, general rejection by the community of climate scientists, and the other *Daubert* factors, such testimony should arguably be inadmissible.

¹⁷¹ For discussion of the issues involved in computer-generated trial exhibits from the practitioner’s perspective, see Gregory P. Joseph, *A Simplified Approach to Computer-Generated Evidence and Animations*, 43 NYLS L. REV. 875 (1999-2000); Timothy W. Cerniglia, *Computer-Generated Exhibits—Demonstrative, Substantive, or Pedagogical – Their Place In Evidence*, 18 AM. J. TRIAL ADVOC. 1 (Summer 1994). On the concern that visual evidence might be given undue weight, see Hampton Dellinger, *Words Are Enough: The Troublesome Use of Photographs, Maps and Other Images in Supreme Court Opinions*, 110 HARV. L. REV. 1704 (1997). Dellinger remarks:

[T]he Court's use of photographs, maps, and other attachments has been both rich and problematic: rich in that attachments have accompanied opinions in a number of critical cases, and problematic in that their presence has been more distracting than illuminating. At worst, as with the “giant” cross in Capitol Square,

the event that they become relevant to litigation. The scope of the disagreements between models suggests the all-too-likely prospect of a battle between experts, leaving judges and juries to guess about what approach is most plausible.

Somewhat different issues are posed when models are used in regulatory proceedings rather than litigation. In the regulatory arena, the decision maker is an expert administrative agency rather than a layperson (whether judge or jury). Hence, the need for constraints on the consideration of scientific evidence is different. These issues are discussed in the next section.

B. Use of Models in Regulatory Proceedings

How will courts respond when agencies rely on climate models in regulatory proceedings?¹⁷² On occasion, judges have shown a tendency to reevaluate the use of models for themselves. In *State of Ohio v. EPA*,¹⁷³ the Sixth Circuit considered the validity of emissions limitations set by EPA for two electric utility plants in the Cleveland area. The dispute centered on EPA's use of a model known as CRSTER.¹⁷⁴ As the court described, EPA had made some effort to validate the model:

the visual attachments freeze a badly atypical, and thus misleading, version of reality. The foregoing analysis of the Supreme Court's use of attachments reveals clear failings. And there is little reason to be sanguine about the future. Egregious examples of the misuse of attachments have continued to appear in recent years. *With developing computer technologies*, attaching sight-based objects will only get easier, while the susceptibility of such objects to manipulation will only increase.

Id. at 1749 (emphasis added).

¹⁷² For general discussions of EPA modeling and its evaluation by courts, see James D. Fine and Dave Owen, *Technocracy and Democracy: Conflicts between Models and Participation in Environmental Law and Planning*, 56 *Hastings L.J.* 901 (2005); Thomas O. McGarity and Wendy E. Wagner, *Legal Aspects of the Regulatory Use of Environmental Modeling*, 33 *Env. L. Rep.* 10751 (2003).

¹⁷³ 784 F.2d 224 (6th Cir. 1986).

¹⁷⁴ The court described the model in some detail:

The CRSTER model is a single source model designed for application to hot, buoyant, stack effluents of the kind commonly produced by power plant and furnace chimneys. After factoring in background pollution, the CRSTER model is actually capable of modeling up to 19 sources, but only if they are in close proximity to one another—multiple stacks at a single plant, for example. It treats all sources being modeled as occupying the same location. See U.S. EPA 450/2-77-013, *User's Manual for Single-Source (CRSTER) Model*, at 2-24, 2-25 (1977) (hereinafter referred to as the “CRSTER Manual”). The CRSTER model is a “gaussian plume dispersion” model, which means that it describes how a plume of dirty air emerging from a smoke stack will spread upward and outward according to the principles of fluid dynamics.

The model consists of a “preprocessor subroutine,” which translates input data such as meteorological conditions and source characteristics into a format suitable for the model, and a set of subroutines that perform the actual modeling. These subroutines use data translated by the preprocessor to calculate how pollution from the source will spread out in light of the conditions (e.g., wind speed and direction) embodied in that data. In so doing, the model makes a number of simplifying assumptions about such

Several conclusions may be drawn about the CRSTER model on the basis of these four validation studies. First, CRSTER predicted the second-highest 1-hour sulfur dioxide estimated concentrations within a factor of two at two-thirds of the sampling sites. EPA believes that this is an acceptable range of accuracy. Second, CRSTER consistently underpredicted the second-highest 24-hour sulfur dioxide concentrations. Third, plant-specific factors appear to affect the degree to which CRSTER over- or underpredicts sulfur dioxide concentrations. Finally, CRSTER tends to underpredict at greater distances from the pollution source. The four validation tests described here make clear that EPA can validate the CRSTER at a particular site. It appears that on-site validation of CRSTER requires at least one full year of data gathering by EPA.¹⁷⁵

The court held that the use of the model was arbitrary because the model had not been validated for the specific sites involved in the case:

EPA's reliance on the CRSTER model without testing the model against any monitored emissions from the plants and ambient air quality data from the area around the plants is arbitrary under these circumstances. The CRSTER model's unimpressive showing in the validation studies conducted at other sites in Ohio and Massachusetts suggests that the model's accuracy is suspect. Moreover, these studies emphasize that site-specific factors, such as local geography and weather conditions, affect the model's accuracy. We have no information in the record about what effect Lake Erie has on the diffusion of sulfur dioxide from these plants built along the shoreline, although all sides appear to agree that this factor is significant. In the absence of reliable data of some type, the trustworthiness of CRSTER predictions cannot be assessed.¹⁷⁶

The Sixth Circuit's ruling seems to be something of an outlier.¹⁷⁷ Nevertheless, EPA's use of models has a mixed record in terms of judicial review. The most successful challenges

factors as the constancy of wind speed and direction, the uniformity of emission, the inability of the plume to cross a low atmospheric layer called the "mixing level," the absence of vertical wind shear, the nonreactivity of the effluent, and the degree of diffusion of the plume.

The model's predictions are presented in the form of readings at a hypothetical network of sensors or monitors surrounding the source. The model provides for five rings of such sensors along 36 compass azimuths evenly spaced every ten degrees. In addition, the model produces outputs of highest and second-highest concentrations at each receptor, a ranking of the 50 highest concentrations for the year, and various other useful data, some of which are suitable for use as input data for other analytic programs.

Id. at 228-229.

¹⁷⁵ *Id.* at 229.

¹⁷⁶ *Id.* at 230. The court reaffirmed its position in a follow-up opinion, *Ohio v. EPA*, 798 F.2d 880 (6th Cir. 1986).

¹⁷⁷ See McGarity and Wagner, *supra* note , at 10761 (calling the decision "[o]ne of the most infamous and arguably aberrational model cases"). By five years later, the case was being cited in its own circuit merely for the proposition

seem to involve either a failure by EPA to explain its choice of the model clearly¹⁷⁸ or the application of a model in a clearly inappropriate setting (such as using a model for gas emissions to a solid in *Chemical Manufacturers v. EPA*.¹⁷⁹)

If anything, climate models should hold up better in judicial review than the kinds of EPA models that have generally come before the courts. The generally accepted view is that agencies are particularly entitled to deference when they make judgments near the frontiers of science. As the Court said in *Baltimore, Gas & Elec. Co. v. NRDC*,¹⁸⁰ a “reviewing court must remember” when an agency “is making predictions, within its area of special expertise, at the frontiers of science.”¹⁸¹ “When reviewing this kind of scientific determination, as opposed to simple findings of fact,” the Court said, “a reviewing court must generally be at its most deferential.”¹⁸² Climate modeling certainly fits within this category of scientific determination.

Moreover, climate models differ in two important respects from traditional EPA models, both of which should make the climate models easier to defend. EPA models often rely on “untested or theoretical predictions and even policy judgments.”¹⁸³ Correspondingly, courts have generally seemed to “appreciate that imperfect information and limited resources require an

that air models are used to predict ozone dispersion. *See Wall v. EPA*, 265 F.3d 426, 428 (6th Cir. 2001). The court’s earlier suspicion of those models seemed to have been forgotten. *See also Sierra Club v. EPA*, 375 F.3d 537, 540 (7th Cir. 2004) (Easterbrook, J.) (reading *Wall* as allowing flexibility over the use of modeling methods). Of course, modeling methods improved after the case was decided, but the models remain imperfect:

Models have improved since the early days of air quality planning. As simulation models have evolved, they have become increasingly complex; this complexity has reduced the extent to which models oversimplify the real world. Current models use more monitoring data, greater computing power, improved and expanded algorithms, and more efficient, accurate mathematical solution methods than did their predecessors. Nevertheless, models’ skill in simulating ozone concentrations has not increased commensurately, and significant limitations remain for both the mathematical representations and applications of air quality models. Additionally, due to the time and effort involved in developing or updating an air quality model, usually no single “state-of-the-science” model contains a formulation depicting the most modern scientific understanding. As a result, the difficulty of modeling complex processes remains a source of uncertainty.

Fine and Owen, *supra* note , at 924.

¹⁷⁸ See McGarity and Wagner, *supra* note , at 10757-10761, 10770.

¹⁷⁹ 28 F.3d 1259 (D.C. Cir. 1994).

¹⁸⁰ 462 U.S. 87 (1983).

¹⁸¹ *Id.* at .

¹⁸² *Id.*

¹⁸³ McGarity and Wagner, *supra* note , at 10752.

agency to develop models to approximate reality.”¹⁸⁴ Thus, “[b]ecause of the need to cut evidentiary corners, an agency’s decision to forego the validation or calibration of models is usually, but not always, respected by the courts.”¹⁸⁵ When EPA develops models in order to fulfill a regulatory mandate, the models cannot be expected to have the same degree of development or validation as the models developed by scientists in their search for reliable knowledge. Climate models, as we have seen, have been subject to much more searching review within the community of climate scientists, and they are correspondingly more rigorous than the ad hoc models that EPA must often devise for regulatory purposes. Climate models should receive correspondingly greater judicial deference.

Attempts have also been made to use the Data Quality Act to force the government to withdraw climate change models.¹⁸⁶ Industry filed suit to challenge the government’s refusal.¹⁸⁷ The origins of the statute are not encouraging about its potential applications:

The Information Quality Act was an obscure rider to the Treasury and General Government Appropriations Bill for Fiscal Year 2001. It represented the culmination of a multi-year effort by Jim Tozzi, a tobacco industry consultant, to secure a legal vehicle for outsiders to challenge scientific studies disseminated by regulatory agencies. That rider required OMB to promulgate “policy and procedural guidance to Federal agencies for ensuring and maximizing the quality, objectivity, utility, and integrity of information disseminated by Federal agencies.” The agencies were in turn required to promulgate their

¹⁸⁴ McGarity and Wagner, *supra* note , at 10768.

¹⁸⁵ *Id.*

¹⁸⁶ Letter from Christopher C. Horner, *Competitive Enterprise Institute, to Information Officer, EPA, Request for Response to/Renewal of Federal Data Quality Act Petition Against Further Dissemination of “Climate Action Report 2002”* (Feb. 10, 2003), available at <http://www.epa.gov/quality/informationguidelines/documents/7428.pdf>.

¹⁸⁷ Wendy E. Wagner, *Commons Ignorance: The Failure of Environmental Law to Produce Needed Information On Health and The Environment*, 53 *Duke L.J.* 1619, 1713 n. 338 (2004). McGarity provides more details about the dispute:

In early 2003, the Competitive Enterprise Institute, a think tank that has historically opposed national and international efforts to abate greenhouse gases, filed an IQA challenge in three agencies demanding that they “withdraw” the National Assessment on Climate Change (NACC), an interagency report on the role that greenhouse gasses play in global warming. Although the report had received extensive peer review and public vetting, CEI nevertheless launched a classic corpuscular attack on various aspects of the report that were not, in CEI’s view, based on “sound science.” After the White House Office of Science and Technology Policy (OSTP) denied CEI’s petition, CEI sued President Bush and the Director of OSTP seeking a judicial ruling on the merits of its IQA challenge. The case subsequently settled when the federal government agreed to place a disclaimer on the NACC advising that it had not been prepared in accordance with the requirements of the IQA.

McGarity, *supra* note , at 925.

own guidelines and establish procedures under which affected persons could “seek and obtain correction of information that does not comply with the guidelines.”¹⁸⁸

Despite concerns about the IQA, it does not seem at this point to have made a dent in the traditional deference of courts to agencies in technical matters.¹⁸⁹

Because economic models of climate change are much less advanced than the climate models, agencies should use their output only with some degree of caution. It is particularly important to note critical assumptions and uncertainties, as well as to detail efforts to validate models. Placing complete reliance on any one model (or even worse, model run) is debatable practice. Cost-benefit analyses of climate change policies must be regarded as explorations of plausible scenarios rather than as firm economic estimates.

V. Policy Implications of Model Uncertainty

Models of climate change do not entirely agree in their predictions. Moreover, even when they do agree, there are residual grounds for uncertainty for two reasons. First, models “are driven by similar forcing datasets, and hence might share a common error in, for example, the amplitude of low-frequency solar variations.”¹⁹⁰ Second, “at least until recently, the [climate science] community has been reluctant to treat the range of responses from available models as spanning the range of response that could be taken place in the real world,” since models might share a common error.¹⁹¹ There is fairly good evidence that there are no major missing factors, at least in terms of explaining overall Twentieth Century warming trends,¹⁹² but we know that other factors are relevant and imperfectly modeled for future trends and regional impacts (as shown, for example, by the disagreements between models over the expected future degree of warming in various scenarios.)

Sources of uncertainty were discussed earlier. As a recent summary of the literature explains:

¹⁸⁸ McGarity, *supra* note, at 913.

¹⁸⁹ Recent OMB efforts to implement the statute by mandating peer review should not impede agency use of climate models, given the prevalence of peer review and other institutional review procedures. For discussion of OMB’s initiatives, see Patrick A. Fuller, *How Peer Review of Agency Science Can Heop Rulemaking: Enhancing Judicial Deference at the Frontiers of Knowledge*, 75 Geo. Wash. L. Rev. 931 (2007) (student note). One concern of scientists is that they will be exposed to fishing expeditions into their data and methods, but a recent case indicates that the IQA does not provide industry with a judicially enforceable right to such information. *Salt Inst. V. Leavitt*, 440 F.3d 156 (4th Cir. 2006).

¹⁹⁰ Allen, *supra* note, at 1361.

¹⁹¹ *Id.* at 1361. “There is considerable debate over the extent to which currently available models span the range of plausible real-world responses.” *Id.*

¹⁹² Allen, *supra* note, at 1375.

Uncertainty in prediction of anthropogenic climate change arises at all stages of the modeling process The specification of future emissions of greenhouse gases, aerosols, and their precursors is uncertain. It is then necessary to convert these emissions into concentrations of radiatively active species, calculate the associate forcing and predict the response of climate system variables such as surface temperature and precipitation. At each step, uncertainty in the true signal of climate change is introduced both by errors in the representation of Earth system processes in models and by internal climate variability.¹⁹³

Some efforts have been made to quantify uncertainty based on “various other lines of evidence, including perturbed physics ensembles specifically designed to study uncertainty within one model framework, and Bayesian methods using observational constraints.”¹⁹⁴ New types of experiments have been performed to quantify uncertainty about how models respond to external forcings, including evidence about how “uncertainties in parametrizations” (essentially estimates of processes that can be modeled fully) “translate into the uncertainty in climate change projections.”¹⁹⁵ This is accomplished, basically, by running models hundreds of times to see how the results differ.¹⁹⁶

One line of research attempts to estimate the probability distribution of climate sensitivity from historical evidence. These studies find that climate sensitivity is unlikely to be below 1.5 degree Celsius; the upper bound is more difficult to determine for technical reasons – it could exceed 4.5 °C although such high values are much less likely than those in the 2.0 to 3.5° range.¹⁹⁷ A second line of research examines climate sensitivity in models. In each model, the climate sensitivity depends on many processes and feedbacks, and probability distributions can be determined by examining how climate sensitivity tracks variations in various other parameters in the model. Essentially, parameters are subject to variations and the effect on climate response is measured through many runs of the model. The most frequent sensitivity values are around three degrees, but much higher values cannot be excluded.¹⁹⁸

Unfortunately, there is no completely satisfactory way of translating these results into a formal probability distribution.¹⁹⁹ If we assume that all current models are equally likely and

¹⁹³ Meehl and Stocker, *supra* note , at 797 (reference omitted).

¹⁹⁴ Meehl and Stocker, *supra* note , at 754.

¹⁹⁵ *Id.* at 754.

¹⁹⁶ *Id.* at 754.

¹⁹⁷ *Id.* at 798.

¹⁹⁸ *Id.* at 799.

¹⁹⁹ *Id.* at 799.

exhaust the possibilities, we can get a probability distribution, but these are somewhat heroic assumptions.²⁰⁰ Consequently, it may be a mistake to assume that we can derive firm probability experts by comparing the outputs of current models. As one climate scientists explains,

While ensemble projections carried out to date give a wide range of responses, they do not sample all possible sources of uncertainty. For example, the AR4 multi-model ensemble relies on specific concentrations of CO₂, thus neglecting uncertainties in carbon cycle feedbacks, although this can be partially addressed . . . More generally, the set of available models may share fundamental inadequacies, the effects of which cannot be quantified.²⁰¹

There is also the unknown degree of uncertainty involved with the human factor in modeling: the modelers themselves. As human beings, they are prone to biases and errors, like the rest of us, despite the strenuous efforts that the scientific enterprise makes to limit the effects of these weaknesses.²⁰² For example, there is some evidence that climate scientists tend to underestimate future levels of sea level rise in order to avoid being labeled as alarmists or publicity hounds.²⁰³ This source of error is hard to estimate and could easily operate in either direction: climate scientists may be under pressure to obtain dramatic results (thereby producing a bias in favor of large climate changes), but they may equally be under pressure to avoid anything that appears like sensationalism both in the interest of professionalism and to avoid attracting political attacks.

The upshot is that models give us a fair amount of confidence about basic trends but that we must be wary of assuming that their outputs are ironclad predictions of future developments. We can be highly confident about the existence of human-caused climate change and the likelihood that it will have serious effects. There is strong residual uncertainty, however, about the scale of climate change impacts, globally and regionally. This uncertainty might seem to argue against investing in climate change mitigation, but possible high-impact scenarios actually provide a further reason to take precautionary steps.

A. “Insuring” Against Uncertainty

There are good reasons to suspect that some important characteristics of real systems have what a statistician would call very “fat tails,” making extreme events much more likely than

²⁰⁰ Meehl and Stocker, *supra* note , at 799.

²⁰¹ *Id.* at 805.

²⁰² See Mayanna Lahsen, *Seductive Simulations? Uncertainty Distribution Around Climate Models*, 35 SOCIAL STUDIES OF SCIENCE 895 (2005).

²⁰³ See J.F. Hansen, *Scientific Reticence and Sea Level Rise*, 2 ENV. RES. LETTERS (2007) (on-line journal).

one would expect from a bell curve.²⁰⁴ This means that the most likely outcome may be much less serious than the expected value of the harm and that the variance, which measures the degree of risk against which one might want insurance, may be large compared to the expected value.

Rather than following the familiar bell-curve distribution, complex systems often follow power law distributions.²⁰⁵ Thus, the frequency of an event is given by its magnitude taken to a fixed negative exponent. A classic example is provided by earthquakes. There are many more small earthquakes than large ones, and the pattern of decay in frequency fits a power law distribution. Other examples include the size of extinction events, the number of species present in a habitat, and the size of the n^{th} smallest species (meaning that almost all species are rare but a few have very large populations).

Such fat tails are characteristic of power law distributions, with potentially disturbing results in terms of policy concerns. For example, it is possible that a variable subject to a power law to have an infinite variance or even an infinite expected value.²⁰⁶ The expected value is the probability of an event times its value. Variance is a measure of uncertainty. The chances of a large event may decrease rapidly but not rapidly enough to make up for the increasing magnitude of the event. (For example, consider x varying from one to infinity, with $p(x) = x^{-2}$.) If we are talking about an uncertain environmental harm, this means that either the expected value of the harm might be infinite, or the expected value might be finite but the variance might be infinite.

Because climate risks have fat tails, the expected level of climate risk could be quite high, much greater than the median level (where there is a 50/50 chance that the risk is either higher or lower). Even though many possible climate futures may involve smaller harm, the others will be statistically much more dangerous than the threshold we have established as significant. If the worst-case harm from climate change is bad enough, it may be worth incurring considerable cost to avoid the harm even if the harm is considered highly unlikely – after all, the odds of a terrorist being on any one airplane are also extremely low.

There seems to be a broad consensus among economists that uncertainty is not an excuse for inaction. As Thomas Schelling says, “this idea that costly actions are unwarranted if the dangers are uncertain is almost unique to climate.”²⁰⁷ “In other areas of policy, such as terrorism, nuclear proliferation, inflation, or vaccination,” he continues, “some ‘insurance’ principle seems

²⁰⁴ The discussion in the next two paragraphs draws on Daniel Farber, *Probabilities Behaving Badly* 37 UC Davis L. Rev. 145 (2003).

²⁰⁵ Coupled human and natural systems may be even more prone to “nonlinear dynamics with thresholds, reciprocal feedback loops, time lags, resilience, heterogeneity, and surprises.” See Jianguo Liu et al., *Complexity of Coupled Human and Natural Systems*, 317 *Science* 1513 (2007) (reviewing interdisciplinary studies of feedback between natural and human systems).

²⁰⁶ See BENOIT B. MANDELBROT, *THE FRACTAL GEOMETRY OF NATURE* 337-38 (1983).

²⁰⁷ Thomas C. Schelling, *Climate Change: The Uncertainties, the Certainties, and What They Imply About Action*, *ECONOMISTS’ VOICE* 4 (July 2007) (published at www.bepress.com/ev).

to prevail: if there is a sufficient likelihood of sufficient damage[,] we take some measured anticipatory action.”²⁰⁸ Nobel Laureate Kenneth Arrow suggests that we should take uncertainties into account by basing our policies on anticipated harm about 50% higher than the median expected harm, in order to account for the element of risk.²⁰⁹ Innovative theoretical work by the eminent environmental economist Martin Weitzman suggests that uncertainty about possible catastrophic climate change should loom large as a justification for controlling climate change.²¹⁰

It should be noted that the difficulty of quantifying risks is not a justification under U.S. law for ignoring potential risks. This is particularly clear under the National Environmental Policy Act (NEPA.) The Council on Environmental Quality instructs agencies that when important information is not available at a reasonable cost, they must include the following in the EIS:

(1) A statement that such information is incomplete or unavailable; (2) a statement of the relevance of the incomplete or unavailable information to evaluating reasonably foreseeable significant adverse impacts on the human environment; (3) a summary of existing credible scientific evidence which is relevant to evaluating the reasonably foreseeable significant adverse impacts on the human environment; and (4) the agency's evaluation of such impacts based upon theoretical approaches or research methods generally accepted in the scientific community.²¹¹

The regulations define “reasonably foreseeable” to include impacts “which have catastrophic consequences, even if their probability of occurrence is low, provided that the analysis of the impacts is supported by credible scientific evidence, is not based on pure conjecture, and is within the rule of reason.”²¹²

B. Creating Robust Strategies

One way to control for model uncertainty is called robust optimal control. Under this approach, to correct for uncertainty about the correctness of their preferred model, policymakers consider alternate models which are close to their baseline model, in the sense of being

²⁰⁸ *Id.*

²⁰⁹ Kenneth J. Arrow, *Global Climate Change: A Challenge to Policy*, ECONOMISTS' VOICE 4 (July 2007) (published at www.bepress.com/ev).

²¹⁰ Martin L. Weitzman, *The Role of Uncertainty in the Economics of Catastrophic Climate Change* (May 2007), available at <http://ssrn.com/abstract=992873>. Weitzman shows that even a small degree of uncertainty about a single model parameter can become magnified into substantial economic risk.

²¹¹ 40 C.F.R. § 1502.22(b) (2003).

²¹² *Id.*

statistically hard to distinguish from the baseline model. In the climate change context, the implication is that policymakers should react more aggressively and pursue more stringent mitigation strategies.²¹³

RAND researchers are developing methods to use computer assistance in scenario planning.²¹⁴ The key is a technique called Robust Decision Making (RDM):

RDM uses computer models to estimate the performance of policies for individually quantified futures, where futures are distinguished by unique sets of plausible input parameter values. Exploiting recent advances in computing power, RDM evaluates policy models once for each combination of candidate policy and plausible future state of the world to create large ensembles of futures. These ensembles may include a few hundred to hundreds of thousands of cases.²¹⁵

This technique provides a method for examining many potential scenarios in order to determine which characteristics of the scenarios are critical to the success or failure of particular strategies. The RAND technique has considerable potential:

For policy problems that have a large or unlimited number of possible policy approaches, RDM provides a systematic way of exploring these possible policies to efficiently identify and evaluate the policies that are likely to be robust. RDM first uses visualization and statistical analysis to identify policies (from the initial set) that perform well over many possible states. RDM then uses data-mining techniques to reveal under which future conditions such policies are vulnerable to poor performance. Examination of these key vulnerabilities (which can be considered “scenarios”) can suggest ways to craft new policies that hedge against the vulnerabilities. The analysis then identifies one or more new candidate robust policies and re-evaluates the performance of all policies against the different plausible future states. Through each iteration, the candidate policies become increasingly robust, and those key scenarios to which the policies are vulnerable are identified.²¹⁶

These methods may be especially useful when we must make large, long-term investments in infrastructure such as dams, water supply systems, or major power plants. Investments that fare well under some future scenarios may do badly in others, and a major

²¹³ Michael Funk and Michael Paetz, *Environmental Policy Under Model Uncertainty: A Robust Optimal Control Approach* (CESifo Working Paper No. 1938 March 2007).

²¹⁴ David G. Groves, *New Methods for Identifying Robust Long-Term Water Resources Management Strategies for California* (2006), available at http://www.rand.org/pubs/rgs_dissertations/2006/RAND_RGSD196.pdf.

²¹⁵ *Id.* at 125. See also David G. Groves and Robert J. Lempert, *A New Analytic Method for Finding Policy-Relevant Scenarios*, 17 GLOBAL CHANGE 73 (2007).

²¹⁶ *Id.*

purpose is to choose investments that are resilient across the most relevant risks. Computerized scenario analysis can help us determine the key areas in which investments vary in their resilience, so that policymakers can make informed choices between them.

Scenario analysis may also help what factual issues are critical for deciding between options. This makes it possible to focus research on policy-relevant issues. We should not consider the degree of uncertainty to be fixed forever. One role of modeling is to help us identify research priorities.²¹⁷

We have fairly good methods for analyzing situations in which risks can be quantified with reasonable confidence. We need improved methods for dealing with situations where such estimates do not exist or are subject to considerable uncertainty. The RAND methodology is a good start toward achieving such improved methodologies.

C. Rethinking the Role of OMB

Since President Reagan took office over twenty-five years ago, regulatory agencies have been required to perform cost-benefit analyses that are subject to review by the Office of Management and Budget (OMB).²¹⁸ Shortly after taking office President Reagan signed Executive Order 12,291,²¹⁹ aimed at improving the efficiency of informal rulemaking by executive agencies. Section 2 directed that "major" regulations not be promulgated unless, "taking into account affected industries [and] the condition of the national economy," the potential benefits to society outweigh potential costs, and net benefits are at a maximum. Review of the cost-benefit analysis was conducted by the Office of Management and Budget. In 1993, President Clinton issued an executive order maintaining the basic approach but attempting to streamline the process of OMB review. The rule was intended to reduce the number of regulations sent to OMB for approval and to make OMB's review more flexible.²²⁰ The result of

²¹⁷ What modelers "do best" has been described as follows:

[M]obilizing the current science base (uncertainties, warts, and all) into a computational model; thus to assess the plausibility of the imagined futures, under gross uncertainty; thus to identify what we would most like to understand much better, in the here and now, about the uncertainties (be they elements of the science, the policies, or the technologies) that are crucial to discriminating between the reachability of our worst fears or our greatest hopes. Nothing stands still: not images of the future, nor our qualitative models, nor our quantitative models. Call this living in a "recursive predictive world" . . .

Beck, *supra* note , at 202.

²¹⁸ For a description of the development of OMB's role in regulatory oversight, along with sensible suggestions for improving cost-benefit analysis, see Daniel H. Cole, "*Best Practice*" *Standards for Regulatory Benefit-Cost Analysis*, 23 Res. in Law & Econ. 1 (2007).

²¹⁹ 46 FED. REG. 13,193 (1981).

²²⁰ See Ellen Siegler, *Executive Order 12866: An Analysis of the New Executive Order on Regulatory Planning and Review*, 24 ENVTL. L. REP. 10,070 (1994).

this series of executive orders has not only been to strengthen the role of cost-benefit analysis, but also to increase the influence of the White House over rulemakings, at the expense of agencies such as the EPA.²²¹ The Bush Administration has pursued cost-benefit analysis with renewed fervor.²²²

Two general problems with cost-benefit analysis have particular relevance for climate change. First, non-market benefits are difficult to assess, yet ecosystem damage is a critical factor in assessing climate change.²²³ Second, climate change requires the use of discounting because of the long time spans involved, yet the legitimacy of discounting is contested, as is the choice of discount rate.²²⁴

²²¹ See Stuart Shapiro, *Unequal Partners: Cost-Benefit Analysis and Executive Review of Regulations*, 35 ENVTL. L. REP. 10,433 (2005) (arguing that centralized review may lead to increased political influence on outcomes).

²²²

[T]he battle continued to rage when President George W. Bush appointed John D. Graham, a strong proponent of cost-benefit analysis from the Harvard Center for Risk Analysis, to head the office of Information and Regulatory Affairs (OIRA) in the Office of Management and Budget. This nomination was strongly supported by regulated industries and equally strongly opposed by public interest groups. From that position, to which he was confirmed in late 2001, Graham has overseen the centralized review process for health and safety regulations. To the chagrin of public interest groups and the joy of industry-funded think tanks, OIRA greatly stemmed the flow of health, safety and environmental regulation during the Bush Administration. Although EPA promulgated several important regulations, most of which were required by statute, OSHA did not promulgate a single significant health standard during the entire four years.

Thomas O. McGarity, *The Story of the Benzene Case: Judicially Imposed Regulatory Reform Through Risk Assessment*, in ENVIRONMENTAL LAW STORIES 169 (Richard J. Lazarus & Oliver A. Houck eds 2005).

²²³ For a vigorous critique of the way cost-benefit analysis treats environmental and health benefits, see Frank Ackerman & Lisa Heinzerling, *Pricing the Priceless: Cost-Benefit Analysis of Environmental Protection*, 150 U. PA. L. REV. 1553 (2002). Some economists advocate the use of "contingent valuation" studies to measure how much people are willing to pay for non-use values. Contingent valuation is essentially a survey technique. People are given information about an environmental issue and then asked if they would be willing to pay a certain amount to solve the problem. There is a great deal of dispute about whether contingent valuation, even if done carefully, provides a genuine measure of preferences. Cass Sunstein, for example, finds many contingent valuation analyses difficult to take seriously. He stresses what he describes as the "astonishing and devastating fact" that willingness to pay seems constant regardless of the scale of the environmental problem. CASS R. SUNSTEIN, FREE MARKETS AND SOCIAL JUSTICE 142-43 (1997). For an environmentalist critique of contingent valuation, see John Heyde, *Is Contingent Valuation Worth the Trouble?*, 62 U. CHI. L. REV. 331 (1995). Another approach for valuation of non-market costs and benefits is the concept of ecosystem services. For discussion, see *Symposium*, 20 STAN. ENV. L.J. 309 (2001); James Salzman, *Creating Markets for Ecosystem Services: Notes from the Field*, 80 NYU L. REV. 870 (2005).

²²⁴ For discussions of the discounting issue, see Farber, *From Here to Eternity*, 2003 U. ILL. L. REV. 289 (2003); Lisa Heinzerling, *The Temporal Dimension in Environmental Law*, 31 ENVTL. L. REP. 11,055, 11,067 (2001). Over longer time periods, the results of changes in discount rates are even more dramatic, as Cass Sunstein explains:

If an agency chooses a discount rate of 2%, the outcome will be very different from what it would be if an agency were to choose a discount rate of 10%; the benefits calculation will shift dramatically as a result. If a human life is valued at \$8 million, and if an agency chooses a 10% discount rate, a life saved 100 years

Quite apart from these difficulties, the relative weakness of current economic models of climate change makes cost-benefit analysis quite problematic. Simply put, the uncertainties seem to swamp to the ability of the models to provide reliable information on costs and benefits. Moreover, the economic models must rely on climate modeling that also presents significant (though smaller) uncertainties. OMB is particularly ill-suited to making expert judgments on the validity of specific climate models, an area that is much more within the expertise of climate scientists. Thus, OMB's ability to play its accustomed role in cost-benefit analysis is doubtful in this context.

Nevertheless, climate policy necessarily must pay attention to costs. Providing some central guidance on this process throughout the executive branch may be useful. It might be useful for OMB to work with NOAA to develop a relatively small number of scenarios for agencies to consider in making specific decisions, and then to require agencies to submit analyses that consider the effects of varying key economic parameters such as future technological progress in energy technology. This would give policymakers a standard format for considering future scenarios, while also alerting them to inherent uncertainties that they face.

Alternatively, it might be useful to move this important but very complex issue to a separate group outside of OMB, especially given the extraordinary political pressures that might come to bear on climate policy. An independent commission of experts might be established with the mandate to assess the current state of climate knowledge at any given time, including an explicit treatment of uncertainties. The same group could also be charged with similarly monitoring the state of the art in the economic analysis of climate issues, and of developing standardized techniques such as scenario analysis for agencies to use in their decisionmaking. Apart from such an independent commission, the White House will need a reliable source of policy advice, and it might be well to establish a Council of Climate Advisors modeled on the current Council of Economic Advisors in the White House.

D. Dynamic Learning

In thinking about uncertainty, it is also important not to lose sight of the time dimension. At any given time, our knowledge may be sharply limited, causing severe difficulties in addressing environmental issues. But the frontiers of scientific ignorance shrink over time. We need strategies that exploit the possibility of obtaining better information in the future.

from now is worth only \$581. "At a discount rate of 5%, one death next year counts for more than a billion deaths in 500 years."

Cass R. Sunstein, *Cost-Benefit Default Principles*, 99 MICH. L. REV. 1651, 1711 (2001). On the critical role of discounting in current disputes over climate change among economists, see Daniel H. Cole, *The 'Stern Review' and its Critics: Implications for the Theory and Practice of Benefit-Cost Analysis* (2007), available at http://papers.ssrn.com/sol3/papers.cfm?abstract_id=989085.

The possibility of acquiring relevant new information can also significantly change standards for decisionmaking. Although the mathematical analysis is complex,²²⁵ the basic idea is simple enough. If a decision would have irreparable consequences, then it may be worth waiting to obtain new information. Taking an irreversible step ends the possibility of future learning, and therefore involves an extra cost that does not show up in the usual cost-benefit analysis. Waiting is equivalent to purchasing an option contract, and under many circumstances that option is worth buying.

For example, suppose a cost-benefit analysis shows that a project has a 40% chance of producing a net million dollar loss, and a 60% chance of a net million dollar gain. This looks like a good investment. A series of similar projects would produce average net gains of \$200,000. On the other hand, suppose that by waiting six weeks, we can know the outcome of the investment with certainty. At that point, we can decide whether to go ahead or not. When we make the later investment decision, we will invest in the project sixty percent of the time, for an expected gain of \$600,000, with no losses (since we will know enough not to invest in the loss situation). Waiting is the wise course here, because making an immediate decision deprives us of the opportunity to obtain further important information.

The value of waiting can be dramatic. Often, an irreversible project should not be undertaken unless its expected benefits are at least twice its cost.²²⁶ Otherwise, it is often better to wait for more information. Given the magnitude of uncertainty and the likelihood of obtaining more information, the value of waiting may be quite important in environmental law. Destroying a rain forest or an endangered species is irreversible. Usually, whatever economic benefits can be obtained from exploiting the resource will be available if we wait, while the uncertainty about environmental costs will be reduced. Hence, there is a good argument for waiting while attempting to learn more.²²⁷

On the other hand, the value of waiting may disfavor certain forms of pollution control that involve large “sunk costs.” Investments in pollution control equipment can’t be recovered if it turns out that better technologies become available, or that the harm caused by the pollution has been overestimated. We should try to avoid these stranded investments in environmental quality. Simply doing nothing while waiting for more information may be unacceptable, but we might consider less capital-intensive methods of control. These stop-gap alternatives may not be the best solutions, but they can buy time while we seek more information.

²²⁵ See Avinash Dixit, *Investment and Hysteresis*, J. ECON. PERSP. 169 (1992). The basic point is that “[w]here there is uncertainty, there may be learning.” W. Kip Viscusi and Richard Zeckhauser, *Environmental Policy Choice Under Uncertainty*, 3 J. ENVTL. ECON. & MGMT. 97, 108 (1976).

²²⁶ See Dixit, *supra* note , at 116. See also *id.* at 117, 120 for other examples of the magnitude of hysteresis effects. Sometimes, we may be uncertain about the degree of irreversibility itself, and here too the possibility of learning must be taken into account. See Viscusi and Zeckhauser, *supra* note , at 107-08.

²²⁷ See Graciela Chichilnisky and Geoffrey Heal, *Global Environmental Risks*, J. ECON. PERSP. 63, 76-79 1993; Anthony Fisher and Michael Hanemann, *Option Value and the Extinction of Species*, 4 ADVANCES IN APPLIED MICRO-ECON. 169 (1986).

Although these observations are useful in a general sense, they are not easy to apply to the climate change setting. In terms of irreversible investments, option theory suggests that we should try to avoid making them – thus, for example, that we should delay large investments in technologies such as carbon sequestration until we need how badly we need them. On the other hand, there are also irreversible harms to be considered. Ecosystems that are devastated by climate change cannot be easily restored, nor can extinct species be reestablished. Greenhouse gas emissions remain in the atmosphere a long time, contributing to climate change, and heat added to the world over the next twenty years will continue to have an effect as it is transferred to the oceans where change is slower. Putting these together, we can conclude the following: (1) it is worth spending extra today to avoid irreversible environmental harms; (2) however, to the extent we can, we should make this investment in forms that leave flexibility for policy shifts as we learn more about climate change and its impacts. An emphasis on renewable energy, energy conservation, and conservation of carbon, sinks such as the Amazon rainforest, would be consistent with these recommendations. We can always decide to switch back to fossil fuels or cut back on forest protection later, if we so decide.

* * * *

Climate change may be the most complex problem ever to confront the human race. As the level of detail in climate models indicates, predicting future climate depends not only on understanding basic physical laws, but also, on a clear understanding of many details of how the world operates, such as the formation of different types of clouds, various soil types and the water evaporation rates associated with them, vegetation types and their effects on water transpiration and sunlight reflection, and the complex processes underneath glaciers that lead to ice movements. Because the climate system interacts with human activities (and also because we are interested in the human effects of climate change), human societies are also part of the climate equation.

Successful prediction requires not only understanding all of this but being able to make predictions many decades into the future, perhaps centuries. It is not surprising that we must rely on powerful computers to study the interactions of these processes, make predictions, and even translate data and predictions into geographic forms more readily understood by human decisionmakers.

As important as it is to comprehend the knowledge created by these powerful technologies may be, it is also crucial to understand the limits of that knowledge. We are in no position to model future climate with complete assurance, and it remains to be seen how fast we can approach that ideal. In the meantime, at least, climate policy must take very seriously the risk that climate change will turn out worse than expected. Uncertainty must be a central consideration in climate policy – and most of the uncertainty is worrisome rather than reassuring.

This article has reached some broad conclusions regarding climate modeling. Climate models give us valuable information about the range of potential risks from climate change. We

have a clearer understanding of the lower bound on risk than of the high end of the distribution. The models are better at predicting temperature patterns than precipitation patterns, and global predictions are considerably firmer than more localized ones. Climate scientists have created a unique institutional system for assessing and improving models, going well beyond the usual system of peer review. Consequently, their conclusions should be entitled to considerable credence by courts and agencies. Economic models are much less advanced, and their conclusions should be used with caution. Nevertheless, policymakers must contend with significant uncertainty, and the policy process should be designed with this uncertainty in mind.

The significance of modeling is not limited to climate change. More broadly, we need to begin to understand the potential uses of computer modeling and to focus on methods for evaluating the reliability of model predictions. This requires learning more, not just about model results, but about the kinds of institutions and procedures that lend themselves to model reliability. In this respect, the community of climate modelers, with its carefully organized efforts to crosscheck models, may turn out to be the paradigm for future modeling exercises. In the legal system's confrontation with climate models, we may also see the beginning of processes that in the future will control how we use knowledge gained from more and more powerful – but even less easily comprehensible – computer-based methodologies.