Roll the DICE Again: Economic Models of Global Warming

Chapter 9

William D. Nordhaus and Joseph Boyer

Yale University
October 25, 1999

Version is DICE v.101599

Chapter 9. Managing the Global Commons

This final chapter summarizes the approach taken in this study and reviews the major conclusions. We begin with a summary of the new models discussed in this book along with a comparison between this model and other integrated assessment models. We then summarize the major findings from this study. We conclude with some reflections on how societies can use the results of this and other models for the thorny problems involved in actually coping with the threat of global warming.

1. Background

Global warming has become the major environmental policy issue of today. Concerns about the impact of global warming have increasingly been the subject of research and debate among natural and social scientists, and nations have undertaken a controversial new approach to curbing global environmental threats in the Kyoto Protocol of December 1997. The heir-apparent to the Democratic throne, Al Gore, has called global warming one of the major global issues of the 21st century.

Dealing with complex scientific and economic issues has increasingly involved makers unravel some of the complex interactions and understand future outcomes as well as the implications of alternative policies. In the economic literature, the DICE model (*D*ynamic *I*ntegrated model of *C*limate and the *E*conomy) developed in the early 1990s by Nordhaus (see especially Nordhaus [1994b]) was one of the early integrated-assessment (IA) models of the economics of climate change. This model developed an approach that links together from end to end the different facets of global warming. In this study, we present a newly elaborated model – RICE-99 (*R*egional *I*ntegrated model of *C*limate and the *E*conomy) along with its aggregated companion, DICE-99. These models are fully revised representations of the economics of global warming that build upon earlier work by the author and collaborators.

The purpose of the present study is to integrate the economic aspects of emissions of greenhouse gases and damages from climate change with current scientific knowledge of the dynamics of climate change. The study provides a full description of the methodology as well as an analysis of alternative approaches to climate-change policy

The analysis is laid out in eight chapters. The first chapter gives a general introduction to the subject. The following chapter presents the RICE-99 model, starting with a verbal description and following with a list of the equations. Chapter three describes the methods and data used to calibrate the model, and Chapter four provides special detail on the calibration of the damages from climate change. Chapter five presents DICE-99 and describes its relation to RICE-99. Chapter six describes how the model is solved.

The next two chapters present the major results and some of the important conclusions. Chapter seven describes the baseline scenario along with a number of alternative policies. Chapter eight presents an economic analysis of the Kyoto Protocol. The Appendices provide a summary listing of the equations, a variable list, other summary tables, and the computer programs for the different models.

2. Summary of the Model and Analysis

A. The RICE/DICE-99 models

We begin with an overview of the approach. The basic approach taken in analyzing the economics of climate change is to consider the climate change problem as an *economic* problem – one that requires reducing potential consumption of goods and services today in order to reduce the damages and risks of climate change in the future. By taking costly steps to slow emissions of GHGs today, the economy reduces the amount of output that can be devoted to consumption and productive investment. The return for this "climate investment" is lower damages and therefore higher consumption in the future. The purpose of the study is to examine the major tradeoffs involved in climate-change policy and to evaluate the relative efficiency of different policies.

In RICE-99, the world is composed of sovereign regions, represented by large countries (like the U.S. or China) or large regions (like OECD Europe or low-income countries). Each region is assumed to have a well-defined set of preferences over current and future consumption, described by a regional social welfare function that a pure time preference factor to the utility of future generations. Regions are assumed to maximize the social-welfare function subject to a number of economic and geophysical constraints. Society can select among alternative outcomes by choosing different savings rates and different emissions of GHGs.

The model contains both a traditional economic sector, similar to that found in many economic models, and a geophysical module designed for climate-change modeling. In the economic sectors, each region is assumed to produce a single commodity which can be used for either consumption or investment. Regions are not allowed to trade except to exchange goods for rights to carbon emissions.

Each region is endowed with an initial stock of capital and labor and an initial and region-specific level of technology. Population growth and technological change are exogenous, while capital accumulation is determined by each region's optimizing the flow of consumption over time. RICE-99 defines a new input into production called "carbon-energy." Carbon-energy consists of the energy services derived from the consumption of carbon fuels, where carbon fuels are measured in carbon units. CO_2 emissions are therefore a joint product of using energy for productive purposes. The economy can reduce emissions through substitution of capital and/or labor for carbon-energy. Technological change takes two forms: economy-wide technological change and carbon-saving technological change. More precisely, economy-wide technological change is Hicks-neutral, while carbon-saving technological change is assumed to increase the ratio of energy services to CO_2 emissions.

We calibrate the energy-related elements in the production function using existing data on carbon emissions, energy use, energy prices, and energy-use price elasticities. These allow an empirically-based carbon-reduction cost function, whereas most current integrated assessment models make "reasonable" but not empirically-based specifications of the cost schedule. In RICE-99, a carbon supply curve is introduced which means that the costs of producing carbon-energy rise as cumulative extraction increases. Because the model employs the optimal-growth framework, fossil fuels are efficiently allocated, which implies that low-cost resources have scarcity rents (Hotelling rents) and that the scarcity rents on carbon-energy rise over time.

The environmental part of the model contains a number of geophysical relationships that link together the different factors affecting climate change. This part contains a carbon cycle, a radiative forcing equation, climate-change equations, and a climate-damage relationship. The geophysical sectors are simplified representations of more complex models. Although they have been built on first principles, our research shows that they track closely more elaborate models.

In the new models, endogenous emissions are limited to industrial CO_2 (which, as noted above, are a joint product of using carbon-energy). Other contributions to global warming are taken as exogenous. The new models contain a new structural approach to carbon-cycle modeling that uses a three-reservoir model calibrated to existing carbon-cycle models. Climate change is represented by global mean surface temperature, and the relationship uses a mid-range climate sensitivity and a lag derived from coupled ocean-atmospheric models.

Understanding the economic impacts of climate change continues to be the thorniest issue in climate-change economics. The present study presents a new synthesis of damage estimates. The analysis presents new estimates for thirteen major regions rather than for the United States alone, although in the current version of RICE these are aggregated into eight regions. The new study focuses more heavily on the non-market aspects of climate change with particular importance given to the potential for abrupt or catastrophic risk. This approach is taken because the weight of the evidence indicates that the economic impacts of climate change on the market sectors of high-income countries are likely to be relatively limited. The major result is that impacts are likely to differ sharply by region. We estimate that Russia and other high-income countries (principally Canada) will benefit slightly from a modest global warming, while low income regions — particularly Africa and India — and Europe appear to be quite vulnerable to climate change. The United States appears to be less vulnerable to climate change than many countries.

Some unfinished business should be noted. We reiterate that the damage function, particularly the response of developing countries and natural ecosystems to climate change, is poorly understood at present. A particularly important open issue is the possibility of abrupt climate change; this is a central concern because, whereas scientists have improved their understanding of many elements of climate change, the potential for abrupt or catastrophic climatic change, for which precise mechanisms and probabilities have not been determined, cannot currently be ruled out. A related issue is that the present study abstracts from issues of uncertainty, in which risk aversion and the possibility of learning may modify the stringency and timing of control strategies. Additionally, the calculations omit the interactions between climate change and other potential market failures, such as air pollution, taxes, and research and development, which might reinforce or weaken the logic behind greenhouse-gas reduction or carbon taxes. While the model assumes substantial future technological change – both overall and carbon saving – it omits endogenous technological change. Finally, the model assumes that policies are efficiently implemented, which is undoubtedly an optimistic assumption given shortcomings in most environmental policies. These are all topics for another day.

B. Difference between RICE/DICE and other models

The RICE/DICE-99 models are but one family in a growing population of integrated assessment (IA) models of the economics of global warming. What are the major differences among the models and what are their similarities? This is an enormous question, but a few general comments are worth making at this point.

First, recent surveys of IA models tend to classify them into two general categories – optimization and policy evaluation. The optimization models, of which DICE is an example, are ones that have a well-defined objective and can determine "optimal" policies. The policy evaluation models are ones that are more descriptive in nature and trace out different scenarios rather than attempt to identify the best policies.[1] While DICE continues in the optimization framework, the regional DICE-type models, such as RICE-99, are more of a hybrid of the two approaches. RICE-99 contains much descriptive information and, particularly in the spreadsheet versions, can easily be used as a policy-evaluation model; at the same time, because all welfare changes, including reductions in climate damages, are modeled as consumption changes, it can be used as an optimization model.

Second, the major difference between the DICE-RICE family and most other major IA models is that DICE-RICE contains a complete evaluation of the societal impacts or damages from climate change while most other models stop short of incorporating damages. Because damage estimates are so uncertain, their inclusion adds considerable uncertainty to that part of the model. On the other hand, to omit considerations of damages is to lose sight of the fundamental objective of climate change policy, which is to keep greenhouse-gas concentrations below “dangerous levels,” as stated in the Framework Convention on Climate Change. While the “dangerous levels” are still open to debate, it is important to keep the ultimate objectives in mind when considering alternative policies.

Third, each modeler has a special appreciation for his or her model’s strengths and weaknesses. The major strengths of the DICE/RICE-99 models in our view are two: first, that they have been designed for transparency and ease of use and adoption by a wide range of people from students to researchers at the frontiers of their disciplines; and, second, that the components are designed to reflect the state of the art in each area while maintaining a parsimonious representation. For example, RICE-99 contains a simple but (we hope) reasonably accurate representation of the current state of knowledge about economies of different regions for doing long-run policy analysis. The modeling philosophy is that the DICE/RICE-99 models should be like a well-designed car – the parts and the whole are all optimized to get modelers where they want to go at low cost given the prices of time, energy, and ability.

Finally, we would also emphasize some of the weaknesses of the DICE/RICE models relative to other IA models. Other models are far better for specialized tasks. For example, no sensible economist would *ever* use the production sector in these models to consider the role of business cycles or to make short-run forecasts. The energy sector in the DICE/RICE models is designed for global warming economics and is poorly served to analyze interfuel substitution. International trade is omitted. For these and similar issues that need finer detail, there are specialized models that can provide much better resolution.

3. Major Results

This study contains many results that have been reported in earlier chapters. We will highlight five important conclusions in this summary.

The first major point is that an efficient climate-change policy would be relatively inexpensive and would slow climate change surprisingly little. Our estimate is that the present value of global abatement costs for the optimal policy would be around $100 billion, or an annualized cost of about $5 billion per year. Another interesting result is that a short delay in implementing an optimal policy has little cost – indeed, it can cost far less than implementing an inefficient policy. (Recall that all dollar values in the text, tables, and graphs represent 1990 U.S. dollars. Prices for the year 2000 are approximately 25 percent higher using the U.S. GDP deflator.)

The optimal policy reduces the global temperature rise to 2.34 ºC in 2100 and to 3.65 ºC in 2200. More stringent policies are ones that limit CO_2 concentrations to a doubling of pre-industrial levels (which has present value cost of about $1400 billion) and limiting global temperature increases to 2.5 ºC (costing $3500 billion). Our estimate is that the optimal policy has discounted benefits of reduced damages of about $300 billion, for a benefit-cost ratio of 3. The other two environmentally oriented policies have discounted benefits of about $700 billion (for concentrations limitation) and $1100 billion (for limiting temperature increase to 2.5 ºC) for benefit-cost ratios one-half and one-third, respectively.

Second, some prominent policy proposals look highly inefficient. From bad to worst we would rank Kyoto (Annex I trading), Kyoto (OECD trading), limiting CO_2 concentrations to twice pre-industrial levels, Kyoto (no trading), limiting climate change to a 2.5 ºC temperature rise, stabilizing global emissions at 1990 levels, and limiting climate change to a 1.5 ºC temperature rise (see Table 7-2). As presently estimated, none of the policies except geoengineering has major net economic benefits. The most beneficial control option has a net benefit of only $200 billion in present value. On the other hand, inefficient policies can do significant economic damage.

The third point refers to findings about carbon taxes or permit prices. With respect to current climate-change policies, perhaps the most important finding is that the optimal carbon tax in the near term is in the $5 to $10 per ton range. As Table 7-5 and Figure 7-2 show, that price range is an appropriate target for policy for the next decade or so. Surprisingly, the environmentally oriented concentrations-limits and 2.5 ºC-temperature-limits have relatively low carbon taxes: $4 and $12 per ton carbon in 2005, respectively. Policies which have near-term carbon taxes in the $100 per ton range, such as those associated with the Kyoto Protocol, are almost sure to fail a cost-benefit test because they impose excessive near-term abatement. Moreover, all policies that pass a cost-benefit test have near-term carbon taxes less than $15 per ton.

The fourth point concerns the revised view of the threat from global warming. The present study paints a less alarming picture of future climate change than other studies performed in the early 1990s. Whereas many studies projected baseline global temperature increases by 2100 in the 3 to 4 ºC range, a better reference estimate today would be close to 2.4 ºC warming in 2100. It is interesting to compare the results of the new model with the earlier DICE model. The optimal carbon tax and control rate in the early periods in the two models are very close. However, RICE-99 has significantly slower growth in emissions, concentrations, and other greenhouse-gas forcings. The slower buildup of concentrations, along with the evidence of the cooling effect of other gases and the phaseout of the CFCs, implies that the baseline global temperature increase for 2100 is 2.42 ºC in RICE-99 as compared to 3.28 ºC in the original DICE model. In addition, the new RICE-99 model has higher controls than the original DICE model. Hence the optimized global temperature increase in 2100 is 2.34 ºC in RICE-99 compared to 3.10 ºC in the original DICE model.

The final point is that an environmentally benign geoengineering policy would be highly beneficial. We estimate that a technological solution that would costlessly offset the climatic impacts of increasing greenhouse-gas concentrations would have a benefit of around $4 trillion in present value. This point is important because of the finding that the optimal policy in RICE-99 does not slow temperature change over the next century very much. It is important to understand that this result comes about because of the costs of slowing climate change – not because climate damages are negligible.

We conclude that, although not an "environmentally correct" policy, geoengineering is a policy option that deserves more careful study and consideration. It has important advantages over the house-to-house combat of emissions reductions. One important advantage is that geoengineering appears to be inexpensive. Another feature is that it does not require near-unanimous agreement among all major countries to have an effective policy; indeed, the United States could easily undertake geoengineering by itself if other countries would give their assent. Given the controversies surrounding climate change, given the slow pace of effective international agreements, and particularly given the increasing concerns about potentially catastrophic impacts – it is clear that much more attention should be given to geoengineering options.

4. Analysis of the Kyoto Protocol

The analysis of efficient paths is in one sense the analysis of policy in a vacuum – a vacuum in which powerful interest groups, disagreements among nations, incompetence and ignorance of policymakers, and inefficient implementation are all absent. A more realistic analysis would look at the Kyoto Protocol, which is the agreed-upon (but unratified) international agreement on how nations will begin to slow global warming. Our analysis in Chapter 8 has found a few key points.

First, we conclude that the Kyoto Protocol has no economic or environmental rationale. The approach of freezing emissions for a subgroup of countries is not related to a particular goal for concentrations, temperature, or damages. Nor does it bear any relation to an economically oriented strategy that would balance the costs and benefits of greenhouse-gas reductions.

Second, it useful to compare the Kyoto Protocol with our estimates of the optimal policy. The carbon prices in the global version of the Kyoto Protocol are close to our estimates of optimal policy in the first few decades. The global emissions targets embodied in the Kyoto Protocol are close to those in the optimal policy for the first few decades. However, in the longer run, the emissions reductions targeted under the Kyoto Protocol are too low relative to the efficient policy. The basic difficulty is that the Kyoto Protocol targets only the emissions of high-income countries, which are likely to be a dwindling fraction of global emissions.

Third, the cost-effectiveness of the Kyoto Protocol will depend crucially on how it is implemented. One extreme would be the global-trading version, where all nations enter into an efficient trading arrangement and policies are efficiently implemented. Our estimate is that this policy would be reasonably efficient over the next few years. The costs of an efficiently designed Kyoto Protocol are $59 billion, while the benefits of the emissions reduction from the Kyoto Protocol are around $108 billion, for a benefit-cost ratio of 1.8. The global-trading scenario is vanishingly likely, however, for it assumes participation of nations that are unwilling and in some cases unable to participate.

At the other pole would be the case where there is no trading of emissions allowances across major regions– either because of a breakdown in the agreement or because the trading regime is prohibitively expensive. The cost of the no-trade variant of the Kyoto Protocol is about 15 times the cost of the global-trade variant assuming efficient implementation. Even if there is trading among high-income (OECD) regions, the costs are likely to be near the no-trade case. The benefit-cost ratio for the no-trade version is 0.2. These calculations emphasize that efficient design of the policy should be the major concern of policymakers.

Finally, the Kyoto Protocol has significant distributional consequences. The United States bears the lion's share of the costs of implementing the current version of the Kyoto Protocol. These costs will come either through abatement activities or through purchase of permits. The U.S. is a net loser from all variants of the Protocol while other high income countries and the rest of the world either break even or benefit from the Kyoto Protocol.

5. Concluding Thoughts

The present study will be comforting to some and outrageous to others. If there is a single message, it is that climate change is a complex phenomenon, unlikely to be catastrophic in the near term, but potentially highly damaging in the long run. But it is a threat that is best approached with warm hearts and cool heads rather than bleeding hearts or hot heads. Global warming is a serious concern. Our best guess is that the present value of damages is around $4 trillion, so it is well worth the effort to reduce the damages if that can be accomplished at low cost. Our analysis suggests that current efforts to slow global warming through the Kyoto Protocol pay a high price but accomplish little.

The models developed here indicate that the pace of global warming will be slightly slower, and the near-term damages will be marginally smaller, than had been found in other studies or in earlier versions of the DICE/RICE models. The slower pace of future climate change is a hopeful but cautionary note to end on. Perhaps we can sleep more soundly on the basis of current evidence that climate change in the coming century is unlikely to enter the catastrophic range, particularly if we take effective steps to slow climate change. However, the size of the revisions in the projections in the last decade — and the fact that they come from so many different sources — is a reminder of the enormous uncertainties that society faces in understanding and coping with the climate-change problem. So while we may sleep more soundly at night, we must be vigilant by day for changes that might lead our globe off in more dangerous directions.

Endnotes:

1. Excellent recent surveys of IA models are contained in Chapter 10 in IPCC [1996c] and Kolstad [1998].