# A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies

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*Most analyses treat global warming as a single-agent problem. The present study presents the Regional Integrated model of Climate and the Economy (RICE) model. By disaggregating into countries, the model analyzes different national strategies in climate-change policy: pure market solutions, efficient cooperative outcomes, and noncooperative equilibria. This study finds that cooperative policies show much higher levels of emissions reductions than do noncooperative strategies; that there are substantial differences in the levels of controls in both the cooperative and the noncooperative policies among different countries; and that high-income countries may be the major losers from cooperation.* (*JEL* H41, Q4, Q2, Q20)

Although the issue of greenhouse warming was first seriously studied a century ago, it has over the last decade emerged as the central international environmental question. Most nations have adopted the Framework Convention on Climate Change negotiated at the 1992 Rio Earth Summit. Under the Convention, nations agreed to take steps to limit carbon dioxide ($CO_2$) and other greenhouse gas (GHG) emissions before they reach ''dangerous'' levels. Having increased its $CO_2$ emissions at an average growth rate of almost 2 percent annually for about a century, the United States has committed itself to capping its emissions at 1990 levels, and many other high-income countries have made similar or even more ambitious proposals (for a review of commitments, see Daniel M. Bodansky [1995] or International Energy Agency (IEA) [1994]).

The climate-change issue is so controversial primarily because the stakes are so high. If unchecked, recent surveys indicate that over the next century the globally averaged surface temperature will rise around 3°C (degrees Celsius), which would produce climates that are unprecedented during the entire span of human civilization. While warming may seem benign, it has major and unpredictable impacts on weather patterns, ocean currents, sea-level rise, river runoffs, storm and monsoonal tracks, desertification, and other geophysical phenomena. Many scientists and ecologists view these changes and uncertainties with alarm.

The other half of the calculus is the cost of slowing climate change. Even the most draconian policies (such as a virtual phaseout of fossil fuels) would only slow and not stop climate change, and significant steps to slow the rate of increase of climate change would cost hundreds of billions of dollars annually using today's energy technologies. Given the many economic issues facing humanity, it would require an unusually dire risk and uncommonly statesmanlike behavior for nations to divert 1 or 2 percent of their national incomes today to reduce conjectural risks that will not occur until well into the next millennium.

In addition to the grave risks and huge costs, the issue of greenhouse warming is difficult because the problem is so complex. It involves a series of poorly understood systems, including the carbon cycle, climate reactions, geophysical, ecological, and biological impacts of

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climate changes, economic impacts, along with potential adaptations and new technologies, with all of these stretching over a period of a century or more. Social and natural scientists have made impressive advances in understanding each of these systems over the last quarter century, and numerous efforts are underway today to link together the different components into an *integrated assessment* of climate change policies. One of the earliest integrated models was the DICE model, which is a globally aggregated model integrating a general-equilibrium model of the global economy with a climate system including emissions, concentrations, climate change, impacts, and optimal policy (see Nordhaus, 1992, 1994). Other recent integrated models of climate change include Alan S. Manne and Richard Richels (1992), Stephen C. Peck and Thomas J. Teisberg (1992), and Zili Yang (1993).

Globally aggregated models have the shortcoming of losing many of the interesting and important details of different regions. Perhaps the central shortcoming, however, is that global models ignore the fact that policy decisions to reduce GHG emissions are taken primarily at the national level. It is single nations, not the United Nations, that determine energy and environmental policy, so any grand design to slow global warming must be translated into national measures. The purpose of the present study is to improve the realism of integrated assessments by lodging policy making at the more appropriate national level. This involves introducing a number of regions of the world and considering different degrees of cooperation among nations.

The present paper reports on the results of the current version of the RICE model.[1] It outlines briefly the philosophy, sketches the modeling structure, and describes the major results.

## I. Description of the RICE Model

### A. *Overview*

This section begins with a succinct description of the RICE model; the equations of the model are provided in Appendix A.[2] The *RICE model*, or *Regional Integrated model of Climate and the Economy*, is a regional, dynamic, general-equilibrium model of the economy which integrates economic activity with the sources, emissions, and consequences of greenhouse-gas emissions and climate change. Most existing models of global climate change take the vantage point of the Global Commoner engaged in determining how nations *should* design sensible strategies to cope with future climate change. The RICE model takes a positive point of view by asking how nations *would in practice* choose climate-change policies in light of economic trade-offs and national self-interests. Put differently, global optimization models ask how nations would choose the optimal (or Pareto-efficient) path for reductions of GHGs. The RICE model allows us to calculate not only the efficient path (which we designate the cooperative approach)[3] but also to compare that path with noncooperative approaches.

In the RICE model, the world is divided into a number of regions. Each is endowed with an initial capital stock, population, and technology. Population and technology grow exogenously, while capital accumulation is determined by optimizing the flow of consumption over time. Output is produced by a Cobb-Douglas production function in capital, labor, and technology. In the long run, capital is fully mobile so that the real return on capital

[1] An experimental version of the RICE model with illustrative data was presented at the MIT Conference on the Environment (see Nordhaus, 1990). The current version (called RICE-6.3.2 for purposes of documentation) incorporates a number of changes, primarily a revision of the treatment of non-$CO_2$ greenhouse gases and improved estimates of the economic and emissions data. A major cause of the long gestation period of this research has been the difficulty in finding a satisfactory algorithm for solving the intertemporal general equilibrium (see below).

[2] The structural equations of the RICE model are generally the same as those of the aggregated DICE model. For a detailed discussion of the derivation of the equations, see Nordhaus (1994). The GAMS program for the RICE model is available from the authors upon request.

[3] This study identifies the cooperative solution as the one that generates an efficient level and distribution of emissions. The solutions that might emerge from international negotiations are a further issue that is not addressed in this study. Issues concerning possible bargaining outcomes are discussed below in Section II.C, "Welfare Effects by Region."

is equalized across regions. The preference function of each region is a utility function which is the sum of discounted utilities of per capita consumption times population, where the pure rate of social time preference (the discount rate on utility) is 3 percent per year in each region. The utility function is logarithmic in per capita consumption.

The major contribution of the integrated approaches like the RICE model is to integrate the climate-related sectors with the economic model. This part of the model contains a number of geophysical relationships that link together the different forces affecting climate change, generate the greenhouse-gas emissions, and measure the impacts of climate change. RICE includes region-specific emissions equations, a global concentrations equation, a global climate-change equation, and regional climate-damage relationships. Endogenous emissions are limited to $CO_2$, while other greenhouse gases are treated as exogenous. Uncontrolled emissions are a slowly declining fraction of gross output—a relationship which is consistent with the observed ''decarbonization'' in most countries over this century that is also predicted by more detailed energy models. $CO_2$ emissions can be controlled by increasing the prices of factors or outputs that are $CO_2$ intensive, and we represent the $CO_2$-reduction cost schedule parametrically by drawing upon a number of studies of the cost of $CO_2$ reductions. Climate change is represented by the realized global mean surface temperature, which uses relations based on current climate models. The economic impacts of climate change are assumed to be increasing along with the realized temperature increase. The impacts of climate change are estimated from a number of different studies, but it must be recognized that this is the most uncertain part of the model.

The major economic choices faced by nations (or the concert of nations) in this approach are (a) to consume goods and services, (b) to invest in productive capital, and (c) to slow climate change through reducing $CO_2$ emissions. The new element introduced in the RICE model and not present in other models of global warming is the possibility of different strategies undertaken by nations. We distinguish three distinct approaches:

- *Market policies.* The market approach is one in which there are no controls on the emissions of greenhouse gases. This has been the approach followed by virtually all nations up to now.
- *Cooperative policies.* The second approach is the ideal one in which global environmental concerns are treated cooperatively through the efficient actions of all nations. In this approach, nations agree to reduce $CO_2$ emissions in a globally efficient way. This solution is efficient but requires an unrealistically high degree of cooperation.
- *Noncooperative policies.* In the third approach, individual nations undertake policies that are in their national self-interests and ignore the spillovers of their actions on other nations. In the noncooperative approach, to the extent that nations are small and the externality is truly global, efforts to reduce $CO_2$ emissions will be much smaller than in the global cooperative solution. This solution is inefficient but realistic.

### B. *Basic Structure*

We outline here the major features and innovations of the RICE model; the equations of the model are contained in Appendix A.

The RICE model divides the global economy into 10 different regions. The first five are 1) the United States, 2) Japan, 3) China, 4) the European Union, 5) and the former Soviet Union (FSU). Each is treated as a single decision maker. The last five regions have different numbers of countries, and each is treated as multiple decision makers. These five regions are 6) India, 7) Brazil and Indonesia, 8) 11 large countries, 9) 38 medium-sized countries, and 10) 137 small countries. (Basic data on the major regions are contained in Appendix B.) To reduce the severe computational complexity of the solution, we sometimes aggregate regions 6 through 10 into one region as the ''rest of the world'' or ''ROW.''

The goal in creating the different regions is to structure the problem so that the noncooperative equilibrium is equivalent to the full but enormous game with about 200 countries. This is done by allocating the smaller countries to groups so that within each group the national benefits from slowing climate change are roughly equal. We then mimic the free-riding temptations of global public goods by dividing the benefit function for each region by the number of countries (that is, decision-making units) within that region.

An example will clarify the way regions are used. Region 9 contains 38 countries—including Bulgaria and Hungary, which are countries with roughly similar populations and economies. We assume that all the countries in region 9 are similar in terms of their sizes, mitigation cost functions, and damage functions. Hence, for region 9 the (slightly simplified) net benefit function to be maximized in the noncooperative case is $N(E_9) = B(E_9)/38 - C(E_9)$, where $N(E_9)$ is the net benefits of emissions for region 9, $E_9$ is emissions in region 9, $B(E_9)$ is the benefit of emissions, 38 is the number of equal-sized decision makers in region 9, and $C(E_9)$ is the cost function. Therefore, when the representative country in region 9 maximizes its net economic welfare in the noncooperative case, not only will it ignore the benefits accruing outside region 9, but it will also internalize only $^1/_{38}$ of the benefits of the region. This procedure includes in a computationally feasible manner all the different countries while ensuring that the incentives for free-riding are maintained.

A major difficulty in constructing the RICE model has been to estimate the regional parameters of the different functions.[4] Gross domestic products, populations, $CO_2$ emissions, and capital stocks are taken from a variety of international sources. Future population growth estimates are taken from the United Nations projections. The major uncertainty in the economic projections is long-run levels of per capita output in the different regions. These projections are based on the assumption of *partial convergence of per capita incomes*. That is, we assume that the relative differences in regions' per capita incomes decline over time but do not disappear. The extent of convergence is a controversial issue, but to the extent that differences in per capita incomes are primarily based on differences in the extent of adoption of available technologies, productivity differences should largely disappear over the long run.

[4] A detailed list of sources and data are available from the authors.

TABLE 1—FUTURE LEVELS OF INCOMES, DIFFERENT REGIONS

| Region | Ratio of region's per capita income to that of the United States ($US_{1990} = 1$) 1990 | 2100 | 2200 |
|---|---|---|---|
| 1) United States | 1.00 | 3.11 | 4.69 |
| 2) Japan | 1.09 | 4.07 | 4.83 |
| 3) China | 0.02 | 0.47 | 1.55 |
| 4) European Union | 0.85 | 2.89 | 4.27 |
| 5) Former Soviet Union | 0.14 | 0.87 | 2.02 |
| 6) Rest of the world | 0.07 | 0.84 | 1.69 |

*Note:* These values are the values of per capita GDP generated by the market solution for the RICE model. The GDPs are calculated using market exchange rates.

The assumed ratios of long-run levels of per capita GDPs to that of the United States are given in Table 1, showing the observed values for 1990 along with projections for 2100 and 2200. While highly conjectural, these estimates are consistent with recent trends in country GDP growth. One interesting feature of this approach is that it gives considerably higher estimates of output and emissions than do the conventional global models, such as those used by governments in the Intergovernmental Panel on Climate Change (IPCC). For the modeling, each region's income growth is generated through Hicks-neutral technological change, which starts at approximately the observed rates for 1960–1990. After 1990, growth rates are assumed to decline exponentially in a manner leading to the asymptotic productivity ratios shown in Table 1.

$CO_2$ emissions are separated into industrial emissions (largely from fossil fuels) and those from land-use changes and are calibrated to 1990 levels. The ratio of $CO_2$ emissions to output is assumed initially to decline at different rates, with each region's decline rate decreasing along with the overall rate of technological change by region. Here again, asymptotic $CO_2$-output ratios are assumed to converge considerably but not completely in the future.

The costs of reducing emissions by region are estimated separately on the basis of the existing studies of the cost of reduction of $CO_2$

emissions. Most studies are based on the United States and Europe, and estimates for other regions have low levels of reliability. We have parametrized the cost function using the functional form from earlier studies but have estimated the *intercepts* of the cost functions on the basis of the international comparisons undertaken by the OECD and by Energy Modeling Forum 13.[5]

Estimates of the economic impacts or damages from climate change are sparse at this stage. There are numerous studies of the estimated impact of climate change on the marketed sectors for the United States, but few reliable studies for the nonmarket sectors or for developing countries. To estimate the impacts in different regions, we assume that the damage function from climate change is identical for each industry across different regions, and that the cost functions have the same parameters as those estimated for the United States. Impacts in different regions are calculated by taking the estimated shares of different sectors (agriculture, coastal activities, and so on) in national output and then aggregating those up to obtain overall national estimates. (This approach is described in Nordhaus [1994].) The results in the aggregate do not differ markedly from the other major estimates (see particularly Samuel Fankhauser [1993] and the survey of experts in Nordhaus [1994]), but it must be emphasized that the distribution of climate impacts across countries is at this stage highly conjectural. Table 2 shows the major inputs assumptions for the different regions.

[5] See Andrew Dean and Peter Hoeller (1992) and Darius W. Gaskins and John P. Weyant (1993). The functional form of the mitigation-cost function in the DICE model was estimated from studies of the cost of $CO_2$ reduction in nine families of models primarily based on the United States and takes the form $C_i(t) = b_{1,i}\mu_i(t)b_2Y_i(t)$, where $i$ is region $i$, $C_i(t)$ = the cost of reducing $CO_2$ emissions, $b_{1,i}$ and $b_2$ are parameters, $\mu_i(t)$ is the emission-control rate or fractional reduction in emissions from the market path, $Y_i(t)$ is region $i$'s gross regional product, and $t$ is the time period. The RICE model assumes that the exponents ($b_2$) are the same across countries and calibrates the intercepts ($b_{1,i}$) to estimates of the cost functions from the different countries or regional models mentioned above.

The climate-change policies are characterized by ''control rates'' and ''carbon taxes.'' Control rates are simply the percentage reductions in $CO_2$ emissions relative to a baseline or uncontrolled path. Carbon taxes represent the marginal cost of reducing $CO_2$ emissions. A carbon tax would equal the price of a carbon-emissions permit if there were tradable permits, and the prices of such permits in different countries would obviously be equalized (at market exchange rates) if permits were freely tradable. In the market solution, carbon taxes are zero. In the cooperative solution, emissions are curtailed in a cost-effective manner. The model does not deal explicitly with mechanisms by which winners might compensate losers, although we discuss some of the issues below.

### C. *Algorithm to Calculate General Equilibrium*

The RICE model presents a radically different philosophy for estimating strategies to cope with global warming from global-optimization models used in many integrated assessments. The baseline calculation is calibrated to a market equilibrium of the world economy with all the differences in populations, technologies, and incomes—the world is taken as it is for the purpose of the baseline calibration. We then calculate different strategies for global warming conditional on the existing distribution of capital, labor, and technology. The strategies include doing nothing (the market solution), finding an efficient solution given the existing distribution of income (the cooperative solution), and finding the solution in which nations select policies to maximize national preferences alone (the noncooperative or nationalistic equilibrium). This public-choice approach is in sharp contrast to many of the debates on climate change today; in these, the distributional issues of who shall pay to slow climate change rise to the top of the agenda.

We now describe the algorithm for finding the cooperative solution in the RICE model. The technique we employ originates with T. Negishi (1960), was discussed briefly in Nordhaus (1990) in the context of global warming, and has been used in similar models

TABLE 2—MAJOR INPUT PARAMETERS FOR THE RICE MODEL

| Region | Cost intercept[a] | Climate damage intercept[b] | $CO_2$ emissions, 1990: Land-use[c] | $CO_2$ emissions, 1990: Industrial[d] | Population 2100[e] | Per capita output (2100)[f] | $CO_2$ ratio, 2100[g] |
|---|---|---|---|---|---|---|---|
| United States | 0.07 | 0.01102 | 0.010 | 1.360 | 0.294 | 68.8 | 0.1190 |
| Japan | 0.05 | 0.01174 | 0.000 | 0.292 | 0.125 | 89.1 | 0.0630 |
| China | 0.15 | 0.01523 | 0.136 | 0.669 | 1.656 | 9.9 | 0.5120 |
| European Union | 0.05 | 0.01174 | 0.100 | 0.872 | 0.427 | 63.0 | 0.0740 |
| Former Soviet Union | 0.15 | 0.00857 | 0.000 | 1.066 | 0.366 | 18.9 | 0.3220 |
| Rest of world | 0.10 | 0.02093 | 1.730 | 1.700 | 6.738 | 18.1 | 1.1850 |

[a] The intercept of cost function equals the fraction of annual output required to reduce net $CO_2$ emissions to 0.
[b] The intercept of climate-damage function equals the reduction in annual net output from an increase of 2.5°C in global mean temperature.
[c] Emissions are measured in billions of tons carbon per year. Land-use emissions are primarily from deforestation.
[d] Emissions are measured in billions of tons carbon per year. Industrial uses primarily from burning fossil fuels.
[e] Population is in billions of people.
[f] Gross domestic product (GDP) is measured at 1990 market exchange rates in thousands of 1990 U.S. dollars.
[g] The ratio is of industrial $CO_2$ emissions to GDP (tons of carbon per $1000 of output in 1990 U.S. dollars).

by Manne and Thomas Rutherford (see, particularly, 1994). The theoretical basis for the algorithm is a theorem of Negishi which relies on the second theorem of welfare economics. Negishi suggested and proved that under certain conditions a competitive equilibrium can be found by maximizing a social welfare function of $N$ agents in which the welfare weight of each of the agents is adjusted to satisfy the agent's budget constraint. We will call this equilibrium the *Negishi solution*.

What are the appropriate welfare weights? In our calibration, we adopt the realistic approach by taking the welfare weights that reflect the actual economic outcome across regions. We do this not as a brief for the existing international distribution of resources and income but because it is the starting point for analyzing potential improvements in economic welfare that would arise from policies that are imposed on the actual world economy. Hence, the weights are ones such that the excess demands in all markets are zero at the given welfare weights and prices.[6] More precisely, the algorithmic procedure is the following. We first solve the RICE model by optimizing a global social welfare function of the form:

$$(1) \quad W = \sum_{i=1}^{N} \phi^i U^i[c^i(1), c^i(2), \dots, c^i(t), \dots, c^i(T)]$$

where $W$ is the value of the global social welfare function and $\phi^i$ are the welfare or Negishi weights for country $i$, $i = 1, \dots, N$. The $U^i$ are the preference functions for the different countries, and the $c^i(t)$ are the consumption bundles of the countries.

The relevant excess demand is found in the intertemporal budget constraint of each region. To find the competitive equilibrium, we add a constraint to the problem that requires each region to satisfy its intertemporal budget constraint, which is represented by terminal net foreign assets, $\mathrm{NFA}^i(T)$, $T$ being the last period:

$$(2) \quad \mathrm{NFA}^i(T) = 0, \qquad i = 1, \dots, N.$$

Next, define $\psi^i(T)$ as the dual variable of $\mathrm{NFA}^i(T)$, which in economic terms is the marginal utility of consumption or income in the last period. Given condition (2), $\psi^i(T)$ is a function of the welfare weights and we can write these functions as $\psi^i(T) = G^i(\phi^1, \phi^2, \dots, \phi^N)$, $i = 1, \dots, N$. Without condition (2),

[6] A brief but illuminating discussion of the Negishi approach is in contained in Andreu Mas-Colell et al. (1995 pp. 630–31).

an arbitrary set of social welfare weights would generate a set of nonzero $\mathrm{NFA}^i(T)$, which implies that at least one region does not live within its budget. However, when the dual variables are equalized across all countries, the welfare-weighted marginal utilities of income are equal and the intertemporal budget constraints is therefore satisfied.

Hence, the algorithm works by searching for the welfare weights, as a function of the dual variables $\psi^i(T)$, so that the marginal utilities of consumption are equalized:

$$(3) \quad \psi^i(T) = G(\phi^1, \phi^2, \dots, \phi^N) = \psi^*, \quad \text{for all } i = 1, \dots, N.$$

Combining (1), (2), and (3), we know that each of the country budget constraints is satisfied and that no region can gain from a change in the resulting allocation. Hence, by the Negishi theorem, we know that this optimized outcome using the welfare weights generated in (3) represents a competitive equi-librium consistent with the initial endowments, technology, and preferences. The equilibrium thus found is the "pure Negishi solution."

Unsatisfactory aspects of the solution led to the following refinements of the pure Negishi solution. The major problem with the pure Negishi solution was that it generated extremely large capital flows among regions (this is a common feature in intertemporally optimized models).[7] Because these are unrealistic, we took one further step which was to impose certain flow and stock constraints on debt and current accounts to ensure that net foreign investment does not exceed certain limits. These limitations limited the export-GDP ratio to 1, limited the ratio of net foreign assets to output to 0.1, and limited the current account deficit to GDP ratio to 0.1 (see Appendix A for details). These constraints were based on observed limitations, but they made virtually no difference for the results of the analysis below.

Given these constraints on international capital flows, our algorithm will not produce the necessary complete price equalization for carbon-trading permits, which are assumed to be fully tradable and reach price. To ensure price equalization for carbon-emission rights, we adjust the Negishi weights across regions for every period. We call this new algorithm the *time-dependent Negishi solution*. It differs from the pure Negishi solution because it incorporates the constraints on capital flows so that the regional budget constraints are binding for every period. As a result, carbon-emissions permits have equal prices in all regions in each time period (at market exchange rates). Under this revised algorithm, we seek the *time-dependent Negishi weights*, $\phi^i(t)$. To find these, we first solve the model with an arbitrary set of welfare weights while continuing to impose (2). Following the Negishi theorem, we then reset the welfare weights for all countries and time periods according to the following formula:

$$(4) \qquad \phi^i(t) = \frac{\dfrac{1}{\psi^i(t)}}{\displaystyle\sum_{i=1}^{n} \frac{1}{\psi^i(t)}}.$$

This equation sets the welfare weights equal to the inverse of the marginal utilities of consumption. The search algorithm based on (4) very quickly converges to a solution that satisfies (2) and (3). We have conducted a number of experiments and have found no indication of multiple equilibria.

What is the underlying economic rationale for this algorithm? The solution represents a competitive equilibrium under the assumption that the preferences or technological constraints limit the international flows of capital. For example, there may be strong home-country preferences in portfolios because of limitations of the marketability of human capital. The limitation of this approach is that to the extent that the constraints on capital flows have nonmarket-clearing elements due to rationing, the excess demands will not be zero and we may depart from the market

[7] The difficulty raised by unrealistically high capital flows is not related to the use of the Negishi technique; the same issue would occur if fixed-point methods were employed.

equilibrium (which would in any case be difficult to compute).

Once we have obtained a competitive equilibrium, we then perturb various elements, such as the climate parameters or the cost functions, and resolve the maximization in (1). We do this holding the welfare weights constant across runs. This resolves the index number problem of changing prices by calculating the welfare changes at the market welfare weights.[8]

### D. *Finding the Noncooperative Equilibrium*

The algorithm just described provides the solutions for both the market and the cooperative equilibrium. A different approach is necessary to find the noncooperative equilibrium. The noncooperative or nationalistic equilibrium exists as the equilibrium of the strategies of the different countries. We hence need an assumption about strategies and a method of finding the equilibrium.

As for strategies, we assume that each nation determines its policies by maximizing its domestic intertemporal utility function assuming that other nations' strategies are unaffected by its policies. The noncooperative strategies are hence dynamic, full-information, Nash strategies, and we are seeking the Nash equilibrium. Technically, our solution is a Nash equilibrium in a finite game with perfect information, and it is therefore time consistent. Such games have pure strategy Nash equilibria which can be calculated through backward induction, which is essentially what our algorithm does (for a discussion, see Mas-Colell et al. [1995 Chapter 9]).

More precisely, we assume that each nation sets its own control rate over time $[\boldsymbol{\mu}^i = \{\mu^i(1), \mu^i(2), \mu^i(3), \ldots, \mu^i(t), \ldots, \mu^i(T)\}; i = 1, \ldots, N]$ so as to maximize its national objective function taking the control rates of the other regions $\{\boldsymbol{\mu}^1, \ldots, \boldsymbol{\mu}^{i-1}, \boldsymbol{\mu}^{i+1}, \ldots, \boldsymbol{\mu}^N\}$ as given. Beginning with an initial set of control rates, we iterate through the different regions by optimizing for each region holding the control rates and resulting emissions, concentrations, and impacts in other regions from the previous iteration fixed. We continue to cycle through this sequence until the set of control rates are unchanged given the set of noncooperative strategies of other countries, which is then the Nash equilibrium. The outcome matches well the theoretical predictions and is in our simulations invariant to initial conditions, which suggests that the Nash equilibrium is unique.

How reasonable is this solution concept? While the pure Nash equilibrium is a sensible assumption for small countries like Chad, whose global warming policies will hardly make the front pages, it may lack realism for large or influential countries. Large countries like China and influential countries like the United States would probably want to take into account the effect of their policies on other countries' policies. The ambivalent policy on global warming by the United States over the last decade has undoubtedly strengthened the hand of those in other countries who want to do little. An alternative approach would be for countries to posit conjectural variations or reactions of other countries to their policies. For example, the United States might assume that Japan or Europe would be a follower in terms of carbon-tax policies or tradable emissions policies. Another possibility would be to model coalitions of different countries. We have not explored these alternative solution strategies in the present paper. Once we admit nonzero conjectural variations, we are in a deep thicket and the possibilities become unlimited. Future research will examine the possibility of coalitions of countries.

### E. *The Economic and Environmental Impact of Alternative Strategies*

Using the algorithms just described, we will analyze the three different strategies as described in Table 3: market, cooperative, and noncooperative. In addition, for reference we sometimes compare the results of the RICE model to those of its parent, the DICE model, which is essentially a one-region efficient or cooperative solution.

[8] The RICE model runs on the GAMS software (see Anthony Brooke et al., 1988). The full model including searching for welfare weights takes approximately 6 hours on a 486-66 processor.

TABLE 3—ALTERNATIVE SOLUTION CONCEPTS FOR THE RICE MODEL

1. *Market RICE:* This strategy assumes that there is no correction for the climate-change externality and that there is therefore no abatement of $CO_2$ emissions.
2. *Cooperative RICE:* In this strategy, countries undertake policies that reduce greenhouse-gas emissions efficiently. The reduction of $CO_2$ emissions is efficient across countries and across time.
3. *Noncooperative RICE:* This strategic concept assumes that each country sets its $CO_2$ emissions controls to maximize its own economic welfare assuming that other countries' control strategies are invariant to a country's policies.

## II. Results

We now report the results of the policies and strategies described above. As in all modeling efforts of this kind, they should be interpreted with caution as this study is the first empirical application of noncooperative game theory to global environmental policy. On the other hand, the major results concerning the level of stringency of climate-change policies have been relatively stable over a wide variety of models and alternative specifications of the RICE model, so we have considerable confidence in these estimates (conditional, of course, on the assumptions underlying the major components, such as those concerning the long-run growth projections, the costs and damages, and the discount rate).

### A. *Output, Emissions, and Climate Change*

The projections for the major economic and environmental variables are shown as Figures 1 through 4. One important outcome of this study is that the RICE model has substantially higher projected world output and emissions by the end of the next century than do many other integrated assessments, such as the earlier DICE model.[9] Projections for regional outputs are shown in Figure 1; these indicate that the projected relative sizes of the Chinese and ROW economies grow sharply over the next century. The output growth in the RICE model is significantly larger than that in many projections prepared by international study groups, most of which envision a stability of current relative income differentials rather than the projected partial convergence in the RICE model. Note as well that we use market exchange rates because we will want to find the equilibrium in which the prices of internationally-traded carbon-emissions permits are equalized.

Emissions are also considerably higher in RICE than in the many other projections. For example, $CO_2$ emissions in the RICE model reach 38 billion tons of carbon by the year 2100 in the market or uncontrolled run. This compares with an estimated 21 billion tons in the DICE model and a range of 5 to 35 billion tons in the IPCC projections (see T. M. L. Wigley [1994] for a description). $CO_2$ emissions grow substantially faster in the RICE model partially because of the projected rapid growth in output and partially because of the rising output share of regions with high emission-output ratios.

Figure 2 shows the resulting $CO_2$ emissions under the different solution concepts and also compares estimates from this study with the earlier DICE model. Model estimates (not shown) indicate that the share of $CO_2$ emissions will rise sharply in China, region S1 (India), region S3 (middle-sized developing countries like Thailand), and region S4 (smaller developing countries). These four regions accounted for about one third of $CO_2$ emissions in 1990 but are projected in the market runs of the RICE model to comprise three quarters of emissions by 2100.

$CO_2$ concentrations are shown in Figure 3. Given the higher emissions rates in the RICE model, its concentrations rise more rapidly than in the DICE model. It is useful to examine the date of doubling of $CO_2$ concentrations relative

[9] This statement is based on a comparison of the results in the RICE model with the projections of the Intergovernmental Panel on Climate Change (IPCC) (1990), the results in Nordhaus (1994), and preliminary results of the survey of models by the Energy Modeling Forum 14 directed by John Weyant, Energy Modeling Forum (EMF) (1995).

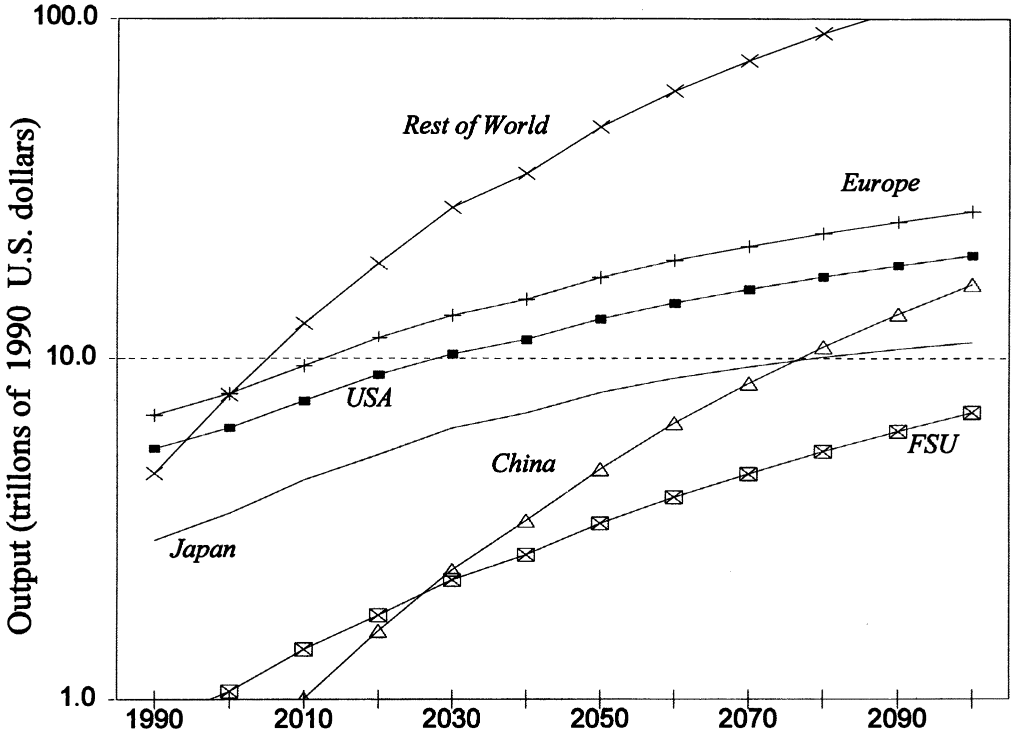


FIGURE 1. REGIONAL OUTPUTS: COOPERATIVE SCENARIO

to preindustrial concentrations; that benchmark is taken to be 1,200 billion tons of atmospheric $CO_2$ concentrations (or 565 parts per million of $CO_2$). The doubling date is 2100 in the (cooperative) DICE model, 2070 in the cooperative RICE model, and 2065 in both the market and the noncooperative model. The doubling time for the $CO_2$ equivalent of all greenhouse gases is slightly earlier than those for $CO_2$ alone.

The projected increase in global mean temperature over the 1990–2100 period is shown in Figure 4.[10] The estimated temperature increase from the mid-nineteenth century to 2100 is estimated to be 3.06°C in the market run. The cooperative strategy lowers global temperature by 0.22°C in 2100, whereas the noncooperative strategies reduce warming by considerably less (a reduction of 0.086°C in 2100), both compared to the market strategy. One reason that the difference in the temperature increase between the cooperative and the market runs is so small is because of the long time lag between changes in emissions and temperature increases (the difference between the runs grows over time as the lags in the emissions-concentrations-temperature relationship plays out).[11] Additionally, the difference is small because of the nonlinear relationship between $CO_2$ concentrations and temperature.[12] But the major rea-

[10] The climate model used in the RICE model is a calibrated version of the two-equation Schneider-Thompson model with an equilibrium temperature sensitivity coefficient of 3°C for a doubling of $CO_2$ concentrations. The derivation of the climate model is discussed in Nordhaus (1994).

[11] The projected temperature difference between the cooperative and market runs is 0.41°C in 2200 whereas that between the noncooperative and market runs is only 0.12°C in 2200.

[12] More recent estimates of global warming show considerably less near-term warming than earlier estimates (compare the current RICE with the 1992 DICE model). Recent evidence suggests that the cooling effects of sulfates derived primarily from fossil-fuel emissions will lower global mean temperature increases until the end of the next century.

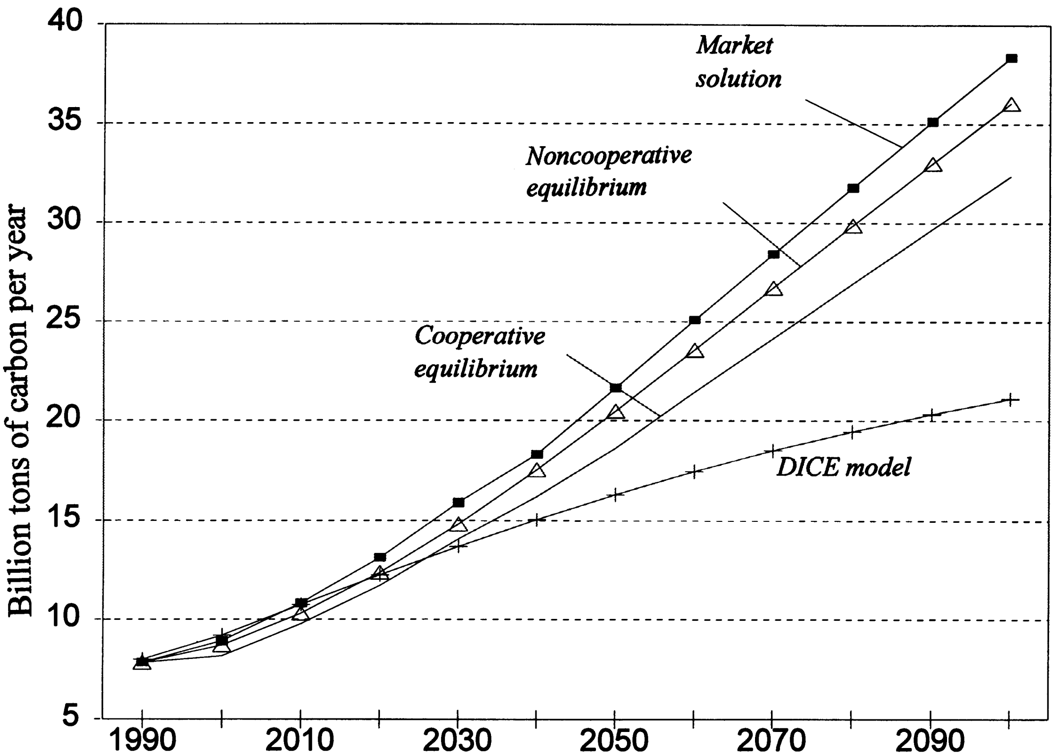


FIGURE 2. $CO_2$ EMISSIONS: DIFFERENT APPROACHES

son for the small decrease in temperature between the market and cooperative runs is that the high cost of control means that the economically efficient strategy is for only a small reduction in $CO_2$ emissions.

### B. *Policy Variables*

We next examine the policy variables for the different degrees of cooperation among nations (market, noncooperative, and cooperative). The results are shown in terms of both the control rates for $CO_2$ emissions and the carbon taxes. Carbon taxes should be interpreted as the marginal cost of control of $CO_2$ whether these are efficiently implemented through taxes, regulations, or tradable permits.

The major results are shown in Figures 5 through 9. The central finding of this study is that the noncooperative policies produce significantly lower control rates and carbon taxes than does global cooperation. The reason is straightforward: when countries free-ride on the climate-change policies of other countries, then they cut back their own efforts substantially. Begin with the emissions control rates, shown in Figure 5. The global average rate of control of $CO_2$ is around 10 percent in the cooperative solution. This varies by region, with relatively high controls in China and the former Soviet Union; for these regions, we estimate the marginal costs of control to be relatively low. For the efficient case, the lowest control rates are in Japan and the European Union, which are already relatively energy efficient and where the marginal costs of controls are consequently relatively high. According to the data used in the RICE model, the efficient control rates for 2000 range from 17 percent in China to about 7 percent in Japan. The United States is in the middle of the pack, with an efficient control rate of slightly below 9 percent. The control rates rise over time as the marginal damages from $CO_2$ emissions rise. (Note that

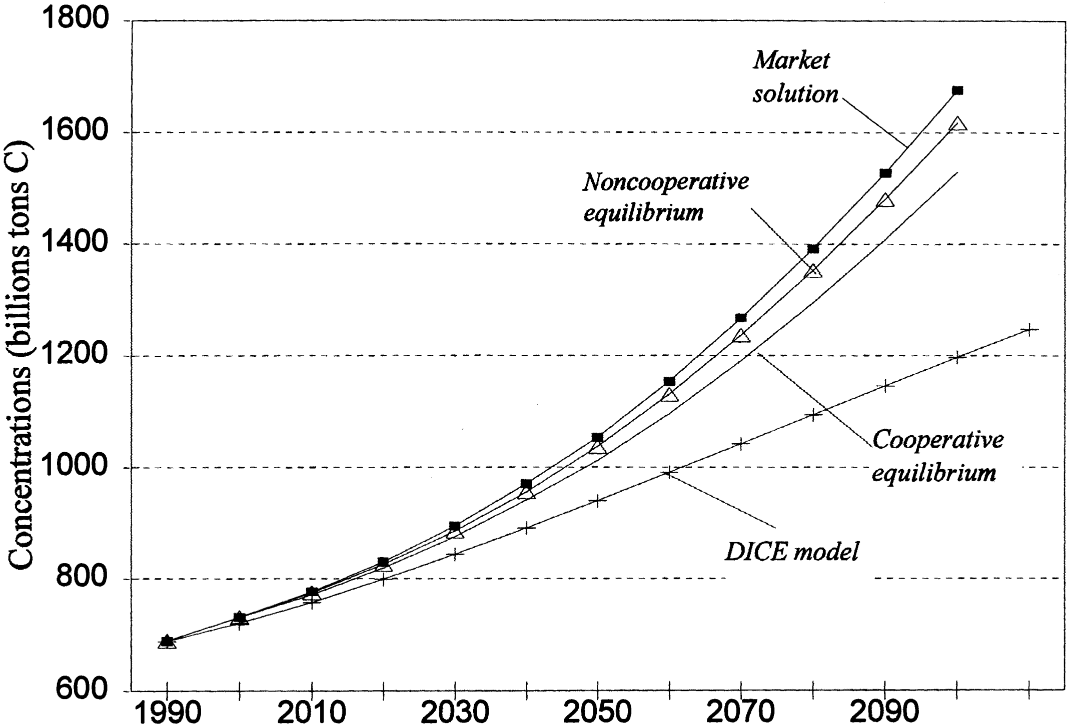


FIGURE 3. $CO_2$ CONCENTRATIONS

these relative control rates would be roughly proportional to those shown here if the overall level of controls were raised or lowered.)

One immediate conclusion that comes from this result is that current approaches to combating global warming make no sense from the point of view of pure economic efficiency. The current Framework Convention calls for major emissions reductions in the OECD region with no immediate reductions in the developing countries—this being exactly the opposite of the efficient solution. The only potential rationale for the Framework Convention is that it puts a very high weight on equity (by relieving poor countries of obligations to reduce emissions) and rules out the possibility of side payments (say through allocation of emissions permits).

The control rates in the noncooperative solution are markedly lower (not shown but available from the authors). There are two major findings here. First, the aggregate global emissions control rate for the noncooperative equilibrium is in 2000 only 2.3 percent as compared with the average of 9.7 percent in the cooperative case. The reason for the lower control rate is completely intuitive: it results from the free-riding wherein each nation ignores the impacts of its $CO_2$ emissions on the welfare of other nations (as well, of course, as assuming that other nations' efforts are unaffected by its own self-interested behavior). The size of the free-riding effect is the major new result here.

The second interesting conclusion in the noncooperative approach is the distribution of control rates. This model predicts that the largest (albeit small) efforts will be taken by the largest regions—particularly by the United States and the European Union. This prediction seems quite on the mark. It also correctly suggests that developing countries, particularly small and poor countries such as Benin and Kyrgyzstan, will not be in the forefront of global-warming politics.

Figures 6 through 7 show the results for estimated carbon taxes. Looking first at Figure 6, we can compare the aggregate carbon taxes

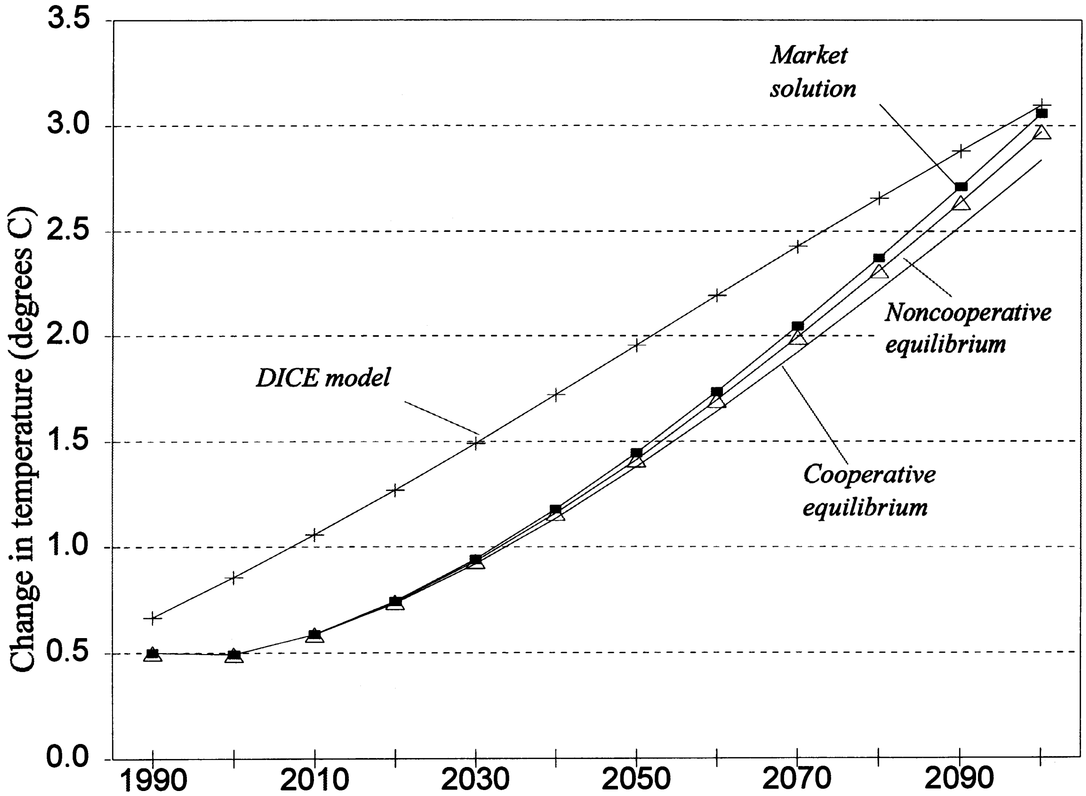


FIGURE 4. TEMPERATURE CHANGE

under different strategies. Note that the cooperative RICE model looks quite similar to the older DICE model (which also found the global optimum). The carbon tax starts slightly higher and grows more rapidly because of the steeper trajectory for emissions. The first-period carbon tax in the cooperative case is \$6.19 per ton carbon in 2000 versus \$5.94 in the DICE model. (Here and throughout, all dollar figures refer to prices in 1990 U.S. dollars at 1990 market exchange rates.)

The cooperative tax rates are significantly higher than the noncooperative or nationalistic policies for all regions and periods. The weighted average carbon tax for the noncooperative policy is 24 cents per ton carbon for the noncooperation equilibrium in 2000. The distribution of carbon taxes for the noncooperative policy is shown in Figure 7. For the noncooperative strategies, large countries tend to have significantly more (but not very) stringent controls as compared to small countries. The noncooperative carbon taxes are highest in the European Union (\$0.86 per ton in 2000) and the United States (\$0.65 per ton in 2000). The difference reflects the slightly larger output in the European Union. For smaller countries, the tax rates are much smaller: 10 cents per ton in India, and only 1 cent per ton in the S4 group of countries.

It seems appropriate to conclude that *outside the United States, Europe, and Japan, the rational noncooperative strategy would be simply to ignore global warming at the present time*. Even by the end of the 21st century, no country acting in a noncooperative framework would have carbon taxes above \$2 per ton C. If we define the "cooperation ratio" as the ratio of the noncooperative carbon tax to the cooperative carbon tax, we can calculate that

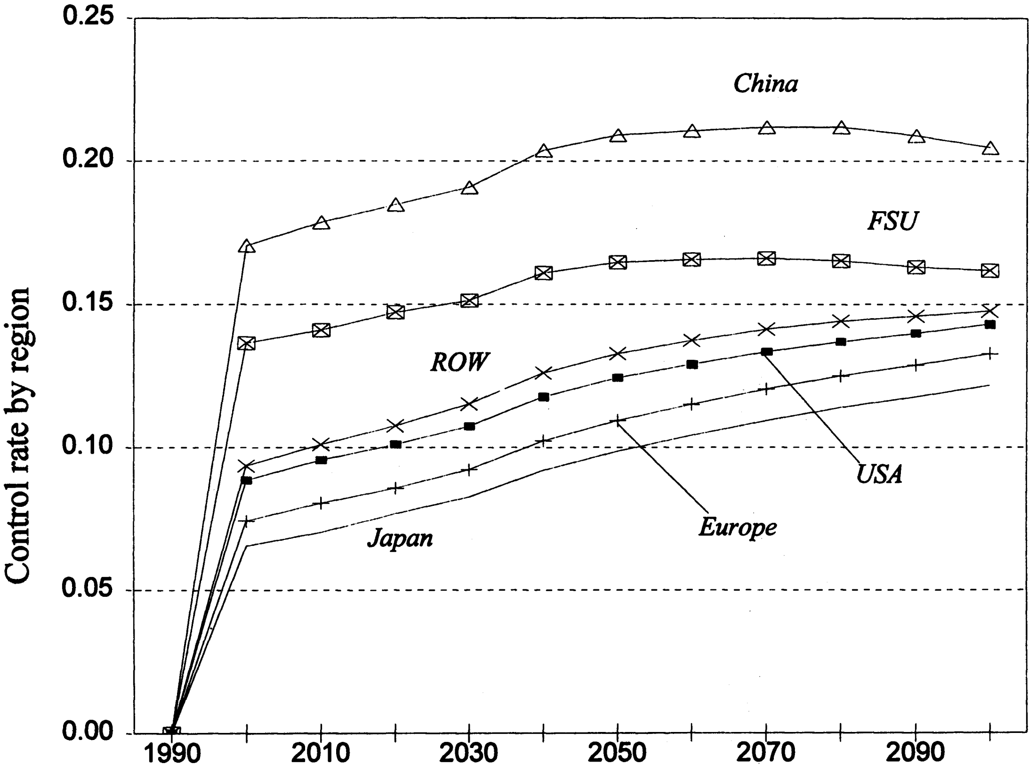


FIGURE 5. $CO_2$ CONTROL RATES: COOPERATIVE SCENARIO

this ratio ranges from essentially zero in the smallest countries to between 10 and 15 percent for the United States and Europe.

What happens to the cooperation ratio over time? According to our calculations, the degree of cooperation is expected to fall in the noncooperative solution. Cooperation in the Nash equilibrium decreases as the extent of inequality of country income falls. Hence, the extent of cooperation is calculated to decline slightly over the next four decades as the share of the United States, Japan, and Europe declines and the distribution of economic sizes of nations becomes more equal. *Greater equality leads to smaller incentives to be a good global citizen.*

For small countries (with GDPs of under \$20 billion) the noncooperative optimal control rates and carbon taxes are minuscule, \$0.01 per ton carbon versus \$5.98 in the global cooperative case. While the taxes in the noncooperative strategies are significantly lower than those in the global cooperative strategies, some have expressed surprise that they are not even lower. The reason is that there are a few countries or regions (notably the United States, China, Japan, and Europe) which are large enough so that it is their own self interest to reduce $CO_2$ emissions even ignoring the benefits to other countries. Were China to break up, were Europe to make decisions on a national level, or were the Republican Revolution in the United States to devolve environmental decisions to the states, the predicted degree of cooperation would be even lower.

There are a few other intriguing details of the runs worth noting. China is definitely a key player and exhibits a different pattern. Figure 5 shows that China has the highest cooperative control rates of all the regions—this reflecting the relatively high $CO_2$ emissions per unit output (see Table 2). But countries which are hardly players today (India, China, and the

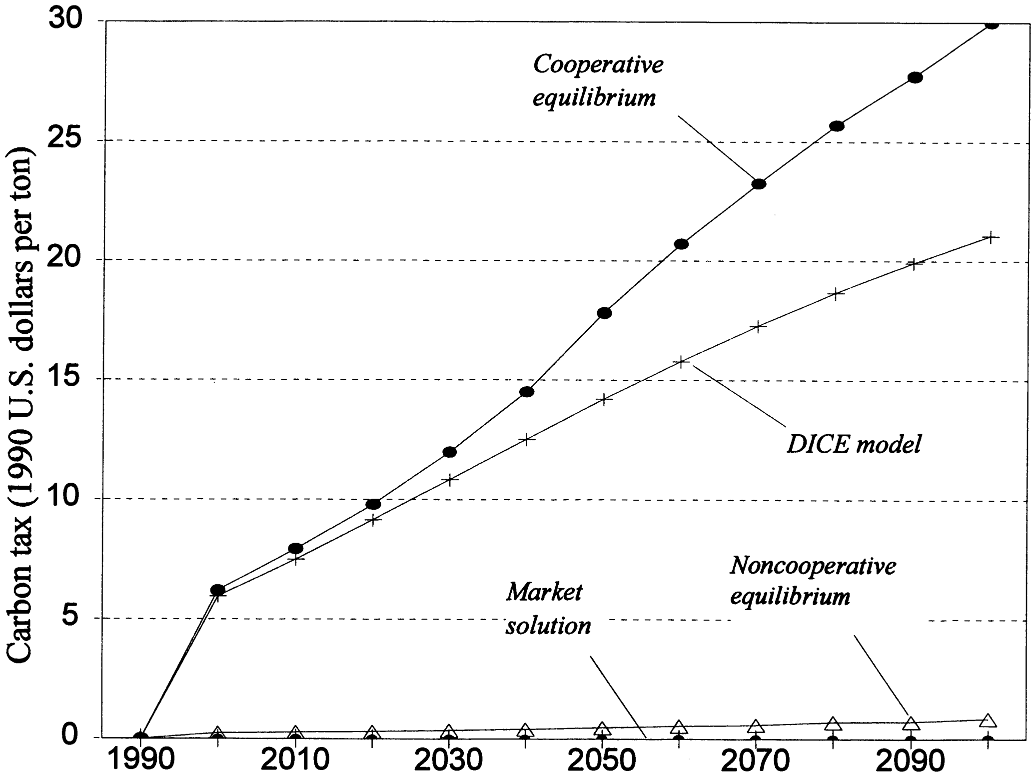


FIGURE 6. AVERAGE CARBON TAXES

smaller developing countries) dominate $CO_2$ emissions by the middle of the next century and will have to behave cooperatively if the gains from cooperation are to be realized.

### C. *Welfare Effects by Region*

What are the overall economic effects by region? The gain to cooperation is calculated as the present value of the change in consumption valued using the region-specific discount rates on consumption (not to be confused with the pure rates of social time preference, or discount rates on utility, which are equal across regions). The discount rates in this calculation are region and time specific, and they average about $4^1/_2$ percent per year (in real terms) over the next century. In these runs, there are no international transfers, which essentially means that each country is assigned its optimal policy without any side payments from other countries. This is equivalent to each country receiving in the cooperative equilibrium a quota of tradable emissions permits equal to the quantity of its own emissions.

The resulting impacts upon economic welfare are shown in Table 4. Note first that the overall results from the cooperative RICE solution are quite close to those of the original DICE model. The former is about one quarter higher because of the higher growth rates in the RICE model. By contrast, the noncooperative, six-region RICE model shows extremely slim net benefits–only \$43 billion in discounted benefits as opposed to \$344 billion for the cooperative RICE or \$271 for the cooperative DICE model.

Figure 8 shows the gains to different regions for the cooperative and noncooperative cases.

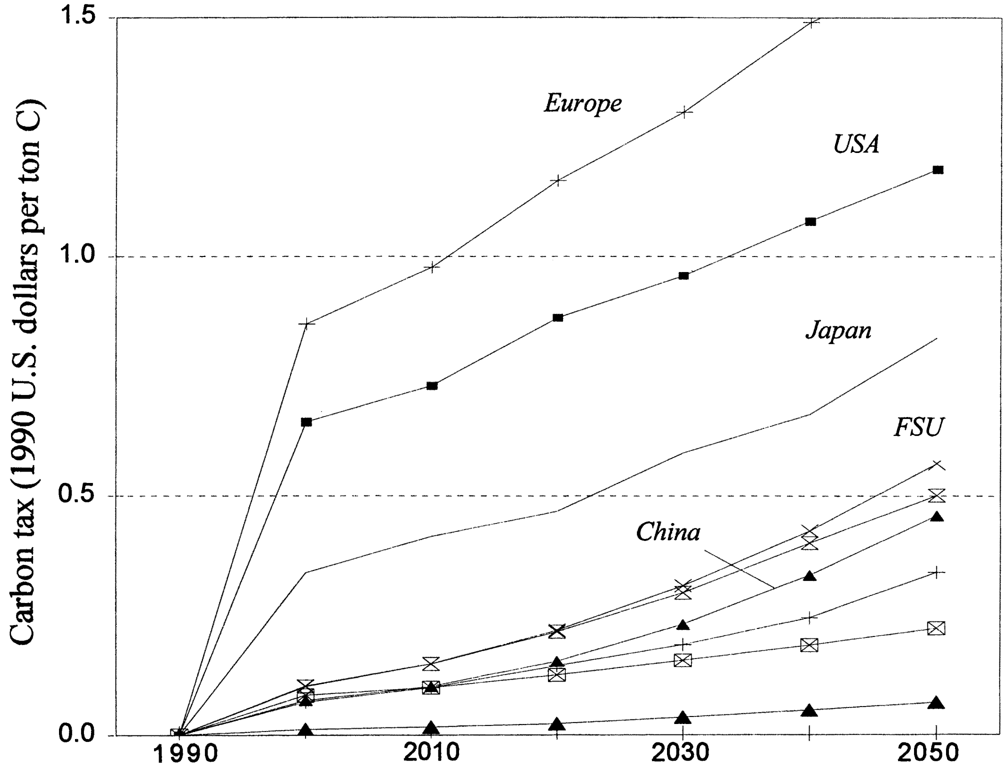


FIGURE 7. NONCOOPERATIVE CARBON TAXES

Table 4 and Figure 8 present a number of surprises in the regional results. The noncooperative solution produces positive net benefits relative to the market solution for all regions. This result is expected because the noncooperative policies improve welfare while the external interactions among countries are ones that are beneficial relative to the market case. The net benefits in the noncooperative case are relatively uniform across the different regions, with most of the positive effects coming from the reductions in damage from climate change.

The major surprise in these results is the lopsided benefits from the cooperative strategy. *The United States actually loses in the cooperative solution relative to the noncooperative equilibrium*. The reason is that, with its relatively large emissions, the United States would be slated to incur major costs today, while its benefits would be relatively small given its declining share of the world economy. Similarly, the former Soviet Union has quite modest net benefits in the cooperative strategy because it is required to undertake significant mitigation efforts and has few benefits because of its northerly location. By contrast, the ROW region reaps major net benefits from the cooperative solution because the mitigation efforts are undertaken primarily in the high-income countries early in time while the major benefits in terms of damages avoided accrue to the developing countries in several decades.

These results indicate that the cooperative solution—one in which nations are allocated emissions equals to their efficient emissions—might well not emerge as the outcome of a bargaining process in which nations will only sign on to an agreement that improves their economic welfare. Of course, the pattern of net gains can in principle be altered through different schemes for allocating emissions rights to countries (that is, by adding side payments to the program analyzed here); the gains and losses could be made much more equal over

TABLE 4—NET BENEFITS OF DIFFERENT STRATEGIES BY REGION RELATIVE TO THE MARKET EQUILIBRIUM (BILLIONS OF 1990 U.S. DOLLARS, DISCOUNTED TO 1990)

| | Net benefits by region | | | | | | |
|---|---|---|---|---|---|---|---|
| Strategy | United States | Japan | China | European Union | Former Soviet Union | Rest of world | Total |
| Market | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Noncooperative | 2.9 | 3.6 | 8.7 | 7.9 | 2.7 | 16.5 | 42.5 |
| Cooperative | 0.8 | 46.3 | 39.4 | 28.5 | 4.1 | 224.8 | 343.8 |
| DICE (cooperative)[a] | na | na | na | na | na | na | 271.0 |

*Note:* Each entry indicates the net benefits for a region relative to the market or uncontrolled strategy. NA is not available.
[a] From the aggregate DICE model in Nordhaus (1994).

space and time through different allocations or side payments. Determining possible bargaining outcomes is, however, a difficult empirical issue that is outside the scope of the present paper and is the subject of current research by the authors. What this study examines is the set of national emissions that is consistent with an efficient allocations of emissions over space and time. The interesting new result of this paper is that a scheme with no side payments will reduce the standards of living of all major regions for at least half a century and will reduce the discounted net welfare of the United States when all time periods are considered. Moreover, it is interesting to note that all the emission-rights allocations proposals that are currently under consideration are even more unfavorable to the United States than the one underlying the cooperative equilibrium and are therefore even less likely to be acceptable to high-income countries than the program examined here.

What is the time profile of benefits? Figure 9 shows the time paths of *discounted cumulative consumption* in different regions. More precisely, the numbers are the sum of the consumption differences between the cooperative strategy and the market strategy from the beginning of the period (1990) until the date shown on the horizontal axis. For each region, the consumption figures are discounted back to 1990 and the discount rate is the region-specific and variable discount rate on consumption.

This figure shows the problem of global warming in a nutshell., It indicates how each region would experience the economic impacts of a cooperative strategy relative to the market solution through different time periods. For example, it shows that the United States would have a cumulative discounted consumption loss from cooperation relative to the market of $12 billion through 2050. *The calculation indicates that a cooperative global-warming accord would reduce the cumulative discounted consumption of all countries except Japan through 2050*. The ROW region suffers major losses, approaching a total of $100 billion by mid-century. Moreover, as can be seen by adding the numbers for the different regions together, there is still a negative effect on cumulative global consumption by the middle of the next century.

On a longer time scale (not shown), the ROW breaks even by the end of the next century and is the major beneficiary after that point. The United States and the former Soviet Union experience a reduction in discounted cumulative consumption through the end of the next century. All the curves are heading up at the end of the period, and the discounted cumulative totals over the 250-year estimation period, shown in Table 4, are positive for all regions and quite large for the ROW region.

The estimates of the regional costs and benefits in the RICE model are sensitive to parameters of the mitigation-cost and climate-damage functions, but the major determinant of the patterns is initial emissions and growth of output, which are considerably more secure than the cost and damage estimates. The basic dilemma is clear: the long period between emissions reductions and reduced climate damage means that countries must be extraordinarily farsighted. In addition, the pattern of

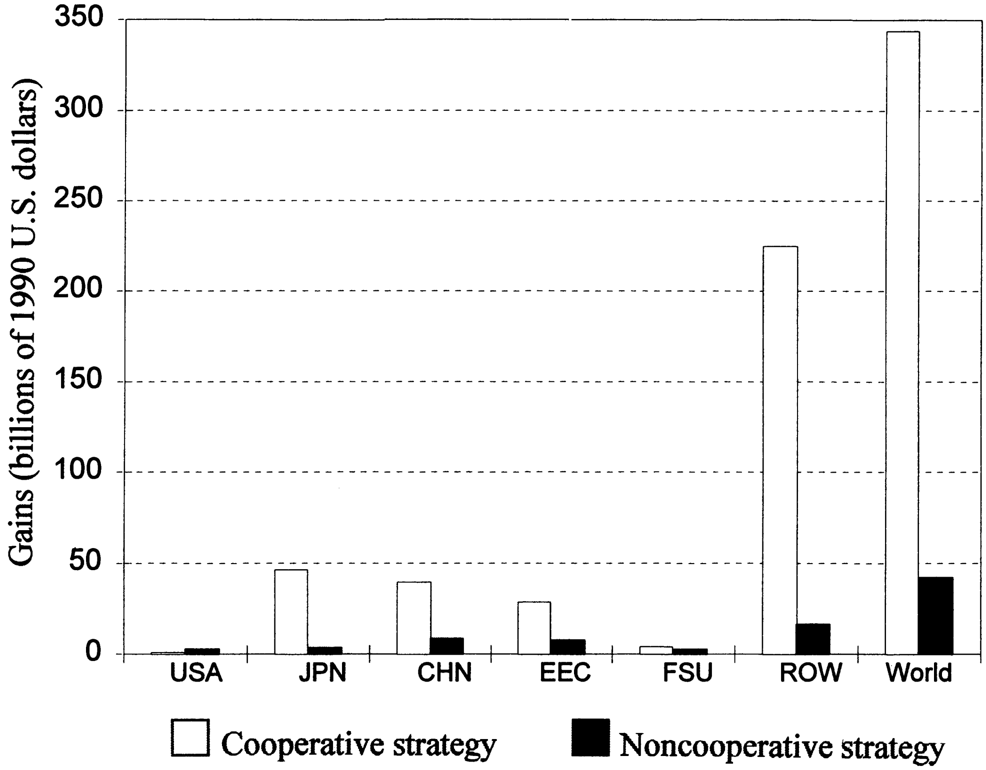


FIGURE 8. GAINS FROM CLIMATE-CHANGE POLICY: COOPERATIVE AND NONCOOPERATIVE POLICIES (TOTAL GAINS DISCOUNTED TO 1990)

gains and losses, with the major long-run gains coming to developing countries while the net benefits to the United States and the former Soviet Union are minimal, is a most surprising and troubling finding.

### D. *Sensitivity Analysis*

To understand the full range of outcomes and policy responses to the threat of global warming, we must assess the fact that many of the underlying processes are imperfectly understood. Social scientists have developed a variety of tools to incorporate uncertainty into quantitative modeling, and these can help put bounds on potential future outcomes.[13] Although uncertainties are often critical to determining policies, formal techniques for determining the uncertainty of future trajectories or of impacts have been rarely applied to major policy issues.[14]

A full-scale analysis of the uncertainties associated with the RICE model—including uncertainty about model structure as well as about individual parameters—is beyond the scope of the current article. Many of the central uncertainties have been examined in the context of the DICE model (see Nordhaus,

[13] See M. Granger Morgan and Max Henrion (1990) for a recent survey of tools for the analysis of uncertainty in quantitative risk and policy analysis.

[14] One notable and controversial example of the systematic application of statistical techniques is the Rasmussen report (Nuclear Regulatory Commission, 1975), which estimated the risk of accidents of different levels of severity in commercial nuclear power plants. An exemplary study used probabilistic assessments for ozone depletion (National Academy of Sciences, 1979).

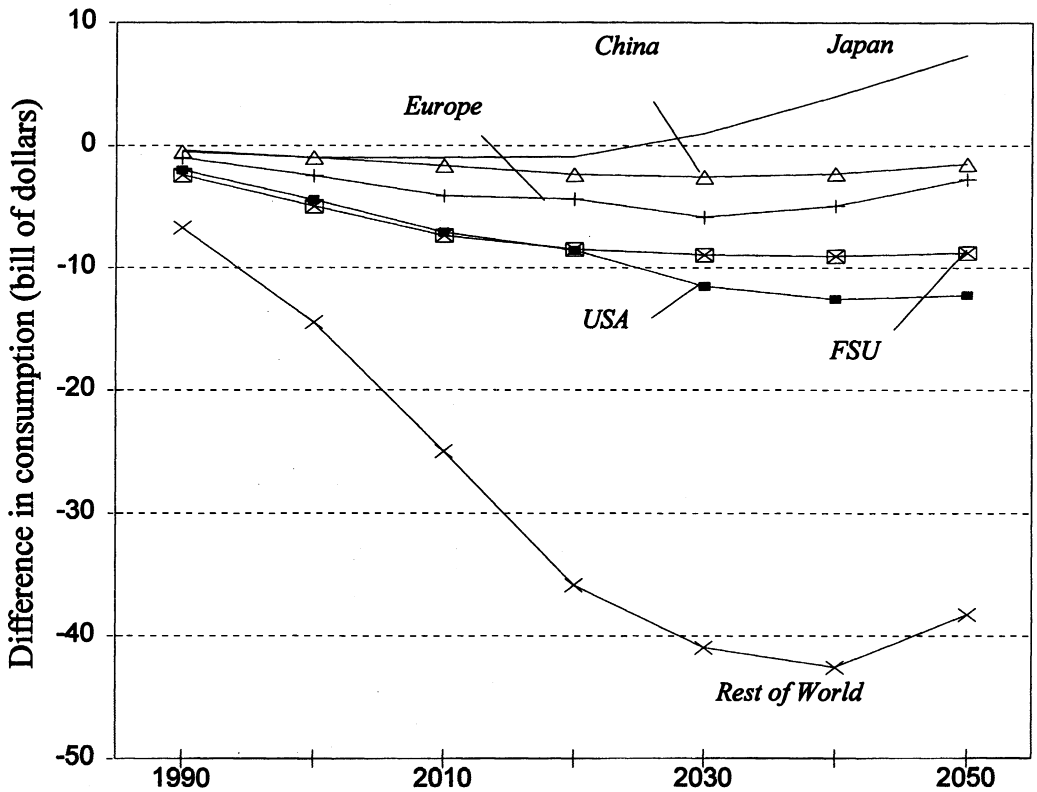


FIGURE 9. CUMULATIVE DISCOUNTED CONSUMPTION: COOPERATIVE VERSUS MARKET STRATEGY (TOTAL GAINS FOR CONSUMPTION THROUGH THE GIVEN DATE, DISCOUNTED BACK TO 1990)

1994 Chapters 6–8), and those results apply equally well to the RICE model. To understand the extent of sensitivity of the model we present here a limited sensitivity analysis with respect to the important parameters of the model. For each of the important parameters of the model (see the description in Appendix A), we have varied the parameter by changing it from the subjective 50th percentile to the subjective 90th percentile.[15] The exact derivation of the uncertainty range was developed in Nordhaus (1994 Table 6.1), and the reader is referred to that reference for a full discussion.

Figure 10 shows the results of the sensitivity analysis. That figure shows the sensitivity of three important variables in the cooperative equilibrium: the carbon tax in 2000, the efficient reduction of $CO_2$ emissions in 2000, and the change in global mean temperature in

[15] Symbolically, we can represent the RICE model as a mapping, $\mathbf{Y}_t = \mathbf{F}(\mathbf{X}_{t-\tau}; \Gamma)$, where $\mathbf{Y}_t$ is the vector of endogenous and policy variables, $\mathbf{X}_{t-\tau}$ is a vector of current and lagged exogenous variables, and $\Gamma$ is the set of uncertain parameters. The base run estimates outcomes for the "best-guess" parameters ($\Gamma^{50}$, which represents the 50th percentile of the distribution of the parameters). In the sensitivity analyses, we estimate the (subjective) 90th percentile of the distribution, $\Gamma^{90}$. Figure 10 shows the ratio of different outcomes for the 90th percentile of a variables to the 50th percentile of that variable; that is, $\Delta_i = \mathbf{F}(\mathbf{X}_{t-\tau}; \Gamma_i^{90})/\mathbf{F}(\mathbf{X}_{t-\tau}; \Gamma^{50})$, where $\Delta_i$ is the ratio of outcomes for variables of interest when varying the $i$th parameter, $\Gamma^{50}$ is the vector of $\Gamma$ with all variables set at their 50th percentile while $\Gamma_i^{90}$ is the vector of parameters with all variables but the $i$th set at the 50th percentile while the $i$th parameter is set at its 90th percentile.

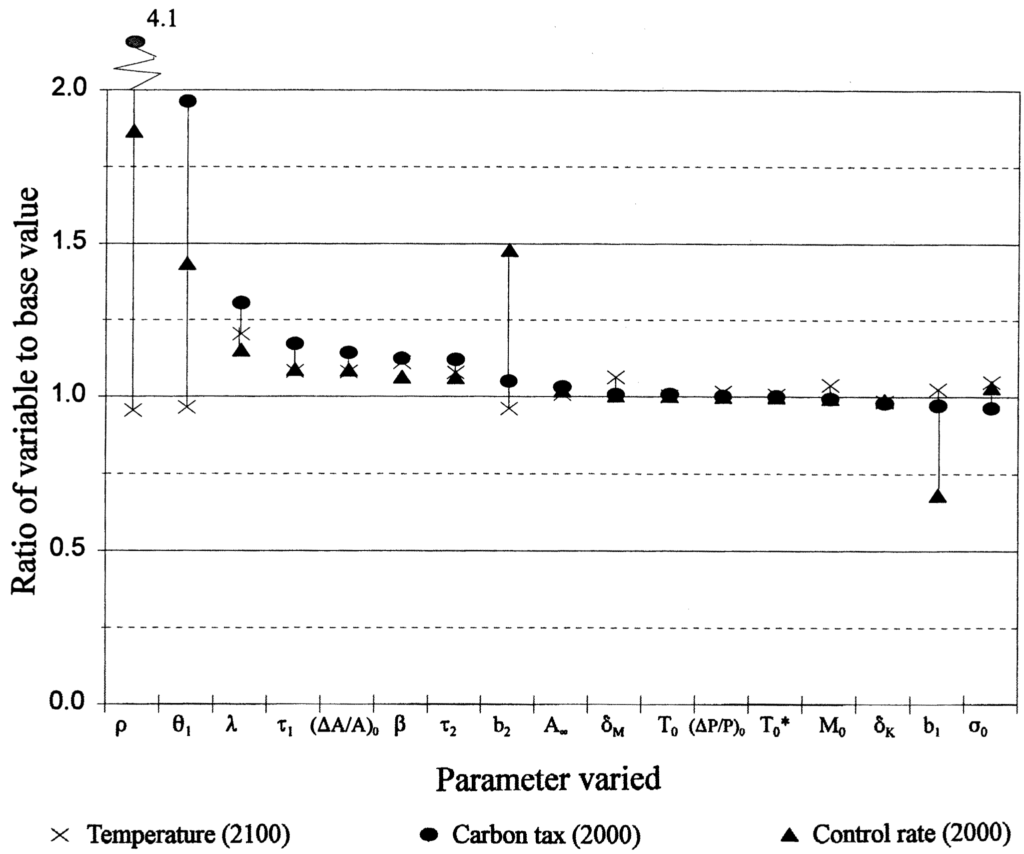


FIGURE 10. SENSITIVITY TESTS FOR PARAMETERS

*Note*: The variables on the horizontal axis are parameters of the RICE model as defined in Appendix A. The markers indicate the ratio of the outcome variable in the sensitivity case to the outcome for the base case. The sensitivity cases set the values of the variables at the subjective 90th percentile. The outcome variables are the optimal cooperative carbon tax in 2000, the optimal cooperative reduction rate for $CO_2$ emissions in 2000, and global mean temperature in 2100.

2100. For each of the three variables, we have displayed in Figure 10 the ratio of the value of the variable in the sensitivity run to the value of the variable in the base case.

Figure 10 indicates that the results are extremely sensitive to the pure rate of social time preference. The low rate of time preference (equal to 1 rather than 3 percent per year) increases the carbon tax by a factor of 4 and the control rate by a factor of almost 2. In addition, the damage intercept (which is the fraction of output lost from a doubling of atmospheric $CO_2$) leads to a marked increase in both the carbon tax and the control rate. The other variables are relatively unimportant for the results.[16]

In analyzing model sensitivity, it is easy to become lost in the details. For policy purposes, however, the single most critical question is how an uncertainty affects *current policy*, which is best seen in the effect on the carbon tax. By this standard, the two crucial parameters are the discount rate (which indicates the

[16] These results parallel closely the findings of other studies on the sensitivity of policy to uncertainties about major variables.

relative importance of the future compared to the present) and the damages from climate change (which measure the willingness to pay to prevent or slow climate change). *It is interesting to note that both major uncertainties involve human preferences rather than pure questions of "fact" about the natural sciences.*

## III. Conclusions

To summarize, this paper has presented the RICE model, which is a new dynamic, multiregion, general-equilibrium model of climate and the economy. It differs from earlier work, which focussed on a globally aggregated approach, by introducing production, consumption, emissions, and damages for different regions. This approach compares three different strategies for the control of global warming: a market approach in which no climate change policies are taken, a global cooperative approach in which all countries choose climate-change policies to maximize global incomes, and a noncooperative or nationalistic approach in which each country takes policies to maximize its own national income. These results are tentative and subject to revision. Further work will be necessary to test their robustness against alternative assumptions, to appraise the results for different coalitions, and to compare the results against other models. Subject to these reservations, the following are the major conclusions.

First, the model produces results for the baseline (market or uncontrolled) which differ significantly from other projections.[17] Output and emissions in the RICE model are estimated to grow much more rapidly than in the DICE model or than in many international projections (such as that of the Intergovernmental Panel on Climate Change). The more rapid growth comes largely from a view of the growth process in which there is considerable but incomplete convergence of per capita incomes of countries. The higher projected growth of output, emissions, and $CO_2$ concentrations as compared with the earlier DICE model is largely offset by revisions in estimated effects of other greenhouse gases. As a result the estimated extent of global warming in the market case by the year 2100—approximately 3°C—differs little between the RICE model and other estimates.

Second, the efficient or cooperative policies in the regional model confirm estimates made in globally aggregated models, such as the DICE model. The best summary variable for efficient controls is the carbon tax, which is calculated to be about $6 per ton carbon in 2000, a number that is virtually identical to estimates for the efficient policy in the DICE model.[18] The estimated degree of control in the RICE model is, however, estimated to grow somewhat more rapidly than in the DICE and other models, with estimated efficient carbon taxes at the end of the next century near $27 per ton carbon.

Third, the RICE model provides estimates of the efficient control rates in different regions as well. In the efficient solution, carbon taxes are identical in all regions. The control rates will differ, however, because of different costs of reducing $CO_2$ emissions. The estimates presented here indicate that the efficient emissions control rates will be highest in China and the former Soviet Union and lowest in Japan and Europe, with the differences being at least a factor of two. These results indicate that there will be substantial inefficiencies in any policy (such as that currently in force under the Framework Convention) that equalizes emissions control rates across countries or does not allow trading of emissions permits.

Fourth, a major contribution of this study is to estimate the difference between the efficient policy and the noncooperative policy. The noncooperative or nationalistic policy is one in which countries maximize their economic welfare taking policies of other countries as given. This implies that small countries, whose climate-change policies have little effect on their own economic

[17] In the discussion that follows, the results for the DICE model refer to DICE-123 as presented in Nordhaus (1994).

[18] All dollar figures refer to prices in 1990 U.S. dollars at 1990 market exchange rates.

welfare, will have little incentive to reduce emissions while the largest countries will have greatly attenuated incentives to engage in costly reductions in $CO_2$ emissions. The calculations here indicate that the controls in the noncooperative case (as measured by the average rate of carbon tax) will be only $^1/_{25}$ of the level of the cooperative case. That is, while the average carbon tax in 2000 is estimated to be about \$6 per ton carbon in the cooperative case, it is calculated to be about \$0.24 per ton in the noncooperative case. Moreover, the divergence between the cooperative and the noncooperative policies is calculated to increase over time as the inequality of county sizes decreases, and this divergence would increase further if large countries like China, India, Russia, Canada or the United States splinter into smaller countries or decision-making units.

Fifth, these results indicate that the stakes in controlling global warming are modest in the context of overall economic activity over the next century. If our estimates are accurate, they indicate that the losses from global warming will be in the range of 1 to 2 percent of global income over the next century. The net costs (that is, climate-change damages less mitigation costs) can be reduced by perhaps $^1/_3$ percent of income by a judicious choice of climate-change policies—although, to be sure, the impact is much greater on our descendants than on ourselves. According to RICE, successful cooperation would lead to net gains, but the failure to cooperate is unlikely to lead to economic disaster over the next century.

Sixth, the pattern of gains and losses from different strategies is quite surprising. All countries gain from the noncooperative approach, although the amount of gain is relatively small. The net gains from cooperation without international transfers are quite unevenly distributed, with the major gains accruing to developing countries with low and rapidly growing emissions. High-income countries have but modest gains to cooperation, but the United States actually loses from cooperating relative to a noncooperative strategy. In addition, the time path of gains and losses indicates that even in the cooperative scenario, all regions except Japan show reductions in cumulative discounted consumption until after the middle of the next century.

Seventh, the results indicate that there are major gains to taking an efficient cooperative approach to coping with global warming as opposed to the noncooperative approach. We estimate that the net economic gain from an efficient policy has a discounted value of \$344 billion relative to the market scenario, while the noncooperative policy has a gain of only \$43 billion. Hence, there are clear gains to attaining a cooperative policy (assuming, of course, that the policy is itself efficient). The gains from cooperation would be even larger if climate change proved to have catastrophic consequences that are very unevenly felt across nations.

In sum, the results of this new integrated model of climate and the economy emphasizes the implications of the fact that while climate change is a global externality, the decision makers are national and relatively small. These inherent difficulties involved in planning over a horizon of a century or more about so uncertain and complex a phenomenon are compounded by the dispersed nature of the decisions and the strong tendency for free-riding by nonparticipants in any global agreement. Countries may therefore be triply persuaded not to undertake costly efforts today—first because the benefits are so conjectural, secondly because they occur so far in the future, and third because no individual country can have a significant impact upon the pace of global warming. The present study indicates that the third of these, the dispersed nature of the decision making and the consequent diluted incentives to act, is a powerful hindrance to setting efficient climate-change policies.

## Appendix A: Equations of the RICE Model

This appendix gives the details of the RICE model. We first list and define the variables and then provide the complete equation listing.

### 1. *Variables*

The variables are as follows. In the listing, $t$ always refers to time ($t$ = 1990, 2000, ...) while $i$ refers to the region ($i$ = 1, ... , $n$ = USA, Japan, Europe, ...). The regional definition is given in Appendix B.

*Exogenous Variables.*

$A_i(t)$ = level of technology
$P_i(t)$ = population at time $t$, also proportional to labor inputs
$O(t)$ = forcings of exogenous greenhouse gases

*Parameters.*

$\alpha$ = elasticity of marginal utility of consumption
$b_{1,i}, b_2$ = parameters of emissions-reduction cost function
$\beta$ = marginal atmospheric retention ratio of $CO_2$ emissions
$\gamma$ = elasticity of output with respect to capital
$\delta_K$ = rate of depreciation of the capital stock
$\delta_M$ = rate of transfer of $CO_2$ from atmosphere to other reservoirs
$\lambda$ = feedback parameter in climate model (inverse to temperature-sensitivity coefficient)
$\rho$ = pure rate of social time preference
$\sigma_i(t)$ = $CO_2$ emissions/output ratio
$\tau_1, \tau_2, \tau_3, \tau_4$ = parameters of climate equation ($\tau_1$ is a function of the heat capacity of the atmosphere and upper ocean while $\tau_2$ depends upon the turnover time between the upper ocean and the deep ocean)
$\theta_{1,i}, \theta_2$ = parameters of climate damage function

*Endogenous Variables.*

$C_i(t)$ = total consumption
$c_i(t)$ = per capita consumption
$\mathrm{CA}_i(t)$ = current account balance
$D_i(t)$ = damage from greenhouse warming
$E_i(t)$ = $CO_2$ emissions
$\mathrm{EX}_{i,j}(t)$ = exports from region $i$ to region $j$
$F(t)$ = radiative forcing from all greenhouse gas concentrations
$\Omega_i(t)$ = output scaling factor due to emissions controls and to damages from climate change
$K_i(t)$ = capital stock
$\mathrm{IM}_{i,j}(t)$ = imports from region $i$ to region $j$
$M(t)$ = increase in mass of $CO_2$ in atmosphere from preindustrial level
$\mathrm{NFA}_i(t)$ = net foreign assets of country $i$
$\phi_i$ = welfare weight on country $i$
$Q_i(t)$ = gross domestic or regional product
$R(t)$ = net rate of return on capital
$T(t)$ = atmospheric temperature relative to preindustrial level
$T^*(t)$ = deep ocean temperature relative to preindustrial level
$u_i(t) = u_i[c_i(t)]$ = utility of per capita consumption
$W$ = social welfare function determined by country consumption levels
$Y_i(t)$ = gross national or regional product (net of climate damage and mitigation costs)

*Policy Variables.*

$I_i(t)$ = gross investment
$\mu_i(t)$ = rate of emissions reduction

2. *Equations*

$$\text{(A1)} \quad \max_{c_i(t)} W = \sum_{t=0}^{T} \sum_{i=1}^{n} \frac{\phi_i U^i[c_i(t), P_i(t)]}{(1+\rho)^t} = \sum_{t=0}^{\infty} \sum_{i=1}^{n} \frac{\phi_i P_i(t)[c_i(t)^{1-\alpha} - 1]}{(1-\alpha)(1+\rho)^t}$$

subject to

$$\text{(A2)} \quad Q_i(t) = A_i(t) K_i(t)^{\gamma} P_i(t)^{1-\gamma}$$

$$\text{(A3)} \quad Y_i(t) = \Omega_i(t) Q_i(t)$$

$$\text{(A4)} \quad C_i(t) = Y_i(t) - I_i(t) + \sum_{j \neq i}^{n} \mathrm{IM}_{i,j}(t) - \sum_{j \neq i}^{n} \mathrm{EX}_{i,j}(t)$$

$$\text{(A5)} \quad c_i(t) = \frac{C_i(t)}{P_i(t)}$$

$$\text{(A6)} \quad K_i(t) = (1-\delta_K) K_i(t-1) + I_i(t)$$

$$\text{(A7)} \quad E_i(t) = [1 - \mu_i(t)] \sigma_i(t) Q_i(t), \quad 0 \le \mu_i(t) \le 1.$$

$$\text{(A8)} \quad M(t) = \beta \sum_{i=1}^{n} E_i(t) + (1-\delta_M) M(t-1)$$

$$\text{(A9)} \quad T(t) = T(t-1) + \frac{\tau_1[F(t) - \lambda T(t-1)] - \tau_2[T(t-1) - T^*(t-1)]}{\tau_3}$$

$$\text{(A10)} \quad T^*(t) = T^*(t-1) + \frac{T(t-1) - T^*(t-1)}{\tau_4}$$

$$\text{(A11)} \quad F(t) = \frac{4.1 \log[M(t)/M(0)]}{\log(2)} + O(t)$$

$$\text{(A12)} \quad \Omega_i(t) = \frac{1 - b_{1,i}\mu_i(t)^{b_2}}{1 + \theta_{1,i} T(t)^{\theta_2}}, \qquad i = 1, 2, \dots, n.$$

$$\text{(A13)} \quad R(t) = \frac{\sum_{i=1}^{n} \gamma Q_i(t)}{\sum_{i=1}^{n} K_i(t)} - \delta_K$$

$$\text{(A14)} \quad \mathrm{NFA}_i(t) = \mathrm{NFA}_i(t-1) + \mathrm{CA}_i(t-1)$$

$$\text{(A15)} \quad \mathrm{CA}_i(t) = R(t)\mathrm{NFA}_i(t) + \sum_{j \neq i}^{n} \mathrm{IM}_{i,j}(t) - \sum_{j \neq i}^{n} \mathrm{EX}_{i,j}(t)$$

$$\text{(A16)} \quad -\mathrm{CA}_i(t) \le 0.1 Q_i(t)$$

$$\text{(A17)} \quad -\mathrm{NFA}_i(t) \le 0.1 Q_i(t)$$

$$\text{(A18)} \quad \sum_{j \neq i}^{n} \mathrm{EX}_{i,j}(t) \le Q_i(t).$$

APPENDIX B: REGIONAL GROUPING IN THE RICE MODEL

| Country or group | Number of countries | Gross domestic product (millions of 1990 US $) | Population, 1990 (thousands) | $CO_2$ emissions, 1990 (millions of tons C) |
|---|---|---|---|---|
| 1) United States | 1 | 5,464,796 | 250,372 | 1,370.0 |
| 2) Japan | 1 | 2,932,055 | 123,537 | 291.5 |
| 3) Former Soviet Union | 1 | 855,207 | 289,324 | 1,065.7 |
| 4) China | 1 | 370,024 | 1,133,683 | 805.5 |
| 5) Europe | 1 | 6,828,042 | 366,497 | 872.3 |
| 6) Huge | 1 | 295,760 | 849,515 | 215.4 |
| 7) Large | 2 | 586,072 | 327,274 | 593.0 |
| 8) Midsized | 11 | 2,155,910 | 442,370 | 789.7 |
| 9) Small | 38 | 1,272,414 | 876,027 | 1,212.0 |
| 10) Tiny | 137 | 318,464 | 607,503 | 623.9 |
| Total | | 21,078,746 | 5,266,102 | 7,839.1 |
| Bottom 5 groups (ROW) | | 4,628,621 | 3,102,689 | 3,434.0 |

Selected countries in groups 6 through 10:

| Code | Country | Gross domestic product (millions of 1990 US $) | Population, 1990 (thousands) | $CO_2$ emissions, 1990 (millions of tons C) |
|---|---|---|---|---|
| S1 | India | 295,760 | 849,515 | 215.4 |
| S2 | Brazil | 479,214 | 149,042 | 317.1 |
| | Indonesia | 106,859 | 178,232 | 275.9 |
| S3 | Canada | 566,694 | 26,522 | 127.6 |
| | Australia | 296,053 | 17,045 | 72.1 |
| | Mexico | 244,046 | 81,724 | 144.1 |
| | Argentina | 141,353 | 32,322 | 33.1 |
| | Turkey | 108,447 | 56,098 | 35.3 |
| | South Africa | 101,963 | 37,959 | 78.0 |
| S4 | Venezuela | 48,599 | 19,325 | 43.0 |
| | Romania | 37,625 | 23,200 | 59.4 |
| | Nigeria | 35,460 | 96,203 | 95.9 |
| | Egypt | 35,400 | 52,426 | 22.3 |
| | Slovenia | 17,331 | 2,000 | 4.8 |
| S5 | Kenya | 8,675 | 24,160 | 5.0 |
| | Iceland | 6,024 | 255 | 0.5 |
| | Honduras | 2,944 | 5,105 | 12.0 |
| | Maldives | 174 | 214 | 0.0[a] |
| | Anguilla | 23 | 7 | 0.0[a] |
| | Tuvalu | 5 | 9 | 0.0[a] |

[a] Less than 50,000 tons per year.

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