Roll the DICE Again:
The Economics of Global Warming

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with the assistance of Joseph Boyer

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Dealing with complex scientific and economic issues has increasingly involved developing scientific and economic models that help analysts and decision makers understand likely future outcomes as well as the implications of alternative policies. The present study presents the details of an integrated-assessment model of the economics of climate change. The model, called *RICE-98* for the *R*egional *D*ynamic *I*ntegrated model of *C*limate and the *E*conomy, builds upon earlier work by the author and collaborators, particularly the DICE and RICE models constructed in the early 1990s.

The purpose of this book is to lay out the logic and details of the RICE-98 model. Like an anatomy class, this description tends to highlight the less sexy aspects of the subject. Rather, again like anatomy, the purpose is to lay out the internal structure of the model and the ways different segments are connected.

The paper is laid out in six parts. The first part gives a general introduction to the subject. The following section presents an overview of the model, starting with a verbal description and followed by a list of the equations. Sections three and four provide respectively a detailed description of the energy and economic sectors and of the environmental sectors. Part five provides some computational details, while the final part presents the major results and some tentative conclusions. The Appendices provide a summary listing of the equations, a variable list, the regional definition, and other summary tables.

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Workers in this area will recognize that this study builds on earlier work of the author and of many others in the field. Although the paper bears the name of two authors, the intellectual inspiration and contribution of many should be recognized. Among those who have contributed directly or indirectly, we would like to thank Jesse Ausubel, Howard Gruenspecht, Dale Jorgenson, William Hogan, Charles Kolstad, Alan Manne, Robert Mendelsohn, Nebojsa Nakicenovic, John Reilly, Richard Richels, Thomas Schelling, Stephen Schneider, Leo Schrattenholzer, Robert Stavins, Ferenc Toth, Karl Turekian, Paul Waggoner, John Weyant, Zili Yang, and Gary Yohe. This research was supported by the National Science Foundation and the Department of Energy. None of these are responsible for the errors, opinions, or flights of fancy in this work.

Part 1. Introduction

"God does not play dice with the universe," was Albert Einstein's reaction to quantum mechanics. Yet humanity *is* playing dice with the natural environment through a multitude of interventions — injecting into the atmosphere trace gases like carbon dioxide that promise to change the global climate, adding ozone-depleting chemicals, engineering massive land-use changes, and depleting multitudes of species in their natural habitats, even as we create new organisms with unknown properties in the laboratory. In an earlier era, human societies learned to manage, or sometimes failed to learn and mismanaged, their grazing or water resources. Today, as human activity increasingly affects global processes, we must learn to use wisely and protect economically our common geophysical and biological resources. This task of understanding and controlling interventions on a global scale is *managing the global commons*.

Climatologists and other scientists warn that the accumulations of carbon dioxide (CO_2) and other greenhouse gases are likely to lead to global warming and other significant climatic changes over the next century. This prospect has been sufficiently alarming that governments have undertaken, by the Kyoto Protocol of December 1997, to reduce their greenhouse-gas (GHG) emissions over the coming years. The Kyoto Protocol raises a number of fundamental issues: Are the emissions limitations proposed there sufficient, insufficient, or excessive? Is the mechanism proposed to combat global warming — partially tradable emissions limitations — workable and desirable? Was it wise to omit developing countries? Is there a trajectory for the Kyoto Protocol that will lead to a comprehensive climate-change policy? Are other approaches, such as harmonized carbon taxes or geoengineering, worth considering? How does the approach in the Kyoto Protocol compare with the economist's dream of an "efficient" policy? And, perhaps most important, will these costly approaches sell in the political marketplace of the world democracies and oligarchies?

Natural scientists have pondered many of the *scientific* questions associated with greenhouse warming for a century. But the *economic, political, and institutional* issues have only begun to be considered over the last decade. The intellectual challenge here is daunting — raising formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes are enormous. Current estimates indicate that the Kyoto Protocol involves a commitment of about $1 trillion in present value to slow climate change. It is no hyperbole to say that the issue of greenhouse warming invokes the highest form of global citizenship — where nations are being called upon to sacrifice hundreds of billions of dollars of present consumption in an effort that will largely benefit people in other countries, where the benefit will not come until well into the next century and beyond, and where the threat is highly uncertain and based on modeling rather than direct observation.

The issue of global warming has proven one of the most controversial and difficult problems facing nations as they cross the bridge into the twenty-first century. Over the last decade, the issue has migrated from the scientific journals to White House Conferences and World Summit meetings. In response, a small navy of natural and social scientists has been mobilized to help improve our understanding. In parallel with the growing interest, industrial, environmental, and political groups have put their oars in the water to pull the ship in directions favorable to their ideologies or bottom lines.

Among the most impressive advances over the last decade has been the development of integrated-assessment economic models which analyze the problem of global warming from an economic point of view. Literally dozens of modeling groups around the world have brought to bear the tools of economics, mathematical modeling, decision theory, and related disciplines on the sticky issues. Whereas a decade ago, in 1988, there was not a single integrated model of the economics of climate change, there are now more than we can keep track of.

The earliest dynamic economic model of climate change was the DICE model (a Dynamic Integrated model of Climate and the Economy). Originally developed out of a line of energy models, the DICE model integrated in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allowed a weighing of the costs and benefits of taking steps to slow greenhouse warming. The first version of the DICE model was presented in 1990 with the major exposition in Nordhaus [1994d]. A regionalized version, known as the RICE model (a Regional dynamic Integrated model of Climate and the Economy), was developed and presented in

Nordhaus and Yang [1996].

Although the basic structure of the DICE and RICE models has survived in the crucible of scientific criticism, at the same time further developments in both economics and the natural sciences suggest that major revisions of the earlier approaches would be useful. While no smoking guns or magic bullets have been discovered, a number of small discoveries and large innovations in models have come forth. Moreover, almost a decade of history has passed, and there have been major improvements in the underlying data on greenhouse-gas emissions and energy and economic data.

The present work represents the fruits of the revision of the earlier models. Virtually the entire model has been restructured and revised. The major changes are the following:

- The major methodological change is a respecification of the production relations. Whereas the earlier RICE models used a parameterized emissions-cost relationship, the new model use a three factor production function in capital, labor, and carbon-energy. The new RICE model develops a new technique for representing the demand for carbon fuels and uses existing energy-demand studies for calibration.

- The new RICE model changes the treatment of energy supply to incorporate the exhaustion of fossil fuels. This approach treats the supply of fossil fuels explicitly and uses a market-determined timing of the depletion of exhaustible fuels. The new model incorporates a depletable supply of carbon fuels, with the base estimate being 10,000 billion metric tons of coal equivalent (or 6,000 billion metric tons of carbon). With limited supplies, coal prices will rise in the market place to choke off consumption of fossil fuels until the backstop price is reached. Rising fossil fuel prices due to scarcity tend to reduce future emissions and to reduce the need for stringent emissions control strategies.

- Most of the data have been updated by almost a decade to reflect data for 1994-97. The output growth in the models is driven off of regional economic, energy, and population data and forecasts. The new model projects significantly lower uncontrolled CO_2 emissions over the next century than the earlier DICE and RICE model, primarily because of slower projected growth and a higher rate of decarbonization of the world economy.

- The climate model is largely unchanged because there have been no major changes in the underlying climate models. Projected global temperature change in the uncontrolled case is significantly reduced because of new information about the negative forcings from sulfates, because of lower forcings from the chlorofluorocarbons, and because of the slower growth in CO_2 concentrations.

- The impacts of climate change have been revised significantly in the new models. The global impact is derived from regional impact estimates. The new models separate the impacts into catastrophic and non-catastrophic components, but the overall economic impacts of climate change for the next century or so are little changed from earlier DICE/RICE analyses.

- The DICE model has been reprogrammed so that it can be analyzed both in a spreadsheet program and in a GAMS program. This allows others to adapt the model more easily to their own uses.

The present study lays out the revisions and their implications in detail. The underlying philosophy of the original DICE and RICE models remains unchanged: to develop small and transparent models that can be easily understood, modified as new data or results emerge, and will be useful for both scientific and policy purposes.

It is our hope that this study can help modelers and policymakers better understand the complex tradeoffs involved in climate-change policy. In the end, good analysis cannot dictate policy, but it can help policymakers thread the needle between a ruinously expensive climate-change policy that today's citizens will find intolerable and a myopic do-nothing policy that tomorrow's citizens will curse us for.

Part 2. The Structure And Derivation of the RICE-98 Models

A. **Introduction**

We first present an overview of the RICE model. This section describes the structure of the model verbally, while subsequent sections present the equations of the models. The following Part then discuss the derivation of the major components of the models.

In considering climate-change policies, the fundamental tradeoff is between consumption today and consumption in the future. By taking steps to slow emissions of greenhouse gases (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 climate investments involve reducing energy consumption or moving to low-carbon fuels; in return for this investment, the impacts on agriculture, coastlines, and ecosystems as well as the potential for catastrophic climate change will be reduced.

But the lags between emissions reductions and climatic impacts are extraordinarily long and uncertain, and this fact makes the economic and scientific questions treacherous. Nations must decide whether they will take climate investments now in order to slow climate change over the coming centuries. Few societal decisions, and no personal ones except those involving Pascal's wager have comparable time horizons, and this encourages political decision makers to temporize on costly steps.

The major difficulty in the RICE-98 model has been to develop a model of the world economy that captures the major properties of medium- and long-run economic growth of the major countries and regions over the next century. Outside of the rarified and generally stylized models used in the climate-change integrated-assessment models, there are essentially no models of the world economy upon which to draw. Useful ingredients can be obtained for the population projections from demographers, who do in fact prepare long-term projections. But for other important variables, ones determining capital formation and technological change, particularly for countries outside the United

States and Western Europe, it has been necessary to develop long-term projections *de novo*.

B. **Verbal Description**

1. Economic sectors

The approach taken here is to view climate change in the framework of economic growth theory. This approach was developed by Frank Ramsey in the 1920s (see Ramsey [1928]), made rigorous by Tjalling Koopmans and others in the 1960s (see especially Koopmans [1967]), and is summarized by Robert Solow in his masterful exposition of economic-growth theory [1970]. In the neoclassical growth model, society invests in tangible capital goods, thereby abstaining from consumption today, in order to increase consumption in the future.

The DICE/RICE models are the extension of the Ramsey model to include climate investments. The capital stock of the conventional neoclassical growth model is extended to include investments in the environment. Emissions reductions in the extended model are analogous to investment in the mainstream model. Society must take steps today, reducing consumption by devoting resources to reducing greenhouse-gas emissions, in order to prevent economically harmful climate change and thereby increasing consumption possibilities in the future.

In the description that follows, we will focus on the fully regionalized model, the RICE model. Most of the statements apply equally well to the DICE model, but the latter is highly simplified and is discussed in Part 4. The world is composed of sovereign countries, represented by large countries (like the U.S. or India) or large regions (like the European Union or Africa).

Each region is assumed to have a well-defined set of preferences by which it chooses its path for consumption over time. This preference or “social welfare function” is chosen to represent reasonably well the decision structure of nations. The preferences are increasing in per capita consumption, with diminishing marginal utility of consumption. The welfare of different generations is combined using a time-separable function that applies a pure rate of time preference to different generations. Nations are then assumed to maximize the social welfare function subject to a number of economic and geophysical constraints. The decision variables that are available to the economy are consumption, the rate of investment in tangible capital, and the climate investments, primarily emissions reductions of greenhouse gases.

The model contains both a traditional economic sector found in many economic models and a novel climate sector designed for climate-change modeling. We first describe the traditional sector of the economy — the economy without any considerations of climate change. Each country or region is assumed to produce a single commodity which can be used for either consumption or investment. In the baseline model, there is no trade in goods or capital, but countries in certain cases trade rights for carbon emissions and receive (homogeneous) consumption goods in return.

Each region is endowed with an initial stock of capital and labor and an initial and region-specific level of technology. Each region maximizes its own social welfare function, which is the sum of discounted utilities of per capita consumption times population; the utility function is logarithmic in per capita consumption. Population growth and technological change are exogenous in the baseline model, while capital accumulation is determined by optimizing the flow of consumption over time.

The major methodological change in the economic sector is a respecification of the production relations in the RICE-98 model from earlier vintages. (The DICE model retains its simple “reduced-form” production structure as in earlier vintages.) The major change in RICE-98 is to define a new input into production called “carbon-energy.” Carbon energy is the carbon equivalent of energy consumption and is measured in carbon units. Output is produced with a Cobb-Douglas production function in capital, labor, and carbon-energy inputs. CO_2 emissions are therefore a joint product of carbon-energy. Technological change takes two forms: economy-wide technological change and energy-saving technological change. Economy-wide technological change is Hicks neutral, while energy-saving technological change is modeled as reducing the output-carbon elasticity (or the amount of carbon emissions per unit output at given input prices).

We calibrate the production function using existing data on energy use, energy prices, and energy-use price elasticities. These allow a data-based carbon reduction curve, whereas most current integrated assessment models make “reasonable” but not data-based specifications of demand. On the supply side, the earlier DICE and RICE models assumed that carbon fuels are superabundant at a fixed supply price. In the RICE-98 model, a carbon supply curve is introduced. The supply curve allows for limited (albeit huge) long-run supplies at rising costs. Because of the optimal-growth framework, fossil fuels are efficiently allocated, which implies that low-cost resources have scarcity rents and that the “Hotelling rents” on carbon-energy prices rise over time.

2. Climate-related sectors

The "non-traditional" part of the model contains a number of geophysical relationships that link together the different forces affecting climate change. This part contains a carbon cycle, a radiative forcing equation, climate-change equations, and a climate-damage relationship.

In the earlier DICE/RICE models, endogenous emissions included all GHG emissions, although CO_2 was quantitatively the most important. In RICE-98 and DICE-98, endogenous emissions are limited to industrial CO_2. The major change is that the chlorofluorocarbons (CFCs) are now outside the climate-change control strategy; this specification reflects the fact that CFCs are strictly controlled outside the framework of the climate-change agreements under different protocols. It is not generally appreciated that control of CFCs has had a significant impact on projected global warming. Industrial emissions are, as noted above, treated as a joint product of carbon-energy in the new models.

Other contributions to global warming are taken as exogenous. These include CO_2 emissions from land-use changes as well as the non-CO_2 greenhouse gases. Although it would be more complete to include other GHGs (and five other gases are in principle included in the Kyoto Protocol), these are extremely complex and poorly understood.

Also, projections by the IPCC and within the DICE/RICE models indicate that the radiative forcings from uncontrolled CO_2 concentrations are likely to be at least ten times larger than those from non-CO_2 greenhouse gases (see Table 3-13 which is discussed in Part 3).

The original DICE and RICE models used an empirical approach to estimating the carbon flows, estimating the parameters of the emissions-concentrations equation from data on emissions and concentrations. A number of commentators noted that this approach may understate the long-run atmospheric retention of carbon because it assumes an infinite sink of carbon in the deep oceans. DICE-98 and RICE-98 replace the earlier treatment with a structural approach that uses a three-reservoir model calibrated to existing carbon-cycle models. The basic idea is that, albeit vast, the deep oceans provide a limited sink for carbon in the long run. In the new specification, we assume that there are three reservoirs for carbon — the atmosphere, a quickly mixing reservoir in the upper oceans and the short-term biosphere, and the deep oceans. The upper reservoirs — including the atmosphere, the biosphere, and the upper ocean — are assumed to be well mixed in the short run, while the mixing between the upper reservoirs and the deep oceans is assumed to be extremely slow. The RICE/DICE-98 approach matches the original DICE model and other calculations in the early periods but has better long-run properties. A full discussion of the new approach is contained in Part 3.

Climate change is represented by global mean surface temperature, and the relationship uses the consensus of climate modelers and a lag suggested by coupled ocean-atmospheric models. This segment is unchanged from the original DICE and RICE models.

Understanding the economic impacts of climate change continues to be the thorniest issue in climate-change economics. Estimates of climate-change impacts in most integrated assessment modeling rely on a wide variety of estimates of the damage from climate change in different sectors for different regions. Starting with Nordhaus [1989, 1991a], assessments tended to organize impacts of climate change in the framework of national economic accounts, with additions to reflect non-market activity. The present study follows first-generation approaches by analyzing impacts on a sectoral basis. There are three major differences from many earlier studies. First, the approach here is focused on developing estimates for all major countries and regions rather than for the U.S. This focus is obviously necessary both because global warming is a global problem and because of a common view that impacts are likely to be significantly larger in poorer countries. Second, this study focuses more heavily on the non-market aspects of climate change with particular importance given to the potential for catastrophic risk; this approach is taken because of the finding of the first-generation studies that the impacts on market sectors are likely to be relatively limited. The major results are 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 . At the other extreme, low income regions — particularly Africa and India — and Europe appear to be quite vulnerable to climate change. The United States appears to be relatively less vulnerable to climate change than many countries. The results are discussed in detail in Part 3.

The final point involves the appropriate interpretation of the framework used here. The model can be interpreted either in an optimizing framework or as the outcome of idealized competitive markets. To employ the competitive-markets interpretation, we would need to take the leap of faith that the public goods nature of climate change is somehow overcome in an efficient manner. That is, it assumes that countries efficiently internalize in their decision-making the *global* costs of their emissions decisions. There is little evidence of such global generosity, but the current approach has the virtue of calculating the equilibrium that would emerge were each region to behave in such a farsighted, efficient, and altruistic fashion.

C. **Derivation of the Equations of the RICE-98 Models**

We turn next to a specific list of the equations of the RICE-98 model along with a discussion of their derivation. The relationships are divided into three groups: the objective function, the economic relationships, and the geophysical relationships. Although the economic sectors are conventional in their approach, modifying them for the climate-change problem requires careful attention, and the major issues are considered in the next Part. The major issues of the climate sector and the interaction of economy and climate are analyzed in the following Part.

1. Objective function

A central organizing framework of the DICE/RICE models is the underlying objective of the economy. We assume that the purpose of economic and environmental policies is to improve the living standards or consumption of humans now and in the future. The relevant economic variable of interest is “generalized consumption,” which denotes a broad concept that includes not only traditional market purchases of goods and services like food and shelter but also non-market items such as leisure, cultural amenities, and enjoyment of the environment.

The fundamental assumption we adopt is that policies should be designed to optimize the generalized level of consumption now and in the future. This approach rests on the view that more consumption is preferred over less. Moreover, increments of consumption become less valuable as consumption levels increase. In technical terms, these assumptions are operationalized by maximizing a social welfare function that is the discounted sum of the utility of per capita consumption. This social welfare function is a mathematical representation of three basic value judgments: (i) that higher levels of consumption have higher worth; (ii) that there is diminishing marginal valuation of consumption as consumption increases; and (iii) that society will undertake investments so as to increase consumption in periods where the marginal utility of consumption is highest. In addition, the approach includes time preference that allows for differing the relative emphasis on different generations.

The RICE model adds a significant level of complexity to the original DICE model by incorporating the simultaneous growth paths of the different countries or regions. The exact objective function, or criterion to be maximized, for region J is:

$$\text{(2.1)} \qquad \max \quad \sum_J \phi^J W^J$$

where

$$\text{(2.2)} \qquad W^J = \sum_t U^J[c_J(t),L_J(t)]R(t) \quad = \quad \sum_t L_J(t)\{\log[c_J(t)]\}R(t)$$

W^J is the objective of region j, $U^J[c_J(t),L_J(t)]$ is the utility of consumption for region J, $c_J(t)$ is the flow of consumption per capita at time t, $L_J(t)$ is the level of population at time t, and R(t) is the utility discount factor. The exact form of the utility function will be described below. The model operates in periods of 10 years; all flow variables in the empirical model are reported as flows per year, while the convention is that stocks are measured at the beginning of the period.

Equation (2.1) is the objective function, corresponding to the market equilibrium. The market equilibrium can be calculated as the maximization of the social welfare functions of the different regions with the appropriate set of welfare weights, ϕ^J. This approach is known as the "Negishi technique."[2] The interpretation is that the "optimization" determines the efficient competitive-market equilibrium of the different regions.

Major parameters in this approach are the utility discount rate and discount factors. Utility is discounted by a factor that represents social time preference among different generations. The underlying parameter is the pure rate of social time preference, $\rho(t)$. In both the RICE-98 and DICE-98 models, it is assumed that the discount rate

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[2] This approach is described in Nordhaus and Yang [1996].

declines over time, and the discount factor is then given by:

$$R(t) = \prod_{v=0}^{t} [1+ \rho(v)]^{-10}$$

This parameter is a social choice variable that is implicit in many societal decisions, such as fiscal and monetary policies. In conjunction with other variables, it is closely connected with the market rate of interest (or marginal productivity of capital) and with the savings rate. The original RICE and DICE models used a constant pure rate of time preference of $\rho(t) = 3$ percent per year, which implied that $R(t) = (1+ \rho)^{-10t}$. The constant rate of 3 percent per year was considered to be consistent with historical savings data and interest rates. In the DICE-98 and RICE-98 models, the pure rate of time preference is assumed to decline over time because of uncertainty about future conditions.

2. Economic Constraints

The next set of equations represents the different regions or countries. The first equation is the definition of utility, which was described and motivated in the last section. Utility represents the current value of well being and is assumed equal to the size of population $[L_J(t)]$ times the utility of per capita consumption $u[c_J(t)]$. Equation (2.2a) is the general case of a power function to represent the form of the utility function:[3]

$$U^J [c_J(t),L_J(t)]= L_J(t) \{c_J (t)^{1-\alpha} - 1\}/(1-\alpha) \qquad (2.2')$$

In this equation, the parameter α is a measure of the social valuation of different levels of consumption, which has several interpretations. It represents the curvature of the utility function, the elasticity of the marginal utility of consumption, or the rate of inequality aversion. Operationally, it measures the extent to which a region is willing to

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[3] This formulation subtracts one from power function in the numerator of (2.1) so that the limit of the expression is $L_J(t)[\log(c_J(t)]$.

reduce the welfare of high-income generations to improve the welfare of low-income generations. In the RICE and DICE models, we take (the limit of) $\alpha = 1$, which yields the logarithmic or Bernoullian utility function:

$$U^J\,[c_J(t),L_J(t)] = L_J(t)\ \{\log[c_J(t)]\} \qquad (2.2'')$$

For most regions, the growth of population is assumed to follow an exponential path, and the basic projection method is as follows: Population growth in the initial period is calibrated to current U.N. projections, as discussed below. We then assume that the growth rate declines over time at a geometrically declining rate and then stabilizes. More precisely, and discretizing the equations for simplicity, let $g_{Jpop}(t)$ be the growth rate of population in region J and period t and $\delta_{J\,pop}$ be the rate of decline of the rate in the growth of population in that region. We then have the growth rate of population in time t as:

$$g_{J\,pop}(t) = g_{J\,pop}(t-1)\ (1-\delta_{J\ pop})$$

It is easily verified that this assumption leads to a stable population. Its advantage is that the population trajectory can be represented by two parameters and can be easily fit to different projections. For the base case, for global population the initial growth of population in the decade 1995-2005 is 1.4 percent per year and the decadal decline in the growth rate is about 1.8 percent per year. This assumption leads to an asymptotic maximum population of 11.5 billion people.

Production is represented by a modification of a standard neoclassical production function. For region J, output $[Q_J(t)]$ is given by a constant-returns-to-scale Cobb-Douglas production function in technology $[A_J(t)]$, capital $[K_J(t)]$, labor $[L_J(t)]$, and carbon-energy or carbon-energy substitutes $[E_J(t)]$. Total carbon-type energy $[E_J(t)]$ is composed of carbon energy $[EC_J(t)]$ and backstop energy $[B_J(t)]$.

$$Q_J(t) = \Omega_J(t)\ A_J(t)\ K_J(t)^{\gamma}\ L_J(t)^{1-\gamma-\beta_J(t)}\ E_J(t)^{\beta_J(t)} - p^E{}_J(t)\ EC_J(t) - p^B(t)\ B_J(t) \qquad (2.3)$$

In (2.3), γ is the elasticity of output with respect to capital and is taken equal to 0.3.

$\beta_J(t)$ is the elasticity of output with respect to carbon-energy (discussed further below), and the term $1-\gamma-\beta_J(t)$ is the output elasticity with respect to labor. The term $\Omega_J(t)$ is a damage coefficient that relates to the impact of climate change on output described below. Labor inputs are proportional to population, capital accumulation is defined below, and the energy-carbon aggregate is discussed next. The last term — $p^E{}_J(t)\ EC_J(t) - p^B(t)\ B_J(t)$ — subtracts from gross output the production cost of carbon energy and of backstop energy, respectively.

The historical output and capital data are gathered from a number of sources for the years 1960, 1965, 1970, 1975, 1980, 1985, 1990, and 1995. Data for individual countries are aggregated into regions using market exchange rates. The variable $\Omega_J(t)$ is assumed to be one during the historical period, and projections for future periods are discussed below.

A note on measuring output will be useful at this point. Many studies currently use output measured at purchasing-power parity (PPP) exchange rates. While that approach is appropriate for measuring standards of living, it is not appropriate for measuring growth rates for output in country prices and is generally inconsistent with actual and historical measures of output growth. To ensure consistency with the data and theory, we therefore rely on own-country (rather than international) prices to measure output and growth rates. (The level of output can of course be scaled by a factor to represent living standards at a particular time, but this has little substantive effect on the results.)

A further issue arises because of the assumption of market clearing in the model. The assumption used here is that there are no net flows of capital or goods at the calculated equilibrium (we can assume that they are embedded in the actual market data). This implies that there are zero excess demands for all goods and capital at the going exchange rates and interest rates. To ensure consistency with the approach, we need to convert outputs of different countries at exchange rates that ensure that the rates of return on capital are equalized in different countries (also see the discussion of the Negishi algorithm in Part 5). This implies that the relative prices of the outputs of different countries move inversely with the total return on capital in the countries.

A major uncertainty in the model involves projecting the growth of $A_J(t)$, or total factor productivity (TFP), into the future. TFP growth is assumed to slow gradually over the next three centuries until eventually stopping. The exact technique for deriving estimates is described in the section on calibration. The technical formula within the DICE and RICE models for projecting TFP is similar to that introduced above for population growth. Let $g_{AJ}(t)$ be the growth rate of total factor productivity in period t and δ_{AJ} be the decline rate in the growth of productivity. Productivity growth at time t is then:

$$g_{AJ}(t) = g_{AJ}(t-1)(1-\delta_{AJ}) \ ,$$

where δ_{AJ} is determined so that $A_J(t) \rightarrow A_J^*$ as $t \rightarrow \infty$, and A_J^* is the asymptotic level of total factor productivity for region i.

The next equation shows the disposition of output between consumption $[C_J(t)]$ and gross investment $[I_J(t)]$ for the global economy and the DICE model:

$$(2.4) \qquad Q_J(t) = C_J(t) + I_J(t)$$

This represents the accounting identity in a one-sector economy that output can be devoted either to investment in new capital goods or to consumption.

In the RICE model, we assume there is no international trade in goods or capital. However, there may be trade in carbon-emissions permits, which are paid for in consumption goods. With trade, the prior equation is modified to:

$$(2.4') \qquad Q_J(t) + \tau(t)[EC_J(t) - \Pi_J(t)] = C_J(t) + I_J(t)$$

where $p^E(t)$ is the price of emissions allowances, $\Pi_J(t)$ is the number of carbon emissions allowances that region J receives, $\tau(t)$ is the international carbon price, and $EC_J(t)$ is the actual quantity of carbon emissions.

The next equation is the definition of per capita consumption:

(2.5) $c_J(t) = C_J(t)/L_J(t)$

Finally, we have the capital balance equation for the capital stock:

(2.6) $K_J(t) = (1-\delta_K)K_J(t-1) + 10 \times I_J(t-1)$

where δ_K is the rate of depreciation of the capital stock. In this equation, the depreciation rate of capital is taken to be 0.10 percent per annum. The factor of 10 in equation (2.6) reflects the convention that investment is measured at annual rates while the period in the model is 10 years.

3. Climate-Emissions-Damage Equations

The next set of relationships has proven a major challenge because there are no well-established empirical regularities and very little history that can be drawn upon to represent the linkage between economic activity and climate change. These equations comprise the relationships among economic activity, emissions, concentrations, and climate change. As with the economic relationships, it is desirable to use a parsimonious specification so that the theoretical model is transparent and so that the optimization model is empirically tractable. The methodology is drawn from macroeconomics, in which economic behavior is represented by equations that capture the behavior of broad aggregates (such as consumers or investors); the challenge in this area is that aggregate relationships are needed for optimization approaches like the DICE and RICE models.

The first link is between economic activity and greenhouse-gas emissions. In the DICE/RICE-98 models, greenhouse gases affect climate through their radiative forcing.[4]

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[4] Aggregation of greenhouse gases poses a frightening series of complexities. To begin with, differing lifetimes means that the instantaneous radiative impact must be converted into something that is more appropriate for economic decisions; hence the use of global warming potentials. The aggregation by the IPCC is flawed in that it uses undiscounted integration but truncates after a certain time (say a century). The more appropriate treatment would be to weight the instantaneous radiative potential by the shadow price of the warming for each period (for a discussion, see Schmalensee [1993]). Further complexities arise because some of the associated gases may offset the warming (as in the

Of the suite of GHGs, only industrial CO_2 is endogenous in the model. The other GHGs (including CO_2 arising from land-use changes) are exogenous and projected on the basis of current analysis by the IPCC and other scientific groups. More than 90 percent of the increase in radiative forcing over the next century comes from CO_2, and more than 90 percent is likely to come from industrial emissions, so we devote most of our attention to industrial CO_2 .

Industrial CO_2 is modeled as the byproduct of carbon-energy, which is an input into production. The treatment is straightforward except for the exact definition of carbon-energy. The quantity measure is simple, for the units are simply tons of carbon. The difficulty arises because of the necessity of finding the appropriate price of carbon-energy, $p^E{}_J(t)$, along with the appropriate output elasticity, $\beta^J(t)$. In the RICE-98 model, we have constructed the price and elasticity so that the responsiveness of carbon-energy use to carbon taxes is calibrated to fit existing models of energy demand. The calibration procedure is explained in the next Part.

In modeling GHG emissions, we assume that the carbon elasticity of output [$\beta^J(t)$] changes over time. The change in the carbon elasticity reflects carbon-energy reducing technological change. We determine this parameter on the basis of both historical data and of projections of its change over the near term. Note that the treatment of emissions reduction is a major respecification from the original DICE/RICE models. Emissions are directly calculated rather than calculated as an emissions control rate.

The equations representing the production side of the carbon market are as follows. The first equation defines the retail price of energy.

$$p^E{}_J(t) = q(t) + \text{markup}^E{}_J(t) + \tau(t) \tag{2.7}$$

where $p^E{}_J(t)$ is the price of carbon-energy in region J, q(t) is the world price of carbon-

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case of sulfates). The view presented here is that, given the dominance of CO_2 for future warming, the approach used here will be a reasonably good approximation to a more complete analysis.

energy (assumed to be equalized in world markets), $\text{markup}^E_J(t)$ is the markup of retail prices over the wholesale price of carbon-energy, and $\tau(t)$ is the carbon tax. We measure the markup as the difference between retail and wholesale prices; it includes transportation, distribution costs, and current taxes. We interpret current taxes as Pigovian taxes that reflect the external costs of energy production and consumption. The carbon tax, which is currently zero in virtually all countries, will be the major instrument by which countries implement their restraints on carbon emissions.

The next equation represents the cumulative supply constraints on the production of carbon-energy:

$$\text{(2.8)} \qquad \text{CumC}(t) = \text{CumC}(t-1) + 10 \times \text{EC}(t-1)$$

where CumC(t) is the cumulative production of carbon-energy at the beginning of period t and EC(t) is current world production of carbon-energy.

The next two equations represent the supply curve of carbon-energy.

$$\text{(2.9a)} \qquad q(t) = \xi_1 + \xi_2[\text{CumC}(t)/\text{CumC}^*]^{\xi_3}$$

$$\text{(2.9b)} \qquad E_J(t) = EC_J(t) + B_J(t)$$

In equation (2.9a), q(t) is again the wholesale (supply) price of carbon-energy whereas ξ_1, ξ_2, and $\xi 3$ are parameters. In the RICE model, countries have the option of introducing a backstop technology to replace carbon-energy. Equation (2.9b) relates the supply of all energy in the region to the use of carbon energy, $EC_J(t)$, and production from a backstop technology, $B_J(t)$. The backstop technology for carbon-energy has a relatively high price (around $300 per ton carbon pre markup) and has rate-of-introduction constraints that limit its introduction in early periods.

The next relationship in the economy-climate nexus represents the accumulation of CO_2 in the atmosphere. In the original DICE model, the accumulation and transportation of emissions was assumed to follow a first-order process. This has been revised in light of inconsistencies of the model with established carbon-cycle modeling.

The new treatment uses a structural approach with a three-reservoir model calibrated to existing carbon-cycle models. The basic idea is that the deep oceans provide a limited, albeit vast, sink for carbon in the long run. In the new specification, we assume that there are three reservoirs for carbon — the atmosphere, a quickly mixing reservoir in the upper oceans and the biosphere, and the deep oceans. Each of the three reservoirs is are assumed to be well-mixed in the short run, while the mixing between the upper reservoirs and the deep oceans is assumed to be extremely slow. We assume that CO_2 accumulation and transportation can be represented as the following linear three-reservoir model.

$$(2.10)\ M_{AT}(t) = 10 \times E^C(t) + \phi_{11} M_{AT}(t-1) - \phi_{12} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1)$$

$$(2.11)\ M_{UP}(t) = \phi_{22} M_{UP}(t-1) + \phi_{12} M_{AT}(t-1) - \phi_{21} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1) - \phi_{23} M_{UP}(t-1)$$

$$(2.12)\ M_{LO}(t) = \phi_{33} M_{LO}(t-1) - \phi_{32} M_{LO}(t-1) + \phi_{23} M_{UP}(t-1)$$

where $M_{AT}(t)$ is the mass of carbon in the atmosphere, $M_{UP}(t)$ is the mass of carbon in the upper reservoir (biosphere, and upper oceans), $E^C(t)$ is global CO_2 emissions including those arising from land-use changes, and $M_{LO}(t)$ is the mass of carbon in the lower oceans. The coefficient ϕ_{ij} is the transfer rate from reservoir i to reservoir j (per period), where i and j = AT, LO, and AT. The calibration of equations (2.10), (2.11), and (2.12) is described in Part Three.

The next step concerns the relationship between the accumulation of greenhouse gases and climate change. This sector uses the same specification as in the original DICE/RICE models because there have been no major developments that would lead to a revision of the underlying approach. Climate modelers have developed a wide variety of approaches for estimating the impact of rising GHGs on climatic variables. On the whole, existing models are much too complex to be included in economic models, particularly ones that are used for optimization. Instead, we employ a small structural model that captures the basic relationship between GHG concentrations, radiative forcings, and the dynamics of climate change.

Accumulations of GHGs lead to global warming through increasing the warming at the surface by increased radiation. The relationship between GHG accumulations and increased radiative forcing, F(t), is derived from empirical measurements and climate models. We characterize the relationship in terms of the forcings as a function of the CO_2-equivalent of GHG accumulations as follows:

$$F(t) = \eta\{\log[M_{AT}(t)/M_{AT}^*]/\log(2)\} + O(t) \tag{2.11}$$

where $M_{AT}(t)$ is the atmospheric concentration of CO_2 in billions of metric tons of carbon and F(t) is the increase in radiative forcing over preindustrial levels in watts per square meter (W/m^2), which is the standard measure of radiative forcing. O(t) represents other greenhouse gases (principally sulfates and other particulates, CFCs, CH_4 and N_2O). These other gases represent a small fraction of the total warming potential, their sources are poorly understood, and techniques for preventing their buildup are sketchy today; they are therefore taken as exogenous. The term M_{AT}^* is the pre-industrial level of atmospheric concentrations of CO_2 (taken to be about 280 parts per million).

The major change in this sector has been the exclusion of the CFCs from the endogenous GHGs and a correction to represent the potential cooling effects of sulfates. The net effects of these two changes are to lower sharply projected radiative forcing over the next century. All these issues are discussed in detail in the next Part.

The parameterization in (2.11) is not controversial. It relies upon a variety of data on atmospheric concentrations and combines those into a series on radiative forcing as described in the most recent comprehensive IPCC report (IPCC [1996a]). The major assumption for the present modeling is the finding that a doubling of CO_2 equivalent concentrations would lead to an increase in radiative forcing by 4.1 W/m^2.

The next equation provides the link between radiative forcing and climate change. Here again, the specification is identical to the original DICE/RICE models. Higher radiative forcings warm the atmospheric layer, which then warms the upper ocean, gradually warming the deep oceans. The lags in the system are primarily due to the thermal inertia of the different layers. We can write the model as follows:

(2.12a) $$T_{UP}(t) = T_{UP}(t-1) + \sigma_1\{F(t) - \lambda T_{UP}(t-1) - \sigma_2[T_{UP}(t-1) - T_{LO}(t-1)]\}$$

(2.12b) $$T_{LO}(t) = T_{LO}(t-1) + \sigma_3[T_{UP}(t-1) - T_{LO}(t-1)]$$

where $T_{UP}(t)$ is the increase in the globally and seasonally averaged temperature in the atmosphere over preindustrial levels and the upper level of the ocean; $T_{LO}(t)$ is the increase of temperature in the deep oceans; F(t) is the increase in radiative forcing in the atmosphere, λ is a feedback parameter, and the σ_i are transfer coefficients reflecting the rates of flow and the thermal capacities of the different sinks.

Equations (2.12a) and (2.12b) can be understood in terms of a simple example of the impact of a warming source on a pool of water. Suppose that a heating lamp is turned on (this being the increase in F(t) or radiative forcings). The top part of the pool along with the air at the top are gradually warmed, and the lower part of the pool is also warmed as the heat is diffused to the bottom. The lags in the warming of the surface in this simple example are determined by the size of the pool (that is, by its thermal inertia) and by the rate of mixing of the different levels of the pool. This set of equations was fully described in the original description of the DICE model in Nordhaus [1994d].

The next link in the chain is the economic impact of climate change on human and natural systems. Estimating the damages from greenhouse warming has proven extremely elusive. For the purpose of this study, it is assumed that there is a relationship between the damage from greenhouse warming and the extent of warming. More specifically, the relationship between global-temperature increase and income loss is given by:

(2.13) $$D_J(t) = \theta_{1,J}\, T(t) + \theta_{3,J}\, T(t)^2$$

where $D_J(t)$ is the damage from climate change for a region as a fraction of its gross output and relates the damage to the change in global mean temperature. The damage function is a quadratic function, and the calibration is described in Part Three.

Finally, we can include the damage function into the production function in (2.2) using the Ω relationship as follows:

(2.14) $\Omega_J(t) = 1/[1+D_J(t)]$

Equations (2.1) through (2.14) form the RICE-98 model that is analyzed in the subsequent Part. Appendix Table A-1 lists the equations of the RICE model in a single place. The major variables are summarized in Appendix Table A-3. The computer code for the model is listed as Appendix B.

Part 3. Detailed Description of the Major Sectors

This part describes the major components of the RICE-98 model. Some of the sectors are essentially identical to the original DICE or RICE models, and for those we will refer to the earlier publication. We begin with the economic modules and then move on to the environmental elements.

A. Regional Specification

The RICE-98 model divides the world economy into 13 different regions. The regions were grouped on the following principles. First, most of the "major" countries were considered separately. These included the United States, Japan, Russia, China, and India. The European Union was treated as a single region because of the high level of political and economic integration among those countries.

The other countries were generally grouped together on the basis of regional or economic similarity. The "Other High Income" group includes chiefly Canada and Australia. Middle income countries include several large countries (including South Korea, Brazil, and Argentina). "Lower middle-income" includes Mexico, South Africa, and several populous oil exporters such as Venezuela. "Africa" includes Sub-Saharan Africa except for South Africa. The low-income region includes Indonesia, North Korea, Iraq, and the Philippines. In addition, "Eastern Europe" includes the formerly centrally planned economies of that region, which have extremely high carbon intensities.

Table 3-1 shows the composition of the regions as well as the data on CO_2 emissions, population, GDP, and GDP growth for each country. Tables 3-2 through 3-5 show calculated data on growth in output per capita, energy intensity, and carbon intensity of the different regions. Figure 3-1 shows the estimated CO_2-output ratios for the different regions. It is interesting to note how high are the carbon intensities of the low-income regions.

B. **Calibrating the Economic Growth Model**

1. Details of the Calibration

The RICE-98 model relies upon a Ramsey-Koopmans optimal growth model to drive the economic activity in each region. This section describes the calibration of the model. The important variables necessary for the future economic trajectories are population, capital stock, and the rates of total factor productivity. We discuss each of these in turn.

Initial conditions for the RICE model. With a few exceptions, the initial conditions were set for each region so that the values for population, output, and emissions for the first period in the base (uncontrolled) run equal the historical values. These were modified for the United States, Japan, and Europe to reflect growth of emissions. For the U.S. and Japan, the emissions rates in the RICE model for the period 2000-09 were set to match the projections of the Energy Information Agency 1998 *Annual Energy Outlook*. The values for the capital stock and initial total factor productivity are discussed below.

Empirical estimates for population. As described above, the RICE model uses an exponential smoothing model of population growth. In this approach, the model is fitted exactly to three points of the population trajectory: the initial population level, the asymptotic level of population, and the initial rate of population growth. For intermediate population levels and growth rates, the technique leads to small approximation errors. The approach is particularly useful for updating the model because of the small number of parameters needed for specification. Note that for two regions whose populations are projected to decline – Western Europe and Japan — we directly input data for the first few periods and start the exponential model only when population starts to decline.

Data Sources for population: Data for the initial population level were obtained from *UN Monthly Bulletin of Statistics, July 1996*. For the first four periods for Western Europe and Japan, we use the UN population projections for 1995, 2005, 2015, and 2025 from *UN World Population Prospects, 1994 Revision.* For the stationary (asymptotic) population level, we use the World Bank's estimates from *World Bank Population Projections, 1994-5*. The initial rate of population growth is calculated *from World Bank Population Projections, 1994-5.* For some countries, it was modified to improve the match with the World Bank's projections for 2050.[5]

Capital stock. The capital stock was initially determined from estimates of capital stock for each region. These gave implausible rates of return, so the capital stocks were instead calibrated to estimates of the real returns on capital. The estimated returns and the returns in the RICE-98 model by region are shown in Table 3-6 and Figure 3-2. After the initial period, the capital stock is determined within the model by optimizing each region's level of welfare. The savings rates in different regions are shown in Figure 3-3.

Source of output data. Data on output are taken from *UN Monthly Bulletin of Statistics, July 1996.* We base our assumptions about the initial rate of growth in output per capita on actual growth rates over the period 1970-95, calculated from data taken from the World Bank's *World Development Indicators*. These growth rates of output per capita for the 13 regions are shown in Table 3-3.

Estimates about long-run output growth. There are major uncertainties about the long-run trajectories of economic growth in different regions. Some involve environmental issues, but the most important are likely to be political factors, the presence or absence of wars, and future technological change. To obtain long-run growth trends, we undertook an informal survey of a number of experts in the field. We took the low end of the consensus of experts for most regions and modified those in line with special circumstances and the cyclical position of different regions.

A comparison of the RICE assumptions with those of Angus Maddison — who did not participate in the survey and whose results were independently derived — is

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[5] Those using the computer code for the RICE model should note that the initial labor supply in the production function is normalized to equal industrial carbon emissions because of the specification of technological change. This is a technique to ensure that the rate of technological change behaves properly. We have omitted that complication in this writeup because has no economic significance.

provided in Table 3-7. Our assumptions are generally in line with those in the Maddison study, with the world weighted average growth rate in the RICE model approximately 0.08 percent per year higher for the next two decades. The major difference between the two projections is that we are more optimistic about Africa and Latin America, but also less optimistic about China.

The long-run growth rates, historical rates, and levels of per capita GDP for the different regions in the RICE model are shown in Table 3-8.

Model calibration for long-run output growth. To model the trend of long-run economic growth, the RICE model assumes an exogenous exponential trend in technological progress, similar to that used for population described above. The initial level of productivity [the constant term, $A_J(t)$, in the production function] is chosen to calibrate the initial output level for each region. The initial rate of productivity growth is chosen so that growth between the first and second periods in per capita output matches the assumed rates. The rate of growth of TFP declines at an exponential rate to fit both the initial growth of TFP and the assumed asymptotic level of output per capita. The historical growth rate of output per capita along with the calculated rates are shown in Figure 3-4 and Table 3-8.

Calibration of carbon-saving technological change. Calibration of the rate of decarbonization is made by adjusting the carbon-output elasticity, $\beta_J(t)$ in equation (2.3). This is one of the most difficult issues because the rate of decarbonization depends upon trends in energy sources and energy-sector technological change. We have generally projected these on the basis of historical trends in decarbonization, with adjustments for countries or regions such as Russia and Eastern Europe that have divergent carbon intensities for special historical reasons. Figure 3-5 shows recent trends and near-term projections for the rate of decarbonization. We project a continuation in the trend of decarbonization, with a decline in the global carbon-emissions-to-output ratio of 1 percent per year in the 1995-2005 decade compared to a historical decline in the 1970-95 period of 1.07 percent per year. The assumed rate of decarbonization tends toward zero in subsequent decades along with the decline in the assumed rate of economy-wide technological change.

The projections developed here can be compared with the systematic survey by Nakicenovic, Grubler, and McDonald [1998]. They provide a range of scenarios, but their scenario B is probably closest to the philosophy of the present study. Table 3-9 compares the results of the two studies. The RICE model has somewhat slower output growth and a somewhat slower rate of decarbonization, with the net result being that global industrial emissions are very close in both 2020 and 2050. The IIASA study is a particularly useful comparison because of the detailed energy sector and great care taken in developing scenarios for different regions.

2. Discussion

Gathering the data and constructing the regional models proved the most arduous part of constructing the RICE-98 model. The underlying economic vision is one in which nations act in a purposive manner to accumulate capital and improve future living standards. The savings rates are high in the low-income countries (with gross savings rates ranging 25 to 35 percent of GDP in low-income regions) and are between 20 and 25 percent in high-income regions. The savings rates decline in coming decades as population and economic growth decline.

The return on capital is high in developing countries reflecting the scarcity of capital in those regions. OPEC and Japan have relatively low returns on capital reflecting their production structure, growth prospects, and capital stocks. The net return on capital in the U.S. and Europe begins at the historical rate of around 5 to 6 percent per year and then declines gradually with slower growth. Rates of return in developing countries begin at 7 to 9 percent annually and decline with slower growth and capital accumulation.

Per capita output follows an optimistic scenario in which the four horsemen of the economic apocalypse — war, pestilence, world depressions, and environmental catastrophe — are largely absent. High-income countries are projected to continue growth in per capita output at around 1 percent per year over the next century. Low-income countries have per capita growth rates in the range of 2 to 3 percent annually in the next half century, with a gradual slowdown after that. As Table 3-8 shows, we project some but not complete convergence of developing countries toward today's living standards in the rich countries. Middle-income countries and the former centrally planned economies are projected to reach close to current per capita income levels in the U.S. by 2100. Low-income countries, China, and India are projected to have income levels over 10 times current levels by 2100.

A final remark about the model is in order at this point. The regional economic model underlying the RICE-98 model is one of the most complete models of the global economy available for making very long-run projections and policy experiments. At the same time, many elements, particularly the assumptions for developing economies and economies in transition, are difficult to validate or estimate and subject to large and growing projection errors as they run further into the future. It is probably impossible to provide accurate long-run projections given the rapid rate of social, economic, political, and institutional changes. Perhaps the best one can do is to heed the words of the eminent Harvard economic forecaster, Otto Eckstein, who advised that if we cannot forecast well, we should forecast often.

C. **The Energy-Production Module**

The major change in the economic structure of the RICE-98 model is a completely revised production sector. We describe the derivation in detail in this section.

1. Derivation of Energy Demand Relationships

The RICE-98 use a new approach to the production structure relative to both the original models and to existing climate-change models. The major changes are (1) the RICE-98 model introduces a new concept and technique for incorporating carbon emissions by defining an aggregate called “carbon-energy” and (2) production is revised to correspond to a more traditional economic approach to modeling production and inputs choices. The new approach is described in this section and the actual calibration of the production function is described in the next section.

Output in each country or region is assumed to be produced by capital, labor, and carbon-energy in a Cobb-Douglas framework (see equation (2.3 in the Part Two). The new approach aggregates different energy sources into an aggregate input called "carbon energy." Carbon energy is the carbon equivalent of energy inputs, and the units of measurement are carbon emissions. In this approach, CO_2 emissions are a joint product of carbon-based energy inputs. Energy-saving technological change is modeled as reducing the output-carbon elasticity (or the amount of carbon emissions per unit output at constant input prices). Carbon fuels are supplied according to a supply function in which the marginal cost increases as carbon fuels are exhausted (this sector is discussed in section D of this Part). There is a non-carbon backstop technology that is a perfect substitute for carbon-energy but with a marginal cost well above current energy prices.

The purpose of the aggregation is to simplify the model by having a single energy input and treating all non-carbon fuels as simply combinations of capital and labor. The advantage of this approach is that it greatly simplifies the enormous complexities of interfuel substitution. The disadvantage is that this approach may lose some of the fine detail of the inter-fuel substitution relationships, particularly for high carbon taxes. It is important to ensure that the aggregate model has the same behavior over time and with respect to carbon limitations or carbon taxes as would a more complete disaggregated model. To ensure consistency with more complete models, we parameterize the production function so that the response of carbon-energy to a unit increase in carbon taxes is the same as the response in a disaggregated model. In a disaggregated model, carbon emissions would be given by:

$$EC(t) = \Sigma\, X_i(t)\gamma_i \tag{3.1}$$

where EC(t) is total energy related carbon emissions in year t, $X_i(t)$is the consumption of fossil fuel i in year t, and γ_i is CO_2 emissions per unit of consumption for fossil fuel i. Note that under this approach EC(t) equals CO_2 emissions. For simplicity of exposition, we have omitted the regional designation, but that is incorporated in the actual calculations.

Next, recall the production function from equation (2.3) in the last Part.

$$Q_J(t) = \Omega_J(t)\ A_J(t)\ K_J(t)^{\gamma}\ L_J(t)^{1-\gamma-\beta_J(t)}\ E_J(t)^{\beta_J(t)}\ -\ p^E{}_J(t)\ EC_J(t)\ -\ p^B(t)\ B_J(t)$$

For simplicity, we suppress for now the regional subscripts and collect all the non-energy terms into a constant term k(t), yielding:

$$(3.2) \qquad Q(t) = k(t)\ EC(t)^{\beta(t)} - p^E(t)\ EC(t) - p^B(t)\ B(t)$$

Note that the elasticity of output with respect to carbon-energy, $\beta(t)$, varies over time.

To complete the model, we need to calibrate by calculating the carbon-energy share [$\beta(t)$] and the price of carbon-energy [$p^E(t)$]. This is done for the first period by finding the parameters of the production function which match the flows of output and carbon-energy and which match the estimated change in carbon-energy use from a change in the price of energy. Values of β and p^E are described elsewhere in this part.

To obtain the calibration, we derive two auxiliary equations. The first of the calibration conditions is determined by the first-order conditions for profit maximization. To obtain this, note that output is maximized when

$$\partial Q(t)/\partial EC(t) = 0 = \beta(t)k(t)EC(t)^{\beta(t)-1} - p^E(t)$$

which yields

$$(3.3) \quad EC(t) = \{p^E(t)/[\beta(t)k(t)]\}^{1/[\beta(t)-1]}$$

The second calibration condition determines the markup between the wholesale and the retail price of carbon-energy. The markup (which differs among regions) is given by:

$$(3.4) \quad p^E{}_J(t) = q(t) + \text{markup}^E{}_J(t) + \tau(t)$$

We have included the regional superscript J to indicate which of the different terms differ among regions. $p^E{}_J(t)$ is the retail price of carbon-energy in region J, q(t) is the global price of carbon-energy, and $\text{markup}^E_J(t)$ is the regional markup. The markup includes transportation, distribution, and taxes. (If taxes are interpreted as Pigovian taxes to reflect externalities, then the markup is appropriately included in a welfare analysis.) To determine the calibration, we measure the impact of imposing a carbon tax on demand for carbon-energy as follows:

In the baseline, we assume that $\tau(0) = 0$. To calibrate the model, we measure the impact of an imposition of a carbon tax of $\Delta\tau(0)$ in the first period on demand for carbon-energy as follows (omitting the regional subscripts for simplicity)

(3.5) $$\Delta EC(0)/\Delta\tau(0) = EC(0)/\{ p^E(0)[\beta(0)-1]\}$$

(3.6) $$\chi(0) = \Delta EC(0)/\Delta\tau(0)$$

Equations (3.5) and (3.6) require some discussion. The purpose of these equations is to use existing information on energy-use response to calibrate the equations for carbon-energy. Equation (3.5) is simply the implication of the assumption of output maximization. It states that the impact on carbon-energy of carbon-energy price changes or of carbon tax changes will be equal to the term on the right-hand side of (3.5). Equation (3.6) then defines the parameter $\chi(0)$ as the change in carbon-energy use divided by the carbon price change caused by the tax.

The model is calibrated in two steps. First, the value of $\chi(0)$ is determined using auxiliary information on fossil-fuel demand elasticities, prices, consumption, and carbon coefficients assuming $\Delta\tau(0) = \$50$ per ton. Second, using the value of $\chi(0)$ calculated in (3.6), we can then solve for the two unknowns, $\beta(0)$ and $p^E(0)$, from equations (3.5) and (3.6).

To recapitulate: Output and carbon-energy use are obtained from the data; $\chi(0)$ is obtained from the auxiliary information on the impact of higher prices on energy use; and $\beta(0)$ and $p^E(0)$ are obtained from the solution of (3.3), (3.5), and (3.6).

The intuition behind this approach is the following. The elasticity $\beta(0)$ is chosen so that the model's estimated emissions equal the actual emissions in the initial period. The price of carbon $[p^E(0)]$ is set so that the responsiveness of emissions to a carbon tax in the RICE model agrees with that of a disaggregated model.

2. Data sources for calibrating the energy sector

Industrial carbon-dioxide emissions. Data on total industrial carbon emissions were obtained from CDIAC (Carbon Dioxide Information Analysis Center) of Oak Ridge National Labs, US Department of Energy.

Energy consumption. The different energy fuels [$X_i(t)$] are non-electric coal consumption, non-electric natural gas consumption, electricity consumption, and consumption of petroleum products. Electricity consumption data come from *International Energy Annual 1996*, published by the Energy Information Administration (EIA) of the US Department of Energy. Fuel shares for electricity were derived using EIA's World Energy Projection System, 1997 version. Data for total coal and natural gas consumption are taken from *International Energy Annual 1996,* and non-electric coal and natural gas consumption were calculated as the difference between consumption in electricity and total consumption. Petroleum products consumption data come from *International Energy Annual 1995*.

Energy prices. Estimating the response of carbon emissions to changes in energy prices and carbon prices in equations (3.5) and (3.6) requires price data on each energy source. Data on electricity prices, petroleum product prices, coal prices, and natural gas prices were obtained from the EIA home page; *Energy Prices and Taxes*, various issues (published by the International Energy Agency of the OECD); World Bank technical paper #248, *A Survey of Asia's Energy Prices*; and *International Energy Annual*, various issues.

Price elasticities: After a review of econometric literature, price elasticities of demand for all energy sources were assumed to be 0.7 in OECD countries and 0.84 in the rest of the world.

Carbon emission factors. Carbon coefficients for individual fossil fuels and petroleum products are available from a variety of publications of the Department of

Energy, Energy Information Agency.[6] The carbon coefficient for electricity is the sum of the carbon coefficients of individual fossil fuels weighted by their fuel share in electricity, adjusted for the efficiency of conversion of the fossil fuel into electricity.

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[6] See EIA [1996].

D. **Carbon supply**

The new RICE model contains a revised treatment of energy supply. In the original DICE/RICE models, carbon-energy supply was implicitly treated as inexhaustible. Although this was a realistic approach for the next century, it raised two major questions for the longer run. First, to the extent that limitations on carbon energy supplies were relatively limited, this would put significant constraints on the potential total emissions and therefore on global warming over the longer run. In particular, some of the "scare stories" put forth by William Cline and others, foreseeing the potential for a 10 ºC long-run warming, are definitely inconsistent with a situation of relatively limited coal supplies.

Second, and more interesting from an economic point of view, is the interaction between limited supplies and pricing. To the extent that the carbon-energy supply curve is relatively inelastic, carbon-energy prices would rise sharply as energy supplies were exhausted. This would lead to rising scarcity prices (known as Hotelling rents) on carbon energy fuels. To some extent, the rising Hotelling rents would substitute for carbon taxes, and the goals for climate policies would thereby be accomplished by energy scarcity. In other words, the presence of coal-supply limits leads to the likelihood that some of the carbon tax will be shifted backwards to suppliers rather than to consumers. This backwards shifting occurs to the extent that supply is price-inelastic. Indeed, in the limiting case of perfectly inelastic supply and energy with zero extraction costs, carbon taxes would have no economic effect at all and would simply redistribute rents from the resource owners to the government.

Because of this important interaction between energy supplies and climate-change policy, the new RICE model includes a simple supply relationship for carbon-energy. We now describe this sector. The major assumption concerning energy supply follows the methodology of the last section by aggregating energy into a single carbon-energy input. For these purposes, this input can usefully be considered as coal, which is both the most abundant fossil fuel and has the predominant fraction of carbon that is potentially emitted. We assume that carbon-energy has limited supply with the supply curve becoming near-vertical when cumulative extraction reaches 6000 billion metric of tons

(6000 GtC) of carbon (approximately 10,000 tons of coal-equivalent energy). The marginal cost is relatively flat until cumulative extraction is 3000 GtC of carbon, but it quadruples (to about $500 per ton of carbon-energy) when cumulative extraction reaches 5000 GtC. We draw upon studies by Rogner [1997] for both estimates of the total quantity and for the cost function for carbon-energy.

The first relationship is simply the accounting for cumulative energy use:

(2.8) $CumC(t) = CumC(t-1) + 10\ EC(t)$

where CumC(t) is the cumulative production of carbon-energy at the end of period t and EC(t) is current production of carbon-energy.

The major relationship is the cost function of carbon energy. We assume that there is a maximum economically extractible amount of carbon energy, CumC*. We then assume that the marginal-cost curve for carbon energy takes the following form:

(2.9a) $q(t) = \xi_1 + \xi_2[CumC(t)/CumC^*]^{\xi_3}$

The numerical form of this equation in RICE-98 is

(2.9a') $q(t) = 113 + 700[CumC(t)/6000]^4$

The energy-supply relationship in equation (2.9a) and (2.9a') requires further discussion. To begin with, carbon-energy is assumed to be a global commodity, and its wholesale price, q(t), is determined on world markets. The cost of carbon-energy has two terms. Carbon-energy supplies are estimated to be 6000 GtC of carbon. The first term ($\xi_1 = 113$) is the marginal cost that is independent of exhaustion. This term represents the costs of current extraction today. The second term is a rising cost function. At current levels of cumulative extraction [CumC(1995) = 0], the second term is zero. It is extremely convex, with an exponent of 4, reflecting the finding that the cost function for carbon fuels is relatively elastic in the near term.

The shape of the function is shown in Figure 3-6. When half of exhaustible resources are used, the marginal cost of carbon energy rises from \$113 to \$157 per ton of carbon. Carbon energy becomes increasingly costly as the limits of resources are reached.

Actual energy use can be supplied by a backstop technology:

(2.9b) $E_J(t) = EC_J(t) + B_J(t)$

Hence, total energy inputs, $E_J(t)$, are the sum of carbon-energy, $EC_J(t)$, and backstop energy, $B_J(t)$. In the RICE-98 model, the price of backstop energy is taken to be \$300 per ton of carbon (before the markup). The basic assumption is that there are sources of carbon removal (such as carbon scrubbing or carbon sequestration in trees) that can be undertaken in large scale but at a relatively high price. These are assumed to be substitutes for carbon fuels at the wholesale level, and therefore are calculated with the markup. An alternative interpretation is that a non-carbon fuel is introduced that is a perfect substitute for carbon fuels. The assumption about the production costs is highly speculative because of the lack of experience with carbon removal and the absence of a large-scale substitute. However, there are many potential candidates that would be attractive at the assumed price.

Finally, there are a number of “flow” constraints that prevent the economy from flipping too quickly from one technology to another.

(3.7) $EC_J(t) \geq 0.75\ EC_J(t-1)$
(3.8) $B_J(0, J) = 0$;
(3.9) $B_J(t+1,J) \leq .005 + 1.5\ B_J(t, J)$

Equation (3.7) states that carbon-energy use cannot decline faster than 25 percent per decade. This reflects the cost of changing capital stocks too quickly. Equation (3.8) constrains the backstop to zero in the initial period. Equation (3.9) puts a limit on the first introduction of the backstop technology to a total of 5 million metric tons of carbon displaced in the decade of first introduction; additionally, the rate of growth of the backstop technology is 50 percent per decade in addition to a small increment. None of these equations is important for the first century, but they add continuity to the solution.

E. **The Impacts of Climate Change**

1. Introduction

Sensible policies on global warming should weigh the costs of slowing climate change against the benefits of slower climate change. Ironically, recent policy initiatives, such as the Kyoto Protocol of 1997, have been introduced without any attempt to link the emissions controls with the benefits of the lower emissions. In part, the decoupling of policy from the benefits of the policies comes because many environmental advocates are skeptical of the use of cost-benefit analysis. However, at a deeper level, even economists are troubled by the lack of clear and convincing estimates of the impacts and of the prospect that global warming may trigger unpredictable and potentially catastrophic impacts.

The present section discusses a new set of estimates of the economic impacts of climate change. While the literature in this area is extensive, there are many gaps in coverage of sectors and countries. While building on the existing literature, it is recognized that many of the most important impacts have not been satisfactorily quantified and monetized. Notwithstanding the imprecision of the estimates, it is essential that impacts be considered in the climate-change debate if costs and benefits are to be balanced.

Estimation of climate-change impacts in most integrated assessment models examined a wide variety of estimates of the damage from climate change in different sectors for different regions. Starting with Nordhaus [1990a , 1991a], assessments tended to organize impacts of climate change in the framework of national economic accounts, with additions to reflect non-market activity. These first-generation impact studies for the United States were summarized in the IPCC survey and are shown in Table 3-10. Most estimates find monetized damages of for the United States (at current economic structure) to lie between 1 and 1½ percent of GDP. Other surveys provide estimates of the impacts for other regions and for the world (see especially the survey in IPCC [1996c]).

Four points are worth noting about the first-generation studies. First, there is a deceptive degree of consensus to the estimates. They add up to quite similar amounts, but the details are highly divergent. Second, many of the earliest estimates (particularly those for agriculture, sea-level rise, and energy) were extremely pessimistic about the economic impacts, whereas more recent studies, which include adaptation, do not paint such a gloomy picture.[7] Third, coverage of regions outside the United States is extremely sparse. There is very little serious work on major regions of the globe, such as China, India, or Africa; this is particularly troubling because the impacts of climate change may well be largest in those regions. Finally, and most important, many of the most important concerns about global warming, particularly the concern with catastrophic risk, have not been adequately studied.

In reviewing the first generation results, it is clear that the results of the regional climate models and the estimated impacts were so conjectural that it has continued to be difficult to make solid estimates of the impacts of climate change. Of all the sectors, only agriculture and sea-level change have made significant progress in estimating climate-change impacts on a detailed regional level. In some areas, such as ecosystems and human health, the difficulties are particularly grave because of enormous uncertainties about the underlying physical and biological impacts and the potential for adaptation. For concerns such as ecosystems, valuation is extremely difficult, while there are no established methodologies for valuing catastrophic risks.

2. Present approach

This review summarizes the approach taken to estimate the impacts of climate change. The complete description is given in Nordhaus [1998c]. The approach follows first-generation approaches by analyzing impacts on a sectoral basis. There are three major differences from many earlier studies. First, the approach here focuses more sharply on developing-country estimates. This focus is obviously necessary both because global warming is a global problem and because of a common view that impacts are

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[7] See particularly the study by Darwin et al. [1995] on agriculture, by Rosenthal et al. [1994] on energy, and by Yohe and Schlesinger [1998] on sea-level rise.

likely to be significantly larger in poorer countries. Second, this study focuses more heavily on the non-market aspects of climate change because of the finding of the first-generation studies that the impacts on market sectors outside of agriculture are likely to be relatively limited.

The final difference from earlier studies is that the present approach relies on a *willingness to pay* (or WTP) approach to estimating the value of preventing future climate change. This approach is taken because the author believes that comprehensive regional estimates of impacts are unlikely to be available in the near future. Moreover, scholars are gravitating toward the view that it is the *risks* that are the major cause for concern about future climate change. The WTP estimates measure the estimated "insurance premium" that different societies are willing to pay to prevent climate change and its associated impacts. The advantage of the WTP approach is that it can encompass different approaches to measuring impacts (including surveys as well as statistical impact measures).

This study estimates damages for thirteen different regions. Table 3-11 shows the current mean annual temperature of the ten regions. For these, we have provided both area weighted and population weighted climates. The differences between these two concepts are particularly dramatic for countries like the U.S., Canada, and Russia.

In estimating impacts, we have divided the potential areas of concern into seven categories:

- Agriculture
- Sea-level rise
- Other market sectors
- Health
- Non-market impacts
- Human settlements and ecosystems
- Catastrophic

The general methodology is as follows. For each region j, we estimate the willingness-to-pay (WTP) for a base year, usually the present time. These estimates are based on the present economic, social, and political structure and impose a hypothetical climate change on that structure. We call this impact "the impact index," denoted by $\theta_{ij}(t)$ for the ith component of impacts in the jth region according to economic and social structure of year t (say, t = 1995). Taking U.S. agriculture as an example, $\theta_{agriculture,US}(1995)$ is estimated to be a damage of $3.9 billion or 0.065 percent of U. S. GDP. We take into account future structural change in the economy by assuming that the impact will increase or decrease with the rise in per capita income in the region. The impact of changing income on vulnerability is provided by the impact elasticity, η_i for sector i. We assume that the income elasticity depends upon the per capita income in a particular region. Hence, let $y_j(t)$ be the level of per capita GDP in region J in a given year. Then the vulnerability in region J from component i is:

$$\theta_{ij}(t) = \theta_{ij}(1995) \times [y_j(t)/y_j(1995)]^{\eta_i}$$

For example, we assume that the impact elasticity of agriculture is -0.1 based on the declining share of agriculture in output as per capita output increases. Under this assumption, if U.S. GDP per capita income doubles, the impact elasticity will decline from 0.065 percent to 0.061 percent of GDP.

To benchmark the damage estimates, we take the estimated damages for a 2.5 °C rise in global mean temperature relative to 1900. According to the base run of the RICE-98 model, this will occur around 2110. We therefore benchmark the damage estimates to projections of the change in per capita income over the period 1995-2110.

We present in this report only the summary estimates. The details for the sectors are regions are given in the background paper.

3. Major results

The global damage function is shown in Figure 3-7. The two curves show the damage function with 1990 population weights and with weights of projected 2100 regional outputs. The results for individual regions are shown in Table 3-12. The regional damage functions are shown in Figure 3-8.

The results differ markedly by region. The estimated damages from a 2½ ºC warming range from a net benefit of 0.7 percent of output for Russia to a net damage of almost 5 percent of output for India. The global average impact of a 2.5 ºC global warming is estimated to be 1.5 percent of output using 2100 output weights and 1.9 percent of output using 1995 population weights.

We estimate that Russia and other high-income countries such as Canada will benefit slightly from a 2.5 ºC benchmark warming; the benefits to these regions come because of significant improvements in the agricultural sector as well as gains from nonmarket time use. At the other extreme, low income regions — particularly India and Africa — and Europe appear to be quite vulnerable to climate change. The impact on India comes from its extreme vulnerability to climatic shifts because of the importance of monsoons on agriculture, the disamenity of increasing temperatures on nonmarket time use, as well as the potential for adverse health impacts. For Africa, much of the vulnerability comes from potential health impacts of global warming. Europe appears to be the most vulnerable of high-income regions because of the potential of catastrophic climate change due to shifts in ocean currents as well as significant coastal and agricultural impacts.

The United States appears to be less vulnerable to climate change than many countries. This is the result of its relatively temperate climate, small dependence of its economy on climate, the amenity value of a warmer climate, advanced health system, and low vulnerability to catastrophic climate change.

Our estimates indicate that market impacts are likely to be relatively small; the major concerns are the potentially catastrophic impacts. According to the estimates presented in Table 3-13, the catastrophic impacts are about 1 percent of output for a 2.5 ºC warming but rise sharply to about 7 percent of output for a 6 ºC warming. Because the estimated catastrophic impacts are so uncertain, this implies great uncertainty about the overall impacts.

A word of caution is necessary before closing. It must be emphasized that attempts to estimate the impacts of climate change continue to be highly speculative. Outside of agriculture and sea-level rise for a small number of countries, the number of scholarly studies of the economic impacts of climate change remains vanishingly small. Estimates of the regional climatic impacts of global warming are still inconsistent across different climate models, and economic studies have made little progress in estimating impacts, particularly in low-income countries. Much more work is needed to improve our understanding of the impacts of climate change.

F. **The Carbon Cycle and Other Radiative Forcings**

An important part of the DICE/RICE-98 models is integrating the economic sectors with physical world. Greenhouse-gas emissions affect the carbon cycle as well as other atmospheric trace gases, change the radiative balance of the atmosphere, affect climate, and then feed back to affect human societies and natural ecosystems. One of the most difficult features of developing integrated assessment models like the DICE or RICE models has been to uncover parsimonious relationships between economic activity and climate change. Economists are accustomed to relying on highly simplified representations of economic relationships (such as the much-loved Cobb-Douglas production function), and this approach has proven fruitful in understanding phenomena ranging from business cycles to economic growth. In developing the geophysical sectors of the original DICE model, the appropriate macrorelationships need to be developed. This section describes the model used for the carbon cycle and other radiative forcings.

The use of highly simplified aggregate relationships is motivated on three grounds. First, an understanding of the interaction of economy and climate is advanced if the underlying structure is as simple and transparent as possible; complex systems cannot be easily understood and erratic behavior may well arise because of the interaction of complex relationships. Second, because most of the relationships in the DICE/RICE models are poorly understood, we will devote considerable attention in later Parts to sensitivity analysis and an analysis of the cost of our ignorance. The larger the model, the more difficult it is to undertake comprehensive sensitivity and uncertainty analysis. Finally, from a computational point of view, the RICE model is already straining at the computational capacity of readily available software packages that can be used on personal computers, and we have set as a goal the construction of a model that can be easily used by other researchers. In modeling, small is genuinely beautiful.

To include more sectors of the economy, more layers of the ocean, more greenhouse gases, more energy resources — each of these would reduce transparency, impair the ability to conduct sensitivity analyses, and place the model outside the envelope of current computational feasibility. Apologies are extended to those who feel that their discipline has been violated; along with the apologies goes an invitation to help improve our understanding by providing better parsimonious representations of the crucial geophysical or economic processes.

This section discusses modifications of the treatment of different greenhouse gases (GHGs) and of the carbon cycle in the DICE-98 model. Three major changes in the science and policy of greenhouse gases are incorporated in the DICE-98 model.

> (1) In the original DICE model, CO_2 was aggregated with chlorofluorocarbons (CFCs) to create a CO_2-equivalent stock of GHGs. Since that time, the CFCs have been largely phased out in most high-income counties, and the projected radiative forcings from CFCs is consequently drastically lower than was projected in the early 1990s. Therefore, the RICE/DICE-98 models treats only CO_2 as an endogenous GHG.
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> (2) The original DICE model used an empirical approach to estimating the carbon flows, relying on long-term estimates of emissions and concentrations. A number of commentators have noted that this approach may understate the long-run atmospheric retention of carbon because it assumes an infinite sink of carbon in the deep oceans. The DICE/RICE-98 models therefore replace the earlier treatment with a structural approach that uses a three-reservoir model calibrated to existing carbon-cycle models.
>
> (3) Over the last decade, climatologists have concluded that sulfates are contributing significant radiative cooling. The DICE/RICE-98 models therefore revise the treatment of exogenous greenhouse gases by including projections of sulfate cooling with the positive forcings from other greenhouse gases.

The first section that follows discusses the structure of the carbon cycle in the RICE-98 model. The next section discusses the calibration of the new carbon model, after which estimates of the radiative forcing from other greenhouse gases are discussed.

1. A Revised Approach to the Carbon Cycle

In the original DICE model, the carbon cycle was estimated from time-series data on CO_2 emissions and concentrations. Several commentators noted that this approach may understate the long-run atmospheric retention of carbon because it assumes an infinite sink of carbon in the deep oceans. While this approach is reasonable for projections for the short run, it will provide misleading estimates of long-run concentrations. This point was emphasized in a contribution by Schultz and Kasting (S-K).[8] They indicate that the long-term projections in the DICE model significantly understate atmospheric concentrations of CO_2 .

In considering alternative approaches, it is desirable to have parsimonious representations, to have models that are structural (in the sense of reflecting solid scientific or economic underpinnings), and to rely on models whose essential findings are robust to changes in the specification. In the carbon cycle, the major tradeoff involved is whether complicating the model with a more elaborate specification will produce more reliable results. Initial experiments with the DICE model, confirmed for the present analysis, suggest that current policy is largely unaffected by using a more elaborate specification in the base case. On the other hand, if the analyst is interested in long-run projections or if lower discount rates are used, the original DICE specification can be quite misleading. Because the alternative specification is relatively straightforward, we have adopted it for the RICE-98 model.

The new treatment uses a structural approach with a three-reservoir model calibrated to existing carbon-cycle models. The basic idea is that, albeit vast, the deep oceans provide a limited sink for carbon in the long run. In the new specification, we assume that there are three reservoirs for carbon — the atmosphere, a quickly mixing reservoir in the upper oceans and the short-term biosphere, and the deep oceans. Each of the three reservoirs is assumed to be well mixed in the short run, while the mixing between the upper reservoirs and the deep oceans is assumed to be extremely slow.

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[8] See Schultz and Kasting [1997].

We assume that CO_2 accumulation and transportation can be represented as a linear three-reservoir model. (The model pertains only to CO_2 as other GHGs are taken as exogenous.) Let

$M_i(t)$ = total mass of carbon in reservoir i at time t (billions of metric tons of carbon, or GtC)

ϕ_{ij} = the transport rate from reservoir i to reservoir j

The reservoirs are AT = atmosphere, UP = all quickly mixing reservoirs (the upper level of the ocean down to 100 meters and the relevant parts of the biosphere), and LO = deep oceans.

The major assumptions about the dynamics are the following: First, we assume that the carbon cycle was in equilibrium around 1750. Second, we assume that all emissions are into the atmosphere. Third, there are assumed to be no flows between the atmosphere and the deep ocean.

The dynamics of our system are as follows:

$$(3.10)\quad M_{AT}(t) = 10 \times E^C(t) + \phi_{11} M_{AT}(t-1) - \phi_{12} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1)$$

$$(3.11)\quad M_{UP}(t) = \phi_{22} M_{UP}(t-1) + \phi_{12} M_{AT}(t-1) - \phi_{21} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1) - \phi_{23} M_{UP}(t-1)$$

$$(3.12)\quad M_{LO}(t) = \phi_{33} M_{LO}(t-1) - \phi_{32} M_{LO}(t-1) + \phi_{23} M_{UP}(t-1)$$

where ϕ_{ij} is the transfer coefficient from reservoir i to reservoir j in each period. (Note that the timing in the RICE model has a built in lag. Hence, the stock of carbon in period t+1 reflects the emissions in period t. The interpretation is therefore that the carbon stock is measured at the beginning of the period. The temperature also has a one-period lag.)

2. Calibration

In this section, we describe the calibration of the model in equations (3.10) - (3.12). In the original DICE model, the short-run coefficients were estimated from time-series data and the long-run coefficient was derived from estimates of the adjustment time of the deep oceans.

Schultz and Kasting [1997] show that the approach in the original DICE model significantly underestimates long-run atmospheric concentrations. The RICE-98 model therefore modifies the original DICE model using the three-reservoir approach laid out above and calibrates it to the Bern carbon cycle model with a neutral biosphere.[9]

More precisely, the estimates are derived as follows. We assume that the reservoirs were in equilibrium in "pre-industrial times."[10] For the baseline calibration, we take estimates of the impulse response function from the Bern model for 20, 40, 60, 80, and 100 years. Because of non-linearities in the response, we calibrated the model for a concentration of two times pre-industrial levels. We then choose the parameters ϕ_{12} and ϕ_{23} and the effective initial mass of the upper stratum to minimize the squared deviation of the RICE model impulse response function and that in the Bern model. The RICE parameterized model fits extremely well over the period of fit of 100 years. The average absolute error in the RICE specification is 0.5 percent of the value in the Bern model.

The model then incorporates an active biosphere as follows. According to IPCC [1996a], the mass of carbon in the terrestrial biosphere in 1985 is 2190 GtC, of which 610 GtC is vegetation. We assume that only the vegetation responds to elevated atmospheric carbon, and that the elasticity of biomass in vegetation with respect to atmospheric concentrations of carbon is 0.5 (this being the so-called beta factor). We assume that the biosphere is neutral in the long run and therefore adjust the masses in the different reservoirs to ensure this constraint. Finally, we assume that half the oceans are so poorly mixed that they are unavailable for carbon absorption. After all adjustments, this implies

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[9] See IPCC [1996a], p. 86.

[10] By pre-industrial times, we mean the year 1750.

that the effective masses in the atmospheric, upper reservoir, and lower reservoir in pre-industrial times are calibrated to be 583, 705, and 19,200 GtC.

The transfer rates are 0.333 per decade from the atmosphere to the upper reservoir and 0.115 per decade from the upper reservoir to the lower reservoir. These figures imply a relatively small upper layer of the ocean with a relatively rapid transfer from that to the lower oceans. Carbon-cycle studies have found that carbon exchanges with a 800-year adjustment time between the upper reservoir and the lower reservoir, but that is usually estimated with a much larger upper ocean.[11]

The response functions to pulse inputs of carbon are shown in Figure 3-9. As can be seen, the RICE-98 model with a neutral biosphere fits the Bern model very closely (these are the line and the squares at the top). The solid circles at the bottom show the RICE-98 model with the active biosphere, while the diamonds show the DICE-94 model. The figure shows how the original DICE model tends to underpredict atmospheric concentrations in the long run. The major uncertainty in the carbon cycle, however, is probably the extent to which the biosphere will continue to take up a substantial fraction of cumulative emissions.

Figure 3-10 compares the projections of CO_2 concentrations over the period 1990-2100 using the IPCC-92a emissions trajectory with the Bern and RICE-98 models. The RICE model tends to overpredict emissions over the next century, in part because of the simpler structure and in part because it was calibrated to the higher CO_2 concentrations, which implies a higher atmospheric retention in the near term.

3. Other greenhouse-gas emissions

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[11] This study uses “adjustment time” in the sense of “e-folding time” used in the physical sciences. This concept originates from the dynamics of processes which experience exponential decay. Suppose that a process evolves according to $dx(t)/dt = -\delta x(t)$. Starting in equilibrium with $x(0) = 0$, say there is a shock of ϵ to x at $t = 0$, so $x(t) = \epsilon \exp(-\delta t)$. Therefore, when $t = 1/\delta$, x has declined to $x(t) = x(0)/e = \epsilon/e$. Hence the "e-folding time" is the time for the solution to decay to $1/e = 0.37$ of its original value after a shock.

The RICE model considers primarily greenhouse warming from carbon dioxide. Although there are large uncertainties involved, the total net radiative forcings of non-CO_2 greenhouse gases in 2100 are currently believed to be an order of magnitude smaller than those for CO_2 . Moreover, the policy instruments available to affect other gases other than the CFCs are very poorly understood at the present time. Because of their relatively small importance and the absence of clear policies to affect them, other GHGs are assumed to be exogenous in the RICE-98 model. Table 3-13 shows the assumptions about the radiative forcings of non-CO_2 greenhouse gases.

G. The climate module

Climate modelers have developed a wide variety of approaches for estimating the impact of rising GHGs on climatic variables. The models typically taken to be the most satisfactory are the large general circulation models (GCMs). These require several hundred hours of supercomputer time simply to perform a simulation, and inclusion of these in an optimization model of the kind described here is infeasible.

To develop integrated models of climate and the economy, it is necessary to have a relatively small model that links GHG concentrations and the major climatic variables. We have chosen to include only the impact of GHGs on global mean temperature in the RICE-98 model. Although this analysis focuses primarily upon globally averaged surface temperature, it is recognized that this variable is not the most important for impacts. Variables like precipitation or water flows -- along with extremes of droughts, floods, and freezes -- are more important for economic activity than is average temperature alone. Mean temperature is chosen because it is a useful *index* of climate change that tends to be associated with most other important changes. In the language of statistics, temperature is likely to be a "sufficient statistic" for the other variables that have an important impact upon human and natural societies. This point can be seen in surveys of GCMs — in which the estimated impact of CO_2 doubling on mean temperature is highly correlated with the impact on precipitation.

The approach taken in the RICE model uses that developed in the original DICE model. This uses a simplified "minimodel" to represent the basic dynamics of climate change. It then uses larger models to calibrate the major parameters of the minimodel. It must be emphasized that this representation is highly simplified and is intended only to depict the broad features of climate change.

The description of the climate model will be extremely abbreviated because the specification used here is identical to that used in the original DICE model. No changes in climatology or GCM models have appeared that would lead to revisions in either the specification or the parameters of the model.

The climate system is represented by a multi-stratum system, including an atmosphere, an upper-ocean stratum, and a lower-ocean stratum. The system has an atmosphere that is warmed by solar radiation and is in short-run radiative equilibrium. The atmosphere exchanges energy quickly with the upper oceans, which impose a certain amount of thermal inertia on the system because of their heat capacity. The upper stratum of the ocean also exchanges water with the lower stratum, representing the deep oceans, and the rate of heat transfer is proportional to the rate of water exchange. This model is a box-advection model, which is simpler to include in economic models than the mixed box-advection and upwelling-diffusion approach that is widely used in medium- and large-scale models today. The two state variables in the two-equation model are the globally averaged surface temperature and the deep-ocean temperature.

The approach here follows closely the model developed by Schneider and Thompson [1981]. There are two strata — one being the atmosphere and the mixed upper stratum of the oceans, and the second being the deep oceans. Each of the two strata is assumed to be well mixed. The accumulation of GHGs warms the atmosphere, which then mixes with and warms the upper ocean, which in turn heats the deep oceans. The lags in the system are primarily due to the thermal inertia of the two strata. The equations of the model are

$$T_{UP}(t) = T_{UP}(t-1) + \sigma_1\{F(t) - \lambda T_{UP}(t-1) - \sigma_2 [T_{UP}(t-1) - T_{LO}(t-1)]\} \tag{2.12a}$$

$$T_{LO}(t) = T_{LO}(t-1) + \sigma_3[T_{UP}(t-1) - T_{LO}(t-1)] \tag{2.12b}$$

In this model, $(1/\sigma_1)$ represents the thermal capacity of the atmospheric layer and the upper oceans, $(1/\sigma_3)$ is the transfer rate from the upper level of the ocean to the deep oceans, σ_2 is the ratio of the thermal capacity of the deep oceans to the transfer rate from shallow to deep ocean. A key parameter in all models is λ, or the "feedback parameter." This parameter is a way of representing the equilibrium impact of CO_2 doubling on climate. By solving (2.12) for a constant T, it is easily seen that the long-run or equilibrium impact of a change in radiative forcing is $\Delta T/\Delta F = 1/\lambda$. We use the parameter T_{2xCO2} to represent the equilibrium impact of doubled CO_2 concentrations on global mean surface temperature. From (2.12), therefore, we have that $T_{2xCO2} = \Delta F_{2xCO2}/\lambda$, where

ΔF_{2xCO2} is the change in radiative forcing induced by a CO_2 doubling. The derivation of T_{2xCO2} is given in numerous sources.

For calibration purposes, we have examined three different models. (1) The first is the Schneider-Thompson approach [1981]. This study develops a two-equation model that is identical to equation set (2.12); it has the disadvantage of being highly simplified relative to larger models. To exploit the ST approach, we construct the model explicitly using the parameters developed in the original study. (2) The most completely developed model examined was a coupled atmospheric-ocean model developed by Stouffer, Manabe, and Bryan [1989]. This model is a highly disaggregated representation of both the atmosphere and the oceans and provides a transient calculation of the impact of slowly rising CO_2 concentrations. (3) A third model, much in the spirit of the approach used here, is a parametric representation of the Oregon State University model in a small model of the coupled atmospheric and six-layer ocean model developed by Schlesinger and Jiang [1990]. This model uses the larger model to determine the parameters of the smaller model and then uses the smaller model for calculating transient values over longer periods.

The three models gave similar trajectories. The original DICE and RICE models used the calibration of the SJ model because that appeared closest to that used by expert groups of the U.S. National Academy of Sciences and of the IPCC. This model has an equilibrium warming of $T_{2xCO2} = 4.1/\lambda = 2.91$ ºC for a CO_2 doubling, with an e-fold time for temperature of 30 years. A full discussion is contained in Nordhaus [1994d].

Figure 3-11 compares the projections of the RICE-98 model with the IPCC calculations in IPCC [1996a]. Each projection uses the radiative forcing estimated according to the IPCC92a scenario, as updated for other non-CO_2 forcings in IPCC [1996a]. The RICE-98 model lies above the IPCC primarily because the RICE model uses a temperature-CO_2 sensitivity of 2.9 ºC, as discussed above, whereas the IPCC run has a temperature-CO_2 sensitivity of 2.5 ºC.

* * * *

This concludes our presentation of the structure of the RICE-98 model. In the next part, we discuss the DICE-98 model, which is the simplified, globally aggregated version of the model. In the subsequent part, we apply the model to a number of interesting policy issues.

Part 4. The DICE-98 Model

This part presents the DICE-98 model. The DICE model is a highly simplified version of the RICE model. While losing the regional detail of the RICE-98 model, the DICE-98 model has several advantages. It is more useful for understanding the basic structure of economic policy issues posed by greenhouse warming because it is sufficiently small so that researchers can understand the individual linkages in an intuitive way. It is more easily modified because the number of parameters is much smaller. It is much faster, so that alternative experiments can be tested more easily. And it can be run much further into the future so that the implications of alternative time horizons, discounting assumptions, and carbon or climate models can be more easily traced out. Researchers or policy makers who are interested in having an intuitive understanding of the economics of global warming are well-advised to begin with the DICE model before tackling more opaque and computationally demanding models such as the RICE model or other large-scale models.

A. Model Structure

The basic structure of the DICE-98 model parallels the RICE-98 model in most sectors. The equations of the DICE-98 model are provided in Appendix Table A-2, while the computer code is provided in Appendix C. The major difference between the two models lies in the production sector, where the reduced form approach of the original DICE-94 model has been retained. More specifically, the major elements of DICE-98 are the following:

- The geophysical sectors in DICE-98 are identical to the RICE-98 model. The reason is that the carbon cycle, radiative forcing, and climate equations are globally aggregated, so there is no reason to differentiate between the RICE and DICE models in these segments.

- The treatment of the pure rate of time preference is identical for the RICE and DICE models.

- The modeling structure for population, economy-wide technological change, labor inputs, investment, and the capital stock are identical. The only difference is that the DICE model represents the globally aggregated magnitudes, while the RICE model considers each of these variables separately for each region.

- The damage equation takes the same form in the RICE and DICE models. The DICE model damage function represents the globally averaged damages from climate change.

- The major difference between the two models lies in the treatment of production and carbon emissions. The RICE-98 model introduces a more complete model of the energy sector, with an input we call “carbon-energy” that equals carbon emissions; the DICE-98 model sticks with the simplified reduced form treatment of production. More precisely, the DICE model begins with a Cobb-Douglas production function in labor, capital, and endogenous technological change. Industrial carbon emissions are given by the product of a carbon-intensity factor [$\sigma(t)$] times gross output. Net output is then gross output times a factor that is a function of the emissions control rate and the damages from climate change. We then calibrate the parameters of the output equations to match the trajectory of the RICE-98 model.

- The final difference between the two models is the energy supply sector. In the RICE-98 model, we introduce an explicit supply of carbon-energy, including both limitations on carbon fuels and a backstop technology. In the DICE-98 model, we remove all constraints on total use of carbon fuels. In other words, there are no limits on either cumulative carbon emissions or on the rate of change of emissions in the DICE-98 model.[12]

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[12] Carbon emissions limits cannot be easily introduced in the DICE framework because of the reduced-form treatment of emissions reductions. Substitution away from carbon fuels occurs only when the emissions-reduction (“miu”) function is allowed to take non-zero values. The base case constrains miu to be zero. Scarcity-induced (as opposed to climate-policy-induced) substitution away from carbon fuels cannot be incorporated in this framework. Test runs using the standard version of DICE-98 indicate that there is no substantial impact of scarcity of carbon fuels for over 100 years. More precisely, if limited carbon emissions paralleling those in the RICE model are introduced in DICE, a small Hotelling rent on carbon fuels will come into play. The calculated Hotelling rent on carbon fuels is about $0.05 per ton carbon in 2000 and around $2 per ton carbon in 2100. This is suppressed in the DICE model, leading to slightly higher

In summary, DICE-98 is very similar in structure to the original DICE model, and those who are familiar with the earlier model will find that the new DICE version requires little learning time and is easy to use and manipulate. The major changes are recalibration to fit the new findings of the larger and presumably more accurate economic structure of the RICE-98 model as well as the other minor changes in specification of different sectors.

B. Calibration

The DICE-98 model was calibrated to fit the output of the RICE-98 model. Because of the highly divergent patterns of regional development, the fit between the two models was imperfect, so there will be differences in the answers for different period. The following explains the approach to calibration.

Population, the carbon-output ratio, the initial capital-output ratio, and economy-wide technological change are exogenous variables in the DICE model. These were determined to match initial the real interest rate as well as the path of global population, global output, and global temperature.

More precisely, the model was first calibrated for the base (no control) run. Population was calibrated so that it closely matched the path of aggregate population in the RICE model. Next the initial capital stock was calibrated so that the initial real return on capital was equal to the weighted average real rate of return in the different countries. Next, the initial level, initial growth rate, and decline in the growth rate of total factor productivity were set to match the initial level of output, the average output level in the first four periods, and the average output level in the first eleven periods.

Next, the level of the initial carbon-output ratio was set so that emission in the first period matched actual emissions. Then, the decline in the carbon-output ratio was set so that the path of global temperature in the DICE model tracked the RICE model. A comparison of the outputs of the DICE and RICE models are shown in Table 4-1. It can be

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emissions and climate change. The difference in global mean temperature between the carbon-constrained and carbon-unconstrained runs is however trivially small for two centuries— zero in 2100 and only 0.04 ºC in 2200.

seen that the major economic and environmental variables are very close in the baseline or no-control runs.

The damage function was the globally aggregated function, using regional outputs in 2100 as weights.

The cost function uses the same functional form as the original DICE model. The cost function takes the form $Cost(t)/Y(t) = [1- b_1(t)\mu(t)^{b2}]$, where $\mu(t)$ is the emissions control rate. The cost function is then calibrated so that it matches the abatement cost function in RICE-98. More precisely, the coefficients $b_1(t)$ and b_2 were calibrated by choosing parameters so that the cost-reduction schedule matched both the control rates and the carbon taxes that underlie the RICE-98 model. We can also compare the results with the estimates of the global cost of CO_2 abatement from the IPCC study (IPCC [1996c], p. 336. If we take the estimates from the IPCC as “data” and fit the cost function to the observations by non-linear least squares, we obtain an estimate of $b_1 = 0.062$. The estimate from the RICE model is 0.045.

C. Comparison of DICE and RICE models

Table 4-1 and Figures 4-1 through 4-5 compare the results of the RICE-98 and DICE-98 models. The table shows the ratio of the calculated values in the two models. All the baseline variables track quite closely. Emissions in the DICE model grow slightly less rapidly than in RICE over the next century, with 2100 emissions about 2 percent below the RICE values. CO_2 concentrations in 2100 diverge by 0.6 percent between the two models, and the global temperature increase in 2100 is 1.3 percent higher in DICE than DICE. However, the control rates and the carbon taxes diverge substantially, being about two-thirds higher in the DICE model in the initial period. The emissions-control rate falls in the DICE model relative to the RICE model (in absolute numbers, it rises less rapidly over time). The DICE carbon price is stable at somewhat less than twice the RICE carbon price. The major difference between the carbon prices in the two models comes because of the use of the global damage function in DICE rather than the regional damage function in RICE. In short, the calibrated DICE-98 model is a faithful reflection of the RICE-98 model except for the control rates and carbon taxes.

A final word will be helpful for those contemplating whether to use the RICE or DICE model as research tools. The DICE model is much easier to use and runs much more quickly. The two models track closely for the first 150 years, after which numerical approximations become a problem in RICE. For looking at longer-run tradeoffs, particularly those that do not involve regional analyses, DICE is a more accurate instrument and much easier to use. Problems can arise in either model when it is run too far outside the area for which it was designed and calibrated. For example, in DICE, increasing economic growth rates, population, or carbon intensities may increase total use of carbon fuels well beyond current estimates of availability; RICE contains an upward-sloping supply curve for fossil-fuels, and this constraint prevents excessive cumulative emissions. Caution should be taken to ensure that analyses using the models do not violate implicit assumptions used to simplify the model.

Part 5. Computational Procedures

A. The Solution Technique

We now describe the algorithm for finding the market solution in the RICE model. The technique we employ originates with T. Negishi [1960] and was discussed in Nordhaus and Yang [1996]. The theoretical basis for the algorithm is a theorem of T. 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.*[13]

What are the appropriate welfare weights? The initial or baseline state to which the model is calibrated is the market equilibrium, so the welfare weights should be determined in a fashion that reproduces existing economic conditions over space and time. This condition is chosen, it must be emphasized, not to advocate 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.

In early experiments, Nordhaus and Yang determined that allowing completely free flow of capital led to excessive international mobility. They therefore used 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. In this solution, carbon-emissions permits have equal prices in all regions in each time period (at market exchange rates).

The disadvantage of the time-dependent Negishi solution is that it requires equalization of rates of return across regions. That property is not desired in the current model, so we have introduced a different variant, the *first-period Negishi solution*. In this

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[13] A brief but illuminating discussion of the Negishi approach is in contained in Andreu Mas-Colell, Michael D. Whinston and Jerry R. Green [1995], pp. 630-31.

approach, intertemporal budget constraints are imposed on each region. In this solution, it is assumed that the intertemporal and interregional equilibrium leads to zero capital flows among regions. However, rates of return are not equalized. Hence, we set welfare weights to equalize the first period marginal utilities of income, but they then diverge depending upon income and interest rate movements in the different regions. (This approach leads to differential movements in relative prices of the outputs of different regions, as is explained in Part 2).

More precisely, we first solve the model with an arbitrary set of welfare weights equal to one in each region. We then reset the welfare weights for all countries according equation (5-1):

$$\phi^{J}(1) = [\psi^{J}(1)]^{-1} \tag{5-1}$$

In this equation $\phi^{J}(1)$ is the welfare weight of region J in period 1 and $\psi^{J}(1)$ is the marginal utility of income of region J in period 1. The algorithm based on (5-1) converges to a solution very quickly, and we use a single iteration to determine the welfare weights. The weights are chosen for the base case and are then held invariant across different runs to ensure no index-number issues arise.

B. Computational Experience

We discuss briefly the computational experience with the models. The RICE and DICE models are solved using a language and nonlinear programming system known as GAMS (General Algebraic Modeling System). The technique used is a nested two-level algorithm. The inner algorithm is a refinement of the standard primal simplex method for solving linear programming problems first developed by George Dantzig in the 1940s. The nonlinear constraints and objective function are solved with a reduced gradient and quasi-Newton method along with a projected Lagrangean algorithm due to S. M. Robinson. An introductory explanation to this is contained in Brooke et al. [1988].

In addition, the DICE model is available is a spreadsheet version (in Excel). The spreadsheet version is much more convenient for analysis and manipulation. However, the algorithm relies on Newton methods and does not guarantee convergence to the optimum.

Experience shows that computational errors (sometimes major errors in the solution) can occur, particularly when the number of variables to be optimized becomes large.

The models have been run using the PC version of the GAMS algorithm on various Pentium processors. A 40-period run of the DICE model in the GAMS program takes about 15 seconds using a Pentium 200 processor, while a 30-period RICE run takes about four hours. On a Pentium 450 processor, the 30-period RICE run takes about one hour, and the DICE model takes about 8 seconds. Numerical problems arise in the RICE model in calculating variables after the first 10 period (100 years), although those do not affect current values of policies.

For the RICE-model runs reported in the next part, we use a 20-period (200-year) horizon with transversality conditions on temperature and concentrations. Under these conditions, the numerical accuracy is adequate for the first century, with numerical accuracy to the third significant digit. Model users should attend to approximation errors and non-optimal solutions in the RICE model when the time horizon is longer than 20 periods. We have omitted transversality conditions in the DICE model as the time horizon is sufficiently long to ensure that the terminal conditions are irrelevant (unless the discount rate is lowered to close to zero).

Part 6. Major Results of the New Models

In this final part, we present the results of the RICE-98 model and discuss the most significant results.

A. **Alternative Policies**

In the discussion that follows, we analyze eight approaches to climate-change policy. The first is the uncontrolled or "laissez-faire" run in which there are no controls on greenhouse gases. This serves as a base case for comparison with other studies. The second is the "optimal" policy, a scenario in which greenhouse-gas controls are set so as to maximize the discounted value of the utility of consumption. The third is a scenario in which we wait ten years to implement policies so that our knowledge might be more secure.

The fourth and fifth policies focus on stabilizing emissions. The fourth policy relates to the Kyoto Protocol, agreed upon by nations in 1997, which focuses on the emissions of high-income countries. The fifth looks at policies that limit emissions at the global level — one at the 1990 rate of emissions and the other at 80 percent of the 1990 emissions rate. The sixth proposal is to undertake geoengineering. The seventh and eighth policies limit greenhouse-gas emissions so as to achieve concentrations or temperature objectives. We first describe more precisely the policy experiments to which the model is applied and then analyze the policies.

1. *No controls ("baseline").* The first run is one in which there are no policies taken to slow or reverse greenhouse warming. Individuals and firms would adapt to the changing climate, but governments would take no steps to curb greenhouse-gas emissions or to internalize the greenhouse externality. This policy is one which has been followed for the most part by nations through 1998.

2. *Optimal policy.* The second case solves for the economically efficient or “optimal” policies to slow climate change. This run chooses the emissions trajectory that maximizes global economic welfare subject to the economic and environmental constraints. More precisely, it calculates a Pareto-efficient set of carbon prices and emissions reductions. This policy can be thought of as one in which the nations of the

world agree to set an efficient policy for internalizing the greenhouse externality. It is assumed that the policy is efficiently implemented in the first period, say through uniform and harmonized carbon taxation with lump-sum recycling of revenues or through auctionable quotas with a perfect enforcement system.

3. *Ten-year delay of optimal policy.* This case is one which delays implementing the optimal policy for ten years. This policy allows us to calculate the costs and benefits of delaying implementing policies until our knowledge about global warming is more secure. In this scenario, we assume that sufficient information is in hand so that the optimal policy is implemented beginning in the period 2000-09.

4. *Kyoto Protocol*. Many current policy proposals deal with intermediate objectives like stabilizing emissions. For example, the Kyoto Protocol of December 1997 is designed to limit the emissions of Annex I countries (essentially, OECD countries plus Eastern Europe and most of the former Soviet Union). The Protocol states: “The Parties included in Annex I shall, individually or jointly, ensure that their aggregate anthropogenic carbon dioxide equivalent emissions of the greenhouse gases ... do not exceed their assigned amounts, ... with a view to reducing their overall emissions of such gases by at least 5 per cent below 1990 levels in the commitment period 2008 to 2012.” In other words, Annex I countries will during the period 2008-2012 reduce their emissions of greenhouse gases on average by 5 percent relative to 1990 levels.

We consider two different Kyoto policies in the RICE model runs. Under the “Annex I” runs, emissions for Annex I countries are forever limited according to the Kyoto Protocol, but there are no further emissions reductions after the first commitment period — this is called “Kyoto Annex I.” The Annex I runs imply enormous and politically problematical transfers from OECD countries to Russia and the Ukraine,[14] so a second run limits the emissions reductions to OECD countries only — this is called the “Kyoto OECD” policy. It should be emphasized that under both Kyoto Protocol runs it is assumed that reductions are efficiently implemented within the limiting countries, but there is no global trading and no other countries are assumed to join the agreement.

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[14] See Nordhaus and Boyer [1998] for estimates of the economic flows to Russia and Eastern Europe.

5. *Stabilizing global emissions.* The Kyoto Protocol targets the emissions only of high-income countries. A more efficient approach of a broadened Kyoto Protocol would include all countries. There are two variants of this approach. Under the first, global emissions are limited to 1990 levels, and abatement is efficiently distributed around the world. In the RICE model, global uncontrolled industrial CO_2 emissions are estimated to be 6.13 GtC per year on average for 1990-99. We estimate that 1990 emissions were 0.925 times first-period emissions. Therefore, under this policy, global CO_2 industrial emissions are limited to 5.67 GtC per year. (These emissions exclude emissions from land-use changes, estimated to total 1.13 GtC per year in the 1990-1999 period.) Note that this policy is more stringent that the Kyoto Protocol, which limits emissions only of high-income countries but does not limit developing-country emissions.

Many environmental groups and some governments have advocated more stringent emissions limitations than that envisioned in the Kyoto Protocol or in limiting emissions to 1990 rates. A specific target that has been endorsed is a 20 percent cut in CO_2 emissions from 1990 levels. Under this policy, CO_2 emissions are limited to 4.54 GtC per year. Like the other emissions-limitation policies, this policy has no particular merit, but it is easily understood and can be hammered onto political platforms.

6. *Geoengineering.* A radical technological option would be geoengineering, which involves large-scale engineering to offset the warming effect of greenhouse gases. Such options include injecting particles into the atmosphere that would increase the backscattering and stimulating absorption of carbon in the oceans. The most careful survey of this approach by the 1992 report of the U.S. National Academy concluded, "Perhaps one of the surprises of this analysis is the relatively low costs at which some of the geoengineering options might be implemented."[15] On the basis of the National Academy survey, we treat geoengineering as costing $10 per ton carbon.[16] It should be emphasized that many ecologists and environmentalists have grave reservations about the environmental impacts of the geoengineering options. Nonetheless, because of the high

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[15] National Academy of Sciences [1992], p. 460.

[16] The National Academy report describes a number of options that provide the theoretical capability of unlimited offsets to the radiative effects of GHGs at a cost of less than $1 per ton C (see National Academy of Sciences [1992], Chapter 28). These estimates are likely to prove low given the likelihood of high transactions costs, so we take the higher figure of $10 per ton carbon removed or the equivalent as more realistic.

cost of other mitigation strategies, this scenario is useful as a baseline to determine the overall economic impact of greenhouse warming and of policies to combat warming.

7. *Concentrations stabilization.* One of the new policy approaches that has received considerable attention is to stabilize the concentrations of CO_2 in the atmosphere. This policy is motivated by two ideas. First, concentrations rather than emissions have the potential to produce harmful and dangerous climate change. Second, CO_2 concentrations are closely related to a CO_2 emissions, which are in principle under the control of policy. Concentrations were specifically identified under the Framework Convention on Climate Change, which states that policies should be set to limit greenhouse-gas concentrations below "dangerous levels." Under this approach, we consider policies that would limit CO_2 concentrations to two times their preindustrial levels. This policy is usually taken to be a threshold of 550 parts per million of CO_2, which we model as representing 1140 GtC carbon in the atmosphere.

8. *Climate stabilization.* An unusual approach is much more ambitious and involves taking steps to slow and eventually stabilize the increase in global temperature so as to prevent major ecological impacts. This approach is particularly interesting because it focuses on an objective that is closer to the area of actual concern — climate change — as opposed to most other policies, such as emissions or concentrations limits, which focus on intermediate variables of no intrinsic concern.

There have been a number of proposals for setting "tolerable windows" on climate change. Two interesting ones are to limit temperature increase to 1.5 and 2.0 ºC.[17] There have been in addition proposals to limit the rate of change of temperature. In practice, the proposed rate of change constraints do not bind for the two limits investigated here, so the rate of change constraints have been omitted.

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[17] For a recent discussion, see Toth et al. [1998], which also calculates emissions trajectories that would keep climate safely beneath a temperature trajectory that might trigger changes in the thermohaline circulation. All runs of RICE-98 are well below the trigger trajectory.

B. **Major Results**

1. Overall results

We now summarize the overall results for the scenarios described above. Table 6-1 and Figures 6-12 and 6-14 show the results for the different runs in the current RICE and DICE models as well as the original DICE model. The overall impact of the optimal policy is broadly similar in the different models. The current RICE model finds that the optimal policy produces a net economic gain of $423 billion. This is the present value of the gain to all regions, discounted back to 1995 in 1990 prices.

Concentrating on the RICE model results in Table 6-1, we see that a delay of ten years leads to a trivially small net loss — $4 billion. This important result indicates that the loss from waiting and gathering more information is relatively small, assuming that action is appropriately taken in the future.

The next set of policies concerns emissions limitations. On theoretical grounds, we would expect these policies to be relatively inefficient because they target an inappropriate variable. Emissions are inappropriate because they are not of any intrinsic concern and are only intermediate between economic activity and the ultimate variable of concern, which is damages from climate change. The Kyoto Protocol runs are particularly ineffective because they stabilize only the emissions of the high-income countries. Emissions, concentrations, and temperature increases in both Kyoto runs are very close to the baseline case in the long run. Limiting emissions to the 1990 level of global emissions (which is an extension of current approaches) has a negative net economic impact, with a loss of $1,125 billion in present value. The more ambitious policy of limiting emissions to 80 percent of 1990 rates is even more expensive, with negative net cost of $3.4 trillion.

The policy of limiting CO_2 concentrations to double pre-industrial levels turns out to be very close to the optimal policy. The reason that the two policies are so close is that the optimal policy limits CO_2 concentrations to very close to doubling (see Table 6-5).

Policies that limit temperature to 2 °C are slightly worse than no policy. They tend to underabate in the short run and overabate in the long run. The more ambitious policy that limits temperature to 1.5 °C has significant discounted net economic costs of $2.3 trillion.

Finally, as is intuitively clear, geoengineering options that in effect remove atmospheric carbon at low cost have highly positive net value. Estimates from the DICE-98 model indicate that the value is more than $6 trillion. (The RICE model could not estimate this policy for technical reasons.)

Table 6-8 shows the breakdown of costs, damages, and net benefits for the different policies in the RICE model. It is apparent that there are substantial potential benefits from a successful climate change policy. The reduced damages from slowing climate change range from around $600 billion in present value in the optimal policy to $1.7 trillion in the more ambitious temperature-limitation plan. Increases in production costs are also substantial, however. The optimal abatement policy costs $235 billion in present value costs, while inefficient plans such as steep cuts in emissions or limiting temperature increases to 1.5 ºC impose present value costs in the range of $4 to $5 trillion. The benefit-cost ratio is shown in the last column of Table 6-8. Some of the well-designed plans pass a cost-benefit test, and for the optimal program the benefit-cost ratio is 2.8. The inefficient plans, by contrast, have benefit-cost ratios of 0.2 to 0.4. In judging these ratios, it must be recalled that we assume that policies are efficiently implemented. If inefficient implementation occurs (say through allocation of permits, exclusions, inefficient taxation, or regional exemptions), then the costs will rise and the benefit-cost ratio will quickly pass below the breakeven threshold.

Table 6-2 shows the regional breakdown for the optimal policy. It is important to understand the way that policies are implemented, which will determine the regional allocation of the costs and benefits. Under the current implementation, policies are assumed to be implemented through “harmonized carbon taxes.” That is, each country levies a carbon tax at the optimal rate and collects the revenues. To the extent that countries have relatively high emissions reductions or benefit from modest climate change (both of which occur for in the case of Russia), the policy may lead to economic losses. The major gainer from the policy is the European Union, with almost three-fourths of the net gain. Europe gains primarily because it is highly sensitive to climate change and has a low discount rate. Regions with high carbon intensities and/or high discount rates (such as Russia, Eastern Europe, India, and Africa) have negative net impacts. Note that if there is trading of emissions permits, virtually any regional redistribution of the costs and benefits would be possible through the initial allocation of permits. This is not done in the current version for simplicity of presentation and calculation.

2. Emissions Controls and Carbon Taxes

Table 6-3 and Figures 6-1 and 6-2 show the carbon prices or carbon taxes in the different policies. The carbon prices are the prices of permits to emit carbon in different countries. In most runs, the prices are internationally harmonized either through an assumption of harmonized taxes or because of tradable emissions permits.[18] The optimal policy has a carbon price beginning at $5 per metric ton carbon for the first period (1990-99). The optimal price rises in future years, reaching $8 per ton in 2010, $19 per ton in 2050, and $36 per ton carbon in 2100. For reference, a $10 per ton carbon tax will raise coal prices by $7 per ton — about 25 percent of the current U.S. coal price. Further, a $10 per ton carbon tax would raise gasoline prices by about 2½ U.S. cents per gallon.

The 10-year delay has a zero tax in the first period, but then is virtually indistinguishable from the optimal policy. The policy of no controls obviously has a zero carbon tax. The emissions-stabilization policies have steeply rising carbon taxes, peaking at about $100 per ton in the next century. Policies which stabilize CO_2 concentrations and temperature begin with *lower* carbon prices than the optimal trajectory because they implicitly assume that there is no damage until the threshold is reached. These policies therefore have lower near-term prices but higher prices than the optimal plan after the middle of the next century.

The regional carbon prices for the optimal policy are shown in Figure 6-10. The carbon prices differ across countries because of differing trends in productivity in different regions. Because productivity in China is rising relative to the U.S., its relative prices will be falling and its carbon price in terms of its own output prices will therefore be rising more rapidly.

Table 6-11 shows the control rate for CO_2 for the different policies. These show the extent to which GHG emissions are reduced below their uncontrolled levels. In the optimal path, the rate of emissions reduction begins at a low rate of about 3 percent of

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[18] The calculation of the carbon price is indirect because it is a “dual variable.” The RICE model produces calculated dual variables for both output and for carbon emissions. The units of these are, respectively, the change in the objective function from a unit change in output (*yy1.m*) and the change in the objective function from a unit change in carbon emissions (*ee.m* in most runs). Dividing ee.m by *yy1.m* gives the implicit price of carbon per unit of output, which provides a calculation of the carbon price.

emissions, but it then climbs steadily over the next century, reaching about one-third of baseline emissions by 2100. The path for limiting concentrations is approximately the same. The control rate for emissions limitations is sharply front-loaded and rises steeply, while the path for temperature limitation rises sharply at the end of the next century.

Figure 6-11 shows the regional control rates. The control rates rise sharply for rapidly growing countries of the differential movements in goods prices. In effect, carbon abatement is becoming relatively cheap in developing countries, and their control rates therefore rise.

3. Emissions, Concentrations, and Climate Change

We next show some of the details of the model runs. Table 6-4 and Figure 6-3 show the aggregate estimates, while Figure 6-7 shows the uncontrolled emissions for different regions. Baseline industrial CO_2 emissions in the RICE model project steady growth to about 15 GtC in 2100. It is interesting to note that the emissions and concentrations projections in the RICE-98 model are well below those in many current projections. For comparison, of the 90 scenarios examined in IPCC [1995], the median projection for 2100 was around 22 GtC.[19] On the other hand, many of these scenarios were prepared before the breakup of the Soviet Union and contained high rates of economic growth and low rates of decarbonization. It will be necessary to wait for the next generation of studies to determine whether the relatively low emissions projections in the RICE model are an aberration or a harbinger.

In the optimal case, emissions are limited to 9.7 GtC in 2100. By comparison, emissions are only 7.3 GtC in 2100 for limiting concentrations, and 3.8 GtC in 2100 for limiting temperature to 2 ºC. Beginning at an atmospheric concentration of 735 GtC (355 ppm) in 1995, baseline concentrations rise to 1249 GtC (603 ppm) in 2100. In the optimal control case, concentrations are limited to 1134 GtC (548 ppm) in 2100. Concentrations for 2100 in the CO_2-limitation case are somewhat lower than the optimal control case.

The effect of alternative policies on the projected global mean temperature is shown in Table 6-6 and Figure 6-5. The optimal, concentrations-target, and temperature-target runs have very similar temperature trajectories through the middle of the next

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[19] See IPCC [1995], Figure 6-2.

century. After 2050, the temperature limitation scenario begins to head down relative to the other paths.

One of the surprising results of virtually all policies is how little they affect the temperature trajectory in the next century. The optimal path reduces global mean temperature by 0.19 ºC relative to the baseline in 2100. Surprisingly, the concentration-limitation scenario reduces temperature by even less than the optimal — by 0.14ºC relative to the baseline in 2100. However, the policies have a substantial impact in the next century. The temperature reduction in 2200 relative to the baseline of the optimal, concentration target, and temperature target are 1.06, 1.34, and 1.88 ºC, respectively.

One feature of climate change policies that poses particularly difficult problems is the modest impact that the optimal policy or even more ambitious policies make upon the concentration and temperature trajectories. The reason for the modest impact is straightforward. According to our estimates, the impact of warming upon the global economy is relatively small, amounting to around 2 percent of global output for a 3 ºC average warming. The costs of slowing the warming are very small for the first increment of policy and then rise sharply as the degree of emissions restraint increases. The resultant of these two forces is that an optimal policy has little effect on the near-term temperature increase.

Two other factors lead to the small decrease in the extent of warming in the optimal path. First, there is a great deal of momentum of climate change given the existing degree of buildup of GHGs and the lags in the response of the climate to GHG increases. For example, consider the policy of stabilizing global emissions at 1990 rates — an extremely ambitious target requiring reducing CO_2 emissions by 50 percent below the baseline by the middle of the next century and costing about $2½ trillion in discounted abatement expenditures. Even with all this cost, global temperatures would still rise by around 1.6 ºC above 1900 levels by 2100.

The second reason why the reduction in the rate of warming is so small is the non-linear relationship between GHG concentrations and warming. According to scientific studies, the relationship between equilibrium warming and CO_2 concentrations is approximately logarithmic. This implies that moving from 300 to 315 ppm of CO_2 increases equilibrium temperature by 0.214 ºC while moving from 600 to 615 ppm of CO_2 increases equilibrium temperature by only 0.107 ºC. The implication of this nonlinear relationship is that policies that produce a small decrease in CO_2 concentrations have a relatively small impact upon the path of temperature. This result is the opposite of the usual diminishing returns seen almost everywhere in economic systems.

Figure 6-15 shows the tradeoff between economic impact and long-run temperature change. The upper envelop of the points is (approximately) the efficient frontier of the temperature-economic tradeoff. Points above the zero line on the vertical axis can pass a cost-benefit test since they have net economic benefits that are positive. The optimal policy has the highest value, and the concentrations limitation policy is very close to that. Policies that limit emissions are below the x axis, and therefore do not pass a benefit-cost test.

If you draw a thin line through the upper points in Figure 6-15, this would show the efficiency frontier between long-run temperature increase and economic impacts. Slowing global warming raises living standards for the first segment (from “base” to “optimal”). For relatively efficient policies that have about the same temperature impact as the optimal (such as limiting concentrations), the economic impact is close to that of the optimum because the frontier is flat near the optimum. Then, as more ambitious policies slow warming even more, the economic costs begin to mount up. We also see that inefficient policies, such as emissions limitations, are well below the frontier.

4. <u>Other Economic Variables</u>

The model has a wide variety of other projections that are necessary for a full set of projections. They include both physical output (such as CO_2 emissions) as well as economic values (such as the values of output and consumption). Figures 6-7 through 6-10 show regional detail on uncontrolled emissions, output, and GDP for the 13 regions. One important feature of the RICE model projections is that CO_2 emissions in the high-income countries are projected to be relatively flat over the next century. This is the result of continuing decarbonization of high-income countries plus slower population growth. The rate of decarbonization is shown in Figure 6-17.

C. **Conclusions**

This concludes the presentation of the RICE-98 and DICE-98 models of climate change and the economy. In this section we summarize the principal conclusions. The present study has investigated the implications of economic growth on future climate change as well as the impact of different environmental control strategies upon the global economy. The approach taken here investigates alternative strategies for coping with greenhouse warming. The major results are the following.

To begin with, it must be emphasized that this model, like any model, has a number of important shortcomings. One important shortcoming is that the damage function, particularly the response of developing countries and natural ecosystems to climate change, is poorly understood at present. Whereas scientists have improved their understanding of many routine elements of climate change, the potential for rapid or catastrophic climatic change, for which precise mechanisms and probabilities have not been determined, cannot currently be ruled out. Furthermore, the calculations omit 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. Additionally, the model assumes that policies are efficiently implemented, which is undoubtedly an optimistic assumption given shortcomings in most environmental policies. And finally, this study abstracts from issues of uncertainty, in which risk aversion and the possibility of learning may modify the stringency and timing of control strategies. These are topics for another day.

Although there are many implications of the present study, we will emphasize three in this summary: the ranking of policies, the optimal carbon price, and a revised view of the "climate-change problem."

The first major result of the study is to show the economic impacts of alternative climate-change policies. This study has examined several different approaches to slowing climate change. Among these policies, the rank order from a pure economic point of view and given current information is geoengineering, economic optimum, 10-year delay, concentrations stabilization, no controls, 2 ºC temperature limitation, Kyoto-Annex I, Kyoto-OECD, stabilizing global emissions at 1990 levels, 1.5 ºC temperature limitation, and cutting global emissions by 20 percent. None of the policies except geoengineering has major net economic benefits. The most beneficial control option has a net benefit of only $400 billion in present value — about 1½ percent of world output today. On the other hand, inefficient policies can do significant economic damage.

Second, with respect to current climate-change policies, perhaps the most important finding is that the optimal carbon price in the near term is in the $5 to $10 per ton range. As Table 6-3 and Figure 6-2 show, that price range is an appropriate target for policy for the next decade or so. Policies which have near-term carbon prices 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 under $10 per ton.

Third, the revised RICE model paints a much less alarming picture of future climate change than the earlier DICE model and many 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 guess today would be close to 2 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, the new RICE model 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 (no-control) global temperature increase for 2100 is 2.15 ºC in the RICE-98 model as compared to 3.28 ºC in the original DICE model. In addition, the new RICE model has higher controls than the original DICE model. Hence the optimized global temperature increase in 2100 is 1.97ºC in RICE-98 compared to 3.10 ºC in the original DICE model.

The slower pace of future climate change is a hopeful note to end on, but it is also a cautionary one. Perhaps we can sleep more soundly on the basis of current evidence that climate change in the next century is unlikely to pass 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 head our globe in more dangerous directions.