

# Roll the DICE Again: Economic Models of Global Warming

## Chapter 3

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## **Chapter 3. Calibration of the Major Sectors**

### **1. Regional Specification**

The data for RICE-99 were collected for 13 subregions, which were then aggregated into eight regions for modeling purposes. The eight regions were grouped on the basis of either economic or political similarity. The United States and China form two of the eight regions. OECD Europe was treated as a single unit because of the high level of political and economic integration in that region.

The other regions were generally created on the basis of regional or economic similarity. The “Other High Income” group includes Japan, Canada, Australia, and a few other smaller countries. “Russia and Eastern Europe” includes both Russia and the formerly centrally planned economies of that region, which have extremely high carbon intensities. The significant countries in the “Middle Income” group are Brazil, South Korea, Argentina, Taiwan, Malaysia, and high-income OPEC countries. “Lower-Middle Income” includes Mexico, Turkey, Thailand, South Africa, much of South America, and several populous oil exporters such as Iran. The “Low Income” region, the largest by population, includes South Asia, most of India and Southeast Asia, much of the Asian part of the former Soviet Union, sub-Saharan Africa, and a few countries in Latin America. <sup>1</sup>

Tables 3-1 and 3-2 show the composition of the regions as well as the data on CO<sub>2</sub> emissions, population, GDP, and GDP growth for each region. Tables 3-3 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<sub>2</sub>-output ratios for the 13 subregions.

## **2. Calibration of Production Function**

### **A. Energy-production module**

RICE-99 uses a new approach to the production structure relative to both the original models and to existing climate-change models. The major changes are (1) RICE-99 introduces a new concept and technique for incorporating energy use 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 region is assumed to be produced by capital, labor, and carbon-energy in a Cobb-Douglas framework [see equation (2.5) in Chapter 2]. Carbon-energy

can be described as the energy services derived from carbon-energy (i.e., fossil fuels). In this approach, CO<sub>2</sub> emissions are a joint product of carbon-based energy consumption. Carbon-saving technological change is modeled as reducing the ratio of carbon-energy consumption to energy services (or the amount of carbon emissions per unit output at constant input prices). Carbon-energy is supplied according to a supply function in which the marginal cost increases as carbon fuels are exhausted (this sector is discussed in section 4 of this Chapter). For more detail, see Chapter 2, section 2.

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 industrial carbon emissions to a given increase in carbon taxes is the same as the response in a disaggregated model – a model in which emissions are modeled as the sum of emissions across energy sources.

We follow the convention of measuring output, consumption, and investment in

1990 U.S. dollars at market exchange rates. All dollar values in the text, tables, and graphs represent 1990 U.S. dollars. Prices can be converted into prices for the year 2000 (using the U. S. GDP deflator) by multiplying by 1.25.

While it is common practice to use output measured at international or purchasing-power parity (PPP) exchange rates, this is inappropriate in the current context for three reasons. First, since historical output data at market exchange rates is more readily available than at PPP rates, we rely on these data to make projections about future growth in output and carbon intensity. In order for the output levels we project to be consistent with our projected output and carbon intensity growth rates, we define them as output at market exchange rates. Second, in the context of optimizing a country's consumption path, it should use its internal prices rather than the world average price level. Third, international trading in carbon emissions permits will take place at market exchange rates, so output needs to be measured in market exchange rates for consistency in measurement between trade flows and economic production as well as between the marginal cost of carbon abatement and the international carbon permit price. If users would like to convert the data to PPP income levels, the levels 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.

B. Matching initial period to the data

Recall the production function from equation (2.5) in the last chapter. In the first period, we define carbon services to be equal to carbon-energy use [that is,  $\zeta_J(0) = 1$ ].

This gives us the following:

$$(3.1a) \quad Q_J(0) = \Omega_J(0) \{ A_J(0) K_J(0)^\gamma L_J(0)^{1-\beta_J-\gamma} E_J(0)^{\beta_J} - c_J^E(0) E_J(0) \}$$

$$(3.1b) \quad c_J^E(0) = q(0) + \text{Markup}_J^E$$

$\Omega_J(0)$  and  $q(0)$  are determined in a fashion that will be described below. The capital-elasticity coefficient  $\gamma$  is assumed to be 0.3 on the basis of standard production-function studies.  $L_J(0)$  is the initial population level, taken from the data.  $E_J(0)$  is determined endogenously by market participants.

This leaves the parameters  $A_J(0)$ ,  $K_J(0)$ ,  $\beta_J$ , and  $\text{Markup}_J^E$  open. We calibrate these parameters so that the model matches empirical observation in four key aspects: GDP, industrial emissions, interest rates, and the effect of a carbon tax on emissions. That is, we determine the parameter values by finding for each region the combination that solves the following four equations in the base case when  $t_J(0)=0$ :<sup>2</sup>

(3.2a) First period output = Output from historical data

(3.2b) First period industrial emissions = Industrial emissions from historical data

(3.2c) First period interest rates = Target value

(3.2d) Change in carbon emissions = Calculated from a disaggregated energy  
from \$50 carbon tax in model  
first period

Equation (3.2a) sets the right-hand side of (3.1a) equal to actual output for the region, taken from the historical data. Equation (3.2b) sets the right-hand side of (2.18b) equal to actual industrial emissions from the data, assuming  $h(0) = 0$ .<sup>3</sup>

The interest rate on capital in the first period is its net marginal product. In RICE-99, this is given by its contribution to output and to the next period's capital stock. Equation (3.2c) sets this equal to a target value reflecting historical data and actual differences across regions.

The most important calibration for policy purposes is determining the impact of carbon-emissions constraints. Using equation (3.2d), we set the parameters to equate the

model's emissions reductions to the target for a \$50 carbon tax. From (2.18b) we can calculate the decrease in emissions due to the imposition of a \$50 carbon tax. This gives us the right-hand side of (3.2d). To get the left-hand side of (3.2d), we construct a disaggregated energy sector model, where carbon emissions are given by:

$$(3.3) \quad E(0) = \sum X_i(0) \gamma_i$$

$X_i$  is the consumption of energy source  $i$  and  $\gamma_i$  is CO<sub>2</sub> emissions per unit of consumption for energy source  $i$ . We assume that the demand for each fossil fuel takes the form

$$(3.4) \quad X_i(0) = \omega_i(0) \{P_i(0) / [P_i(0) + \tau(0)\gamma_i]\}^{\eta_i}$$

where  $\omega_i(0)$  is the consumption of energy source  $i$  in the first period,  $P_i(0)$  is the price of energy source  $i$  in the first period, and  $\eta_i$  is the price-elasticity of demand for energy source  $i$ . Using (3.3) and (3.4) we calculate the change in emissions due to the imposition of a \$50 carbon tax, which is then used on the left-hand side of (3.2d).<sup>4</sup>

### C. Data sources

*Population.* Data for the initial population level were obtained from *UN Monthly Bulletin of Statistics, July 1996*.

*GDP.* Data on output were taken from *UN Monthly Bulletin of Statistics, July 1996*.

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

*Energy consumption.* The different energy sources [ $X_i$ ] are non-electric coal consumption, non-electric natural gas consumption, electricity consumption, and consumption of petroleum products. Electricity consumption data were taken from *International Energy Annual 1996*, published by the Energy Information Administration (EIA) of the U.S. Department of Energy. Fossil fuel shares for electricity were derived using EIA's World Energy Projection System, 1997 version. Data for total coal and natural gas consumption were taken from *International Energy Annual 1996*, and non-electric coal and natural gas consumption were calculated as the difference between electricity consumption and total consumption. Petroleum products consumption data were drawn from *International Energy Annual 1995*.

*Energy prices.* 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 the literature on energy demand, price elasticities of demand for all energy demand components with respect to retail prices were assumed to be -0.7 in OECD regions (US, OHI, and OECD Europe) and -0.84 in the rest of the world.

*Carbon emission factors.* Carbon coefficients for individual fossil fuels and petroleum products were taken from a variety of publications of the Department of Energy, Energy Information Agency.<sup>5</sup> The carbon coefficient for electricity is the sum of the carbon coefficients of individual fossil fuels weighted by their fuel share in electricity consumption, adjusted for the efficiency of conversion of the fossil fuel into electricity.

### **3. Exogenous Trend Parameters**

The previous section described calibration of the model to initial-period data. This section describes calibration of the parameters that drive the trends in GDP and carbon emissions. These parameters govern population growth, total factor productivity growth, and the ratio of carbon services to carbon-energy.

## A. Details of the calibration

*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 projection 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 – OECD Europe and Japan — we directly input data for the first few periods and start the exponential model only when projected population starts to decline.

*Data Sources for population:* For initial population, see the previous section. For the first four periods for OECD 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 regions, it was modified to improve the match with the World Bank's projections for 2050.

*Estimates of 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. Historical growth rates of output per capita for the 8 regions in RICE-99 are shown in Table 3-3.

One set of information that informed our projections for economic growth was an informal survey of 10 economists and economic historians who were asked their views about long-run growth trends. The major assumptions underlying our projections are that the growth rate of output per capita will slow in the 21<sup>st</sup> century in the developed regions and that developing regions will grow at rates that produce partial convergence of output per capita by the end of the next century.

A comparison of the RICE-99 assumptions with those of Angus Maddison [1998a] is provided in Table 3-6.<sup>6</sup> Our assumptions are generally in line with those in the Maddison study, with the world weighted average growth rate in RICE-99 approximately 0.16 percent per year higher for the next two decades. The major differences between the two projections are that we are more optimistic about Africa and Latin America and less optimistic about China.

The long-run growth rates, historical rates, and levels of per capita GDP for the

different regions RICE-99 are shown in Table 3-7.

*Model calibration for long-run output growth.* To model the trend of long-run economic growth, RICE-99 assumes an exogenous exponential trend in technological progress, similar to that used for population described above. The choice of the initial level of productivity [the coefficient  $A_j(0)$  in the production function] is described above. 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 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 3-2 and Table 3-7.

*Calibration of carbon-saving technological change.* Calibration of the rate of decarbonization (the rate of decline in carbon intensity<sup>7</sup>) is made by adjusting the parameters that govern the ratio of energy services to industrial carbon emissions [ $\zeta_j(t)$  in equation (2.5b)]. We assume  $\zeta_j(t)$  grows at a declining growth rate in a manner similar to population and total factor productivity. Decarbonization is difficult to project because it depends upon trends in energy sources, on energy-sector technological change, and on policies about energy taxation. We have generally projected these on the basis of historical trends in decarbonization, with adjustments for regions such as Russia and Eastern Europe that have divergent carbon intensities for special historical reasons.

Figure 3-3 shows recent trends and near-term projections for the rate of decarbonization. We project a continuation in the recent trend of decarbonization, with a decline in global carbon intensity of 1.03 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 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. These two studies use methodologies that are completely independent in their underlying construction. Table 3-8 compares the results of the two studies. RICE-99 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 2025 and 2055. The IIASA study is a particularly useful comparison because of the detailed energy sector and great care taken in developing scenarios for different regions.

## B. Discussion

Gathering the data and constructing the regional models proved the most arduous part of constructing RICE-99. 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 regions (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 regions reflecting the scarcity of capital in those regions. The net return on capital in the U.S. and OECD Europe begins at the historical rate of around 5 percent per year and then declines gradually as growth slows. Rates of return in developing regions begin at 6 to 7 percent annually and decline as their economies grow and accumulate capital.

Per capita output follows an optimistic scenario in which the four horsemen of the economic apocalypse — war, pestilence, depression, and environmental catastrophe — are largely absent. High-income regions are projected to continue growth in per capita output at around 1 percent per year over the next century. Low-income regions 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 3-7 shows, we project some but not complete convergence of developing regions toward today's living standards in the rich regions. Middle-income countries are projected to reach close to current per capita income levels in the U.S. by 2100. Eastern Europe and lower-middle income countries get about

halfway there; low-income countries and China are projected to have per capita income levels of about 10 times current levels by 2100.

A final remark about the model is in order at this point. The regional economic model underlying RICE-99 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 are 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.

#### **4. Carbon Supply**

RICE-99 contains a revised treatment of energy supply. In the original DICE/RICE models, the supply of fossil fuels 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 fossil fuel supplies are 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 frightening scenarios put forth by William Cline<sup>8</sup> and others, foreseeing the potential for a 10 °C long-run warming, are definitely inconsistent with standard carbon-cycle and climate models in a situation of relatively limited coal supplies. Indeed, one of the major advantages of using integrated-assessment models is that they can ensure that the different assumptions are consistent both with each other and with mainstream scientific and economic findings.

Second, and more interesting from an economic point of view, is the interaction between limited supplies and pricing. To the extent that the fossil fuel supply curve is relatively price-inelastic, prices will rise sharply as supplies are exhausted. This will lead to rising scarcity prices (Hotelling rents) on carbon-based 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 forward to consumers. This backward shifting occurs to the extent that supply is price-inelastic. Indeed, in the limiting case of perfectly price-inelastic supply of carbon-energy with zero extraction costs, carbon taxes may 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, RICE-99 includes a simple supply relationship for fossil fuels. We now describe this sector, which lumps all fossil fuels together into a single aggregate, of carbon-energy. For these purposes, the one fossil fuel can usefully be thought of as coal, which is both the most abundant fossil fuel and has the predominant fraction of carbon that is potentially emitted (leaving aside the low-grade shales). We assume that carbon-energy has a limited supply with the supply curve becoming highly price-inelastic when cumulative carbon-energy use reaches 6000 GtC (equivalent to consuming approximately 9,000 billion tons of coal). The marginal cost of carbon-energy is relatively flat until cumulative carbon-energy use is 3000 GtC, but it quadruples (to about \$450 per ton) when cumulative carbon-energy 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 carbon-energy use:

$$(2.11) \quad \text{CumC}(t) = \text{CumC}(t-1) + 10 E(t)$$

where  $\text{CumC}(t)$  is cumulative carbon-energy in GtC at the end of period  $t$  and  $E(t)$  is global carbon-energy use in the current period.

The important new relationship is the cost function of carbon-energy. We assume that there is a limited quantity of carbon-energy,  $\text{CumC}^*$ , beyond which marginal costs of

extraction rise very sharply. We then assume that the marginal-cost curve takes the following form:

$$(2.12) \quad q(t) = \xi_1 + \xi_2[\text{CumC}(t)/\text{CumC}^*]^{\xi_3}$$

where  $q(t)$  is measured in 1990 U.S. dollars per ton. Based on Rogner [1997], the numerical form of this equation in RICE-99 is

$$(3.5) \quad q(t) = 113 + 700[\text{CumC}(t)/6000]^4$$

The cost of carbon-energy has two terms. The first term ( $\xi_1 = 113$ ) is the marginal cost that is independent of exhaustion. This term represents the costs of current extraction of carbon-energy today. The second term is a rising cost function. At current levels of cumulative extraction [ $\text{CumC}(1995) = 0$ ], the second term is zero. It is highly convex, with an exponent of 4, reflecting the finding that the cost function for carbon fuels is relatively price-elastic in the near term.

The shape of the function is shown in Figure 3-4. When cumulative extraction is halfway to  $\text{CumC}^*$ , the marginal cost of carbon-energy rises from \$113 to \$157 per ton. Carbon-energy becomes increasingly costly as the limits of resources are reached.

In some earlier versions of RICE, other constraints were added. In RICE-98, a backstop technology was added that prevented the price of carbon-energy from rising above \$500 per ton. In addition, a number of “flow” constraints were added in earlier versions to prevent the economy from flipping too quickly from one technology to another. These included constraints on the reduction of carbon-energy and on the introduction of the backstop constraints. In RICE-99, all these constraints were removed because they made virtually no little difference to the results for the first century and added considerable computational complexity. Users who are interested in evaluating longer-term projections should be warned, however, that because of the absence of flow constraints and a backstop technology, unreasonable outcomes and unrealistically sharp transitions can occur outside the region over which the model was calibrated and will definitely occur in the model as carbon-energy becomes exhausted.

## **5. The Carbon Cycle and Other Radiative Forcings**

An important part of the DICE/RICE-99 models is integrating the economic sectors with the 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 find parsimonious relationships between economic activity and climate change. Economists are accustomed to relying on highly simplified representations of economic relationships (such as the much-used Cobb-Douglas production function), and this approach has proven fruitful in understanding phenomena ranging from business cycles to economic growth. 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, it is necessary to undertake extensive sensitivity analysis to determine the robustness of the model. The larger the model, the more difficult it is to

undertake comprehensive sensitivity and uncertainty analysis. Finally, from a computational point of view, RICE-99 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 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 GHGs and of the carbon cycle in DICE-99 model. Four major changes in the science and policy of GHGs are incorporated in RICE-99 and DICE-99.

1. In the original DICE model, CO<sub>2</sub> was aggregated with chlorofluorocarbons (CFCs) to create a CO<sub>2</sub>-equivalent stock of GHGs. Since that time, the CFCs have been largely phased out in most high-income countries, and the projected radiative

forcings from CFCs are consequently drastically lower than was projected in the early 1990s. Therefore, the only endogenous GHG in RICE/DICE-99 is CO<sub>2</sub>.

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-99 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-99 models therefore revise the treatment of exogenous anthropogenic forcing by including projections of sulfate cooling along with the positive forcings from non-CO<sub>2</sub> GHGs.

4. Projections of the radiative forcings from the non-CO<sub>2</sub> GHGs methane, N<sub>2</sub>O, and tropospheric ozone have been updated over the last decade. RICE-99 forcings take into account these updates.

Subsection A discusses the structure of the carbon cycle in RICE-99. The

following subsection discusses the calibration of the new carbon model, after which estimates of the radiative forcing from other GHGs are discussed.

#### A. Revised approach to the carbon cycle

In the original DICE model, the carbon cycle was estimated from time-series data on CO<sub>2</sub> 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 the original approach was 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).<sup>9</sup> They indicate that the long-term projections in the original DICE model significantly understate atmospheric concentrations of CO<sub>2</sub>.

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 DICE, 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 RICE-99.

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 vast but 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.

We assume that CO<sub>2</sub> accumulation and transportation can be represented as a linear three-reservoir model. (The model pertains only to CO<sub>2</sub> as other GHGs are taken as exogenous.) Let

$M_i(t)$  = total mass of carbon in reservoir  $i$  at time  $t$  (GtC)

$\phi_{ij}$  = the transport rate from reservoir  $i$  to reservoir  $j$  per unit time

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 in the year 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:

$$(3.8) \quad M_{AT}(t) = 10 \times ET(t-1) + \phi_{11} M_{AT}(t-1) - \phi_{12} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1)$$

$$(3.9) \quad M_{UP}(t) = \phi_{22} M_{UP}(t-1) + \phi_{12} M_{AT}(t-1) - \phi_{21} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1) - \phi_{23} M_{UP}(t-1)$$

$$(3.10) \quad M_{LO}(t) = \phi_{33} M_{LO}(t-1) - \phi_{32} M_{LO}(t-1) + \phi_{23} M_{UP}(t-1)$$

The carbon cycle has a built-in lag in which 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.

## B. Calibration

In this subsection, we describe the calibration of the model in equations (3.8) - (3.10). 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. RICE-99 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 (a “neutral biosphere” is one in which changing atmospheric concentrations of CO<sub>2</sub> do not change the mass of carbon in the biosphere).<sup>10</sup>

More precisely, the estimates are derived as follows. We assume that the reservoirs were in equilibrium in “pre-industrial times.”<sup>11</sup> For 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  $\phi_{12}$  and  $\phi_{23}$  and the effective initial mass of the upper stratum to minimize the squared deviation of the RICE-99 impulse response function from that in the Bern model. The RICE-parameterized

function 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 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.<sup>12</sup>

The response functions to pulse inputs of carbon are shown in Figure 3-5. As can be seen, the RICE-99 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-99 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 3-6 compares the projections of CO<sub>2</sub> concentrations over the period 1990-2100 using the IPCC-92a emissions trajectory with the Bern and RICE-99 models. RICE tends to overpredict concentrations over the next century, in part because of the simpler structure and in part because it was calibrated to the higher CO<sub>2</sub> concentrations, which implies a higher atmospheric retention in the near term.

### C. Other greenhouse-gas emissions

RICE-99 considers greenhouse warming primarily from carbon dioxide. Although there are large uncertainties involved, the total net radiative forcings of non-CO<sub>2</sub> GHGs and aerosols in 2100 are currently expected to be an order of magnitude smaller than those for CO<sub>2</sub>. Moreover, the policy instruments available to affect 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 and aerosols are assumed to be exogenous in RICE-99. Table 3-9 shows the assumptions about the radiative forcings of non-CO<sub>2</sub> GHGs.

The effects of the changes in the RICE carbon cycle and projections of other GHGs and aerosols on radiative forcing in 2100 can be seen in Table 1-2. The change in the carbon cycle makes little difference for a time frame as small as a century, but the reduced forcing from non-CO<sub>2</sub> GHGs has a bigger impact than the rather large reduction in baseline carbon emissions.

## **6. 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 RICE-99. 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<sub>2</sub> doubling on mean temperature is highly correlated with the impact on precipitation.

RICE-99 takes the same approach as the one 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 approach here follows closely the model developed by Schneider and Thompson [1981]. 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 accumulation of GHGs warms the atmosphere, which then mixes with and warms the upper ocean, which in turn heats the deep oceans. 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 equations of the model, given in Chapter 2, are:

$$(2.15a) \quad T(t) = T(t-1) + \sigma_1 \{F(t) - \lambda T(t-1) - \sigma_2 [T(t-1) - T_{LO}(t-1)]\}$$

$$(2.15b) \quad T_{LO}(t) = T_{LO}(t-1) + \sigma_3[T(t-1) - T_{LO}(t-1)]$$

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,  $\sigma_2$  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  $\lambda$ , or the "feedback parameter." This parameter is a way of representing the equilibrium impact of CO<sub>2</sub> doubling on climate. By solving (2.12) for a constant temperature, 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  $T_{2xCO_2}$  to represent the equilibrium impact of doubled CO<sub>2</sub> concentrations on global mean surface temperature. From (2.12), therefore, we have that  $T_{2xCO_2} = \Delta F_{2xCO_2}/\lambda$ , where  $\Delta F_{2xCO_2}$  is the change in radiative forcing induced by a CO<sub>2</sub> doubling. The derivation of  $T_{2xCO_2}$  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<sub>2</sub> 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  $T_{2xCO_2} = 4.1/\lambda = 2.91$  °C for a CO<sub>2</sub> doubling, with an e-fold time for temperature of 30 years. A full discussion is contained in Nordhaus [1994b]. Although developments in climate modeling have not revised estimates of the impact of rising GHGs on equilibrium climate change, recent assessments have noted that climate models tend to overpredict the extent of global warming over the last two decades. For example, in the RICE-99 model, using actual concentrations of CO<sub>2</sub> in the atmosphere would produce an increase in global mean temperature for the 1990s that is almost twice the observed increase relative to the first half of the 20<sup>th</sup> century. In light of the overprediction from climate models,  $T_{2xCO_2}$  is often taken to be 2.5 °C in policy evaluations. We have chosen to use a model-based estimate because of the likelihood that

many confounding factors are involved in the overprediction of warming to date.

Figure 3-7 compares the projections of RICE-99 with the IPCC calculations in IPCC [1996a]. Each projection uses the radiative forcing estimated according to the IS92a scenario, as updated for other non-CO<sub>2</sub> forcings in IPCC [1996a]. The RICE-99 model lies above the IPCC primarily because RICE uses a temperature-CO<sub>2</sub> sensitivity of 2.9 °C, as discussed above, whereas the IPCC run has a temperature-CO<sub>2</sub> sensitivity of 2.5 °C.

Table 3-1. Regional Details of the RICE-99 Model

	Industrial	Gross Domestic Product		Population	CO2-GDP
	CO2 Emissions [1000 tons carbon]	[1990 U.S. prices, market exchange rates]		[millions]	Ratio [tons carbon per \$thousand]
	1995	1995	GDP growth rate [percent per year] 1970-95	1995	1995
<b>United States</b>	1,407,257	6,176	2.6	263.12	0.23
<b>Other High Income</b>	556,855	4,507	3.6	191.61	0.12
Japan	307,520	3,420	3.6	125.21	0.09
Canada	118,927	541	3.2	29.61	0.22
Australia	79,096	295	3.1	18.05	0.27
Singapore	17,377	46	8.1	2.99	0.38
Israel	12,642	66	5.0	5.52	0.19
Hong Kong	8,459	84	7.4	6.19	0.10
New Zealand	7,489	49	2.2	3.60	0.15
Virgin Islands (U.S.)	3,121	2	NA	0.10	2.01
Guam	1,129	..	NA	..	NA
Aruba	491	..	NA	..	NA
Bahamas	466	3	NA	0.28	0.14
Bermuda	124	1	NA	0.06	0.08
British Virgin Islands	14	..	NA	..	NA
Andorra	..	..	NA	..	NA
Faeroe Islands	..	..	NA	..	NA
Monaco	..	..	NA	..	NA
San Marino	..	..	NA	..	NA
<b>OECD Europe</b>	850,839	6,892	2.4	380.85	0.12
Germany	227,920	1,787	2.3	81.87	0.13
United Kingdom	147,964	892	2.1	58.53	0.17
Italy	118,927	998	2.6	57.20	0.12
France	92,818	1,189	2.5	58.06	0.08
Spain	63,211	406	2.9	39.20	0.16
Netherlands	37,093	303	2.4	15.46	0.12
Belgium	28,334	189	2.3	10.15	0.15
Greece	20,820	60	2.5	10.47	0.35
Norway	19,774	125	3.5	4.35	0.16
Austria	16,179	165	2.7	5.11	0.10
Denmark	14,975	132	2.1	5.22	0.11
Portugal	14,172	58	3.3	9.93	0.24
Finland	13,923	107	2.4	5.11	0.13
Sweden	12,170	195	1.6	8.83	0.06
Switzerland	10,604	213	1.4	7.04	0.05
Ireland	8,798	53	4.2	3.59	0.16
Luxembourg	2,528	13	NA	0.41	0.20
Iceland	492	6	NA	0.27	0.08
Greenland	137	1	NA	0.06	NA
Liechtenstein	..	..	NA	..	NA

<b>Russia and Eastern Europe</b>	863,849	1,095	1.6	535.09	0.79
Russia	496,182	334	1.2	148.20	1.48
<b>Eastern Europe</b>	367,667	380	2.8	193	0.95
Ukraine	119,599	34	1.0	51.55	3.55
Poland	92,818	74	NA	38.61	1.25
Romania	33,049	35	NA	22.69	0.95
Czech Republic	30,581	37	10.9	10.33	0.83
Belarus	16,185	20	1.2	10.34	0.81
Bulgaria	15,474	25	NA	8.41	0.62
Hungary	15,250	27	2.2	10.23	0.56
Slovakia	10,381	19	10.7	5.37	0.56
Serbia and Montenegro	9,026	60	NA	10.54	0.15
Croatia	4,644	9	NA	4.78	0.49
Estonia	4,488	4	0.7	1.48	1.03
Lithuania	4,043	8	1.0	3.72	0.51
Slovenia	3,197	8	NA	1.99	0.41
Moldova	2,952	2	-0.9	4.34	1.54
Macedonia, F.Y.R.	2,934	4	NA	2.16	0.69
Latvia	2,543	6	0.6	2.52	0.46
Bosnia and Hercegovina	503	9	NA	4.38	0.06
<b>Middle Income</b>	427,153	1,372	4.7	323.67	0.31
Korea, Rep.	101,963	288	8.8	44.85	0.35
Brazil	68,012	370	4.5	159.22	0.18
Taiwan	46,720	195	NA	21.30	0.24
Argentina	35,334	149	1.8	34.67	0.24
Malaysia	29,095	71	7.3	20.14	0.41
Trinidad and Tobago	4,670	6	NA	1.29	0.84
Puerto Rico	4,240	36	NA	3.72	0.12
Netherlands Antilles	1,762	..	NA	..	NA
Cyprus	1,413	7	NA	0.73	0.21
Gabon	967	6	NA	1.10	0.17
Suriname	587	2	NA	0.43	0.36
Martinique	556	..	NA	..	NA
Malta	471	3	NA	0.37	0.16
New Caledonia	468	..	NA	..	NA
Reunion	424	..	NA	..	NA
Macao	336	4	NA	1.97	0.08
Barbados	225	0	NA	1.53	0.75
French Polynesia	153	..	NA	..	NA
Antigua and Barbuda	88	0	NA	0.07	0.20
Gibraltar	62	..	NA	..	NA
St. Lucia	52	0	NA	0.16	0.11
Seychelles	44	0	NA	0.08	0.11
Nauru	38	..	NA	..	NA
St. Kitts and Nevis	26	0	NA	0.04	0.14
St. Pierre and Miquelon	19	..	NA	..	NA
Montserrat	12	..	NA	..	NA
Turks and Caicos Islands	0	..	NA	..	NA
Isle of Man	..	..	NA	..	NA
Northern Mariana Islands	..	..	NA	..	NA
Anguilla	..	..	NA	..	NA
<b>High-income OPEC</b>	129,416	234	3.7	32.03	0.55
United Arab Emirates	18,642	37	NA	2.46	0.50
Qatar	7,920	7	NA	0.64	1.07
Kuwait	13,297	32	NA	1.55	0.41
Saudi Arabia	69,392	108	3.7	18.98	0.64
Libya	10,754	27	NA	5.41	0.40
Oman	3,116	14	NA	2.14	0.22
Bahrain	4,048	5	NA	0.58	0.77
Brunei	2,247	4	NA	0.29	0.64

<b>Lower-Middle Income</b>	560,578	1,156	3.7	571.42	0.43
Mexico	97,662	179	3.4	91.83	0.54
South Africa	83,462	102	2.1	41.46	0.82
Iran, Islamic Rep.	71,987	211	NA	64.12	0.34
Venezuela	49,193	65	2.0	21.67	0.76
Turkey	47,773	129	4.3	61.06	0.37
Thailand	47,773	122	7.5	58.24	0.39
Kazakhstan	37,093	18	1.6	16.61	2.04
Algeria	24,909	76	3.4	27.96	0.33
Colombia	18,429	57	4.5	36.81	0.32
Syrian Arab Rep.	12,561	20	6.2	14.11	0.62
Chile	12,037	16	5.2	14.23	0.75
Peru	8,341	28	2.2	23.82	0.30
Morocco	7,995	26	3.9	26.56	0.31
Cuba	7,933	23	NA	11.01	0.35
Turkmenistan	7,733	1	3.6	4.51	5.96
Ecuador	6,177	7	4.5	11.48	0.83
Tunisia	4,178	15	5.1	8.96	0.29
Dominican Rep.	3,212	7	4.5	7.82	0.43
Jamaica	2,470	4	NA	2.52	0.59
Panama	1,882	8	NA	2.63	0.24
Uruguay	1,468	10	1.8	3.18	0.15
Costa Rica	1,428	7	4.1	3.40	0.20
El Salvador	1,416	7	1.9	5.62	0.22
Paraguay	1,036	6	5.2	4.83	0.18
Papua New Guinea	677	5	3.1	4.30	0.13
Guadeloupe	416	..	NA	..	NA
Mauritius	407	3	NA	1.12	0.13
French Guiana	238	..	NA	..	NA
Fiji	201	2	NA	0.79	0.11
Belize	113	1	NA	0.22	0.21
Cayman Islands	84	..	NA	..	NA
American Samoa	75	..	NA	..	NA
Pacific Islands	65	..	NA	..	NA
Grenada	46	0	NA	0.10	0.21
St. Vincent and the Grenadines	34	0	NA	0.11	0.15
Tonga	28	0	NA	0.10	0.28
Dominica	22	0	NA	0.07	0.13
Vanuatu	17	0	NA	0.17	0.11
Cook Islands	6	..	NA	..	NA
Niue	1	..	NA	..	NA
Namibia	..	..	NA	..	NA
Micronesia	..	..	NA	..	NA
Marshall Islands	..	..	NA	..	NA
Wallis and Futuna	..	..	NA	..	NA
<b>China</b>	871,311	654	8.5	1200.24	1.33

<b>Low Income</b>	620,793	1,216	3.4	2377.02	0.51
India	248,017	447	4.4	929.36	0.55
Indonesia	80,822	158	7.1	193.28	0.51
Korea, Dem. Rep.	70,138	15	NA	23.87	4.82
Iraq	27,020	12	NA	20.10	2.33
Uzbekistan	26,986	15	3.3	22.77	1.77
Egypt, Arab Rep.	25,023	48	5.4	57.80	0.53
Pakistan	23,296	56	5.3	129.91	0.42
Philippines	16,692	49	3.4	68.60	0.34
Azerbaijan	11,620	3	-0.2	7.51	3.52
Viet Nam	8,654	68	NA	73.48	0.13
Bangladesh	5,713	27	3.3	57.80	0.21
Yemen	3,933	11	NA	15.27	0.37
Lebanon	3,641	6	NA	4.01	0.57
Jordan	3,632	9	NA	4.21	0.40
Bolivia	2,859	7	2.5	57.80	0.43
Mongolia	2,308	4	NA	2.46	0.55
Georgia	2,114	3	-3.4	5.40	0.80
Guatemala	1,962	11	3.4	10.62	0.18
Myanmar	1,919	15	NA	45.11	0.13
Sri Lanka	1,607	10	4.5	18.11	0.15
Kyrgyzstan	1,491	1	2.4	4.52	1.18
Honduras	1,052	6	3.8	5.92	0.17
Tajikistan	1,021	2	3.4	5.84	0.61
Armenia	996	1	-0.1	3.76	0.83
Nicaragua	737	4	-0.2	4.38	0.18
Albania	504	3	NA	3.26	0.15
Nepal	418	5	3.7	21.46	0.08
Afghanistan	338	14	NA	23.48	0.02
Guyana	255	1	NA	0.83	0.50
Haiti	174	2	0.4	7.17	0.09
Cambodia	136	2	NA	10.02	0.09
Lao, PDR	84	2	NA	4.88	0.04
Bhutan	65	0	NA	0.70	0.14
Western Sahara	57	..	NA	..	NA
Maldives	50	0	NA	0.25	0.25
Solomon Islands	44	0	NA	0.38	0.16
Western Samoa	36	0	NA	0.17	0.36
Sao Tome and Principe	21	0	NA	0.13	0.29
Kiribati	6	0	NA	0.08	0.17
West Bank	..	..	NA	..	NA
Gaza Strip	..	..	NA	..	NA
Tuvalu	..	..	NA	..	NA
Tokelau	..	..	NA	..	NA
Africa	45,352	199	2.7	532	0.23
Swaziland	124	1	NA	0.90	0.13
Lesotho	..	..	NA	..	NA
Nigeria	24,759	45	2.9	111.27	0.55
Cote d'Ivoire	2,828	12	2.6	13.98	0.24
Sudan	955	14	NA	26.71	0.07
Kenya	1,824	11	5.2	26.69	0.16
Angola	1,256	8	NA	10.77	0.16
Botswana	612	3	NA	1.46	0.20
Congo	346	3	NA	2.63	0.13
Zaire	573	5	NA	43.85	0.11
Zimbabwe	2,657	8	2.9	11.01	0.35
Ethiopia	962	10	NA	56.40	0.10
Senegal	836	6	2.5	8.47	0.13
Ghana	1,104	8	1.9	17.08	0.14
Zambia	656	3	0.9	8.98	0.25
Madagascar	307	3	0.5	13.65	0.10
Guinea	295	3	NA	6.59	0.10
Cameroon	1,131	11	3.3	13.29	0.10
Uganda	285	12	NA	19.17	0.02
Niger	305	3	0.3	9.03	0.11
Mali	127	3	3.0	9.79	0.04
Rwanda	134	1	0.8	6.40	0.09
Malawi	198	2	3.7	9.76	0.12
Benin	173	2	NA	5.48	0.08
Somalia	3	1	NA	9.49	0.00

**Table 3-2. Major Regional Aggregates in RICE-99 Regions**

	<b>Industrial CO2 Emissions</b>	<b>Gross Domestic Product</b> [1990 U.S. prices, market exchange rates]			<b>Population</b>	<b>CO2-GDP Ratio</b>
	[million metric tons, carbon weight]	[billions]	Growth rate of real GDP [% per year]	GDP per capita	[millions]	[tons per \$1000]
	1995	1995	1970-95	1995	1995	1995
<b>United States</b>	1,407.3	6,176	2.6	23,472	263.1	0.23
<b>Other High Income</b>	556.9	4,507	3.6	23,522	191.6	0.12
<b>OECD Europe</b>	850.8	6,891	2.4	18,094	380.9	0.12
<b>Russia and Eastern Europe</b>	863.8	693	1.6	2,098	341.6	1.24
<b>Middle Income</b>	427.2	1,372	4.7	4,239	323.7	0.31
<b>Lower-Middle Income</b>	560.6	1,156	3.7	2,023	571.4	0.48
<b>China</b>	871.3	654	8.5	545	1,200.3	1.33
<b>Low Income</b>	620.8	1,216	3.4	512	2,377.0	0.51
<b>World</b>	<b>6,158.7</b>	<b>22,665</b>	<b>3.0</b>	<b>4,020</b>	<b>5,649.7</b>	<b>0.51</b>

**Notes on Tables 3-1 through 3-5**

Sources:

Output and population data are from ~~World Development Indicators, 1998~~, CD-ROM.

Energy data for 1995 were from United Nations, ~~1995 Energy Statistics Yearbook~~, New York 1997.

Energy data for 1970 were from United Nations Dept. of Economic and Social Affairs Statistical Office,  
~~World Energy Supplies, 1970-73~~, New York, 1975.

Energy data for other years were from the World Bank, ~~World Development Indicators 1998~~.

Data on carbon dioxide emissions were from the web page of the Carbon Dioxide Information Analysis Center  
([http://cdiac.esd.ornl.gov/cdp/95\\_emis\\_1998/top95.tot](http://cdiac.esd.ornl.gov/cdp/95_emis_1998/top95.tot)).

Multiple adjustments were made for countries, particularly for Cuba, North Korea, Afghanistan,  
the former Yugoslavia, and the former Soviet Union.

Aggregate growth rates apply to totals for world or region.

**Table 3-3**  
**GROWTH RATES OF PER CAPITA GDP: Regional Averages**

[Percent per year, annual average]

	<b>1970-75</b>	<b>1975-80</b>	<b>1980-85</b>	<b>1985-90</b>	<b>1990-95</b>	<b>1970-95</b>
<b>United States</b>	1.10%	2.08%	1.60%	1.83%	1.29%	1.58%
<b>Other High Income</b>	2.95%	3.16%	2.42%	3.53%	0.96%	2.60%
<b>OECD Europe</b>	2.32%	2.70%	1.37%	2.74%	0.95%	2.01%
<b>Russia and Eastern Europe</b>	5.20%	4.20%	2.75%	1.08%	-7.04%	1.14%
<b>Middle Income</b>	4.51%	4.14%	-1.91%	1.55%	3.04%	2.24%
<b>Lower-Middle Income</b>	2.46%	2.31%	0.13%	0.92%	0.75%	1.31%
<b>China</b>	3.34%	4.89%	8.72%	6.30%	11.08%	6.83%
<b>Low Income</b>	1.87%	2.53%	-0.37%	1.25%	0.07%	1.06%
<b>World</b>	2.18%	2.96%	0.37%	1.91%	0.62%	1.60%

**Table 3-4**

**GROWTH RATES OF COMMERCIAL ENERGY/GDP RATIO: Regional Aggregates  
[Percent per year, annual average]**

	<b>1970-75</b>	<b>1975-80</b>	<b>1980-85</b>	<b>1985-90</b>	<b>1990-95</b>	<b>1970-95</b>
<b>United States</b>	0.03%	-1.32%	-2.86%	-1.10%	-1.67%	-1.39%
<b>Other High Income</b>	1.90%	-1.51%	-2.48%	-1.00%	-1.82%	-0.99%
<b>OECD Europe</b>	1.43%	-0.81%	-1.19%	-1.74%	-2.95%	-1.06%
<b>Russia and Eastern Europe</b>	-2.76%	-2.01%	1.75%	-2.26%	0.74%	-0.93%
<b>Middle Income</b>	3.12%	1.77%	3.46%	1.65%	-1.16%	1.75%
<b>Lower-Middle Income</b>	9.70%	-0.57%	3.97%	-1.71%	-2.35%	1.71%
<b>China</b>	-1.62%	-0.62%	-5.12%	-2.85%	-8.15%	-3.71%
<b>Low Income</b>	-3.83%	1.16%	4.95%	1.33%	-0.20%	0.64%
<b>World</b>	0.78%	-0.69%	-0.02%	-1.39%	-2.38%	-0.75%

**Table 3-5  
GROWTH RATES OF CO2-GDP RATIO: Regional Averages**

[Percent per year, annual average]

	<b>1970-75</b>	<b>1975-80</b>	<b>1980-85</b>	<b>1985-90</b>	<b>1990-95</b>	<b>1970-95</b>
<b>United States</b>	-1.88%	-1.75%	-3.23%	-0.70%	-1.41%	-1.80%
<b>Other High Income</b>	-1.44%	-1.94%	-3.15%	-1.61%	-0.30%	-1.70%
<b>OECD Europe</b>	-2.03%	-1.32%	-3.18%	-2.68%	-1.94%	-2.23%
<b>Russia and Eastern Europe</b>	-1.87%	-2.09%	-1.64%	-2.71%	2.47%	-1.19%
<b>Middle Income</b>	-1.63%	2.10%	1.85%	0.97%	2.48%	1.14%
<b>Lower-Middle Income</b>	0.10%	-0.05%	0.25%	-0.43%	-0.51%	-0.13%
<b>China</b>	2.39%	-0.99%	-4.09%	-3.43%	-5.93%	-2.45%
<b>Low Income</b>	2.64%	0.83%	0.57%	0.73%	1.54%	1.26%
<b>World</b>	-0.65%	-1.02%	-1.47%	-1.45%	-0.77%	-1.07%

**Table 3-6**  
**Comparison of RICE-99 with Maddison Projections**  
 [Annual average growth rates of per capita GDP]

Maddison region	RICE region	Historical estimates		Projections		Difference
		RICE 1970-95	Maddison 1973-95	RICE 1995-2015	Maddison 1995-2015	
United States	<b>United States</b>	1.58%	1.55%	1.36%	1.30%	0.06%
Japan	<b>Other High Income</b>	2.60%	2.53%	1.32%	1.30%	0.02%
Western Europe	<b>OECD Europe</b>	2.01%	1.72%	1.32%	1.30%	0.02%
	<b>Russia and Eastern</b>					
Other Europe	<b>Europe</b>	1.14%	0.48%	2.63%	2.68%	-0.05%
Other Americas	<b>Middle Income</b>	2.24%	0.68%	2.05%	1.33%	0.72%
Other Americas	<b>Lower-Middle Income</b>	1.31%	0.68%	2.54%	1.33%	1.21%
China	<b>China</b>	6.83%	5.37%	3.37%	4.50%	-1.13%
India and Africa*	<b>Low Income</b>	1.06%	1.78%	2.93%	2.38%	0.55%
<b>Weighted average*</b>		2.52%	2.30%	2.68%	2.52%	0.16%

Source: Maddison [1998a], [1998b], and [1995] and RICE-99 model, base case

\*Weighted by 1995 population

**Table 3-7. Growth in Per Capita Output in RICE-99 Regions:  
Historical Rates and Projections**

Region	-----RICE-99 Model Calculations-----							Per Capita Output [1990 US prices]	
	Actual	Growth Rate of Per Capita Output					Projected	Actual	Projected
		1970-95	1995-2005	2005-15	2015-25	1995-2045			
<b>United States</b>	1.58%	1.62%	1.06%	0.83%	0.98%	0.73%	\$22,862	\$53,480	
<b>Other High Income</b>	2.60%	1.56%	1.05%	0.83%	0.97%	0.75%	22,514	53,013	
<b>OECD Europe</b>	2.01%	1.60%	1.05%	0.81%	0.98%	0.72%	18,818	43,822	
<b>Russia and Eastern Europe</b>	1.14%	3.04%	2.25%	1.90%	2.10%	1.65%	2,095	13,443	
<b>Middle Income</b>	2.24%	2.37%	1.74%	1.46%	1.63%	1.31%	5,091	21,918	
<b>Lower-Middle Income</b>	1.31%	2.91%	2.14%	1.80%	2.00%	1.52%	2,053	11,729	
<b>China</b>	6.83%	3.81%	2.94%	2.54%	2.75%	2.14%	486	5,442	
<b>Low Income</b>	1.06%	3.39%	2.46%	2.07%	2.30%	1.77%	436	3,265	

Note: The estimates of output levels and growth rates use market exchange rates to convert to 1990 U.S. dollars.

The levels of output are calculated to be substantially higher for low-income countries and lower for Japan and Europe if purchasing power parity (PPP) exchange rates are used. Historical growth rates using PPP exchange rates are not available for most countries.

**Table 3-8**  
**Comparison of RICE-99 Reference Case with IIASA Scenario B**

	-----2025-----		-----2055-----	
	<i>IIASA</i>	<i>RICE-99</i>	<i>IIASA</i>	<i>RICE-99</i>
<b>Population (billions)</b>	8.3	7.6	10.4	9.1
<b>World Output (\$ trillions, 1990 prices)</b>	43.4	40.7	78.2	59.3
<b>Industrial Carbon Emissions (GtC per year)</b>	8.6	8.4	9.8	10.0
<b>Carbon Intensity (tons per \$ million)</b>	199	207	125	168

Source for IIASA: Nakicenovic et al [1998], Appendix C. (Extrapolated from 2020 and 2050 projections.)

**Table 3-9**

**Non-CO2 Radiative Forcings According to IPCC-90,  
MAGICC/IPCC-99, and RICE-99**

**A. Estimated Forcings (watts per meter squared)**

Year	[1]	[2]	[3]
	IPCC-90	MAGICC/ IPCC-99	RICE-99
1990	0.95		
2000		-0.07	-0.06
2010			0.07
2020			0.21
2030			0.34
2040			0.48
2050	1.85	0.69	0.61
2060			0.75
2070			0.88
2080			1.02
2090			1.15
2100	2.12	1.14	1.15

**B. Components of forcings, MAGICC/IPCC-99 (watts per meter squared)**

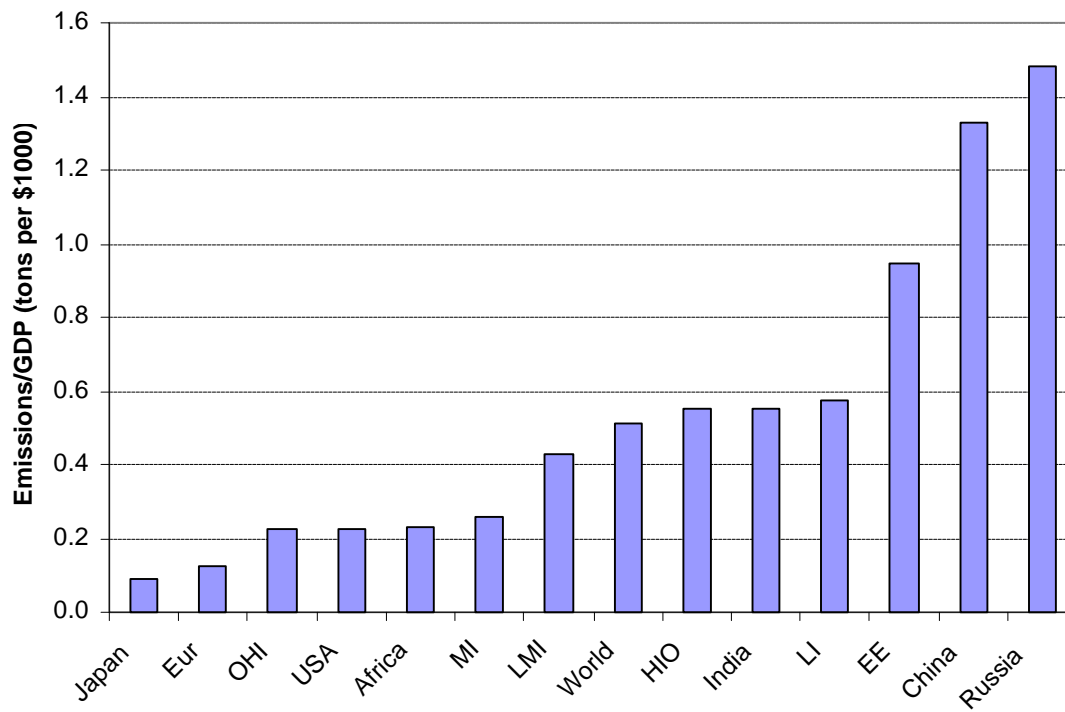
	2000	2050	2100
CO2	1.85	3.55	5.01
CH4	0.48	0.86	1.07
Tropospheric ozone	0.41	0.49	0.55
Halocarbons and stratospheric ozone	0.16	0.24	0.34
N2O	0.17	0.23	0.24
Aerosols (direct and indirect)	-1.29	-1.13	-1.06
Total	1.78	4.24	6.15
Total, non-CO2	-0.07	0.69	1.14

Part A, column [1] is from IPCC [1990], pages 54 and 57

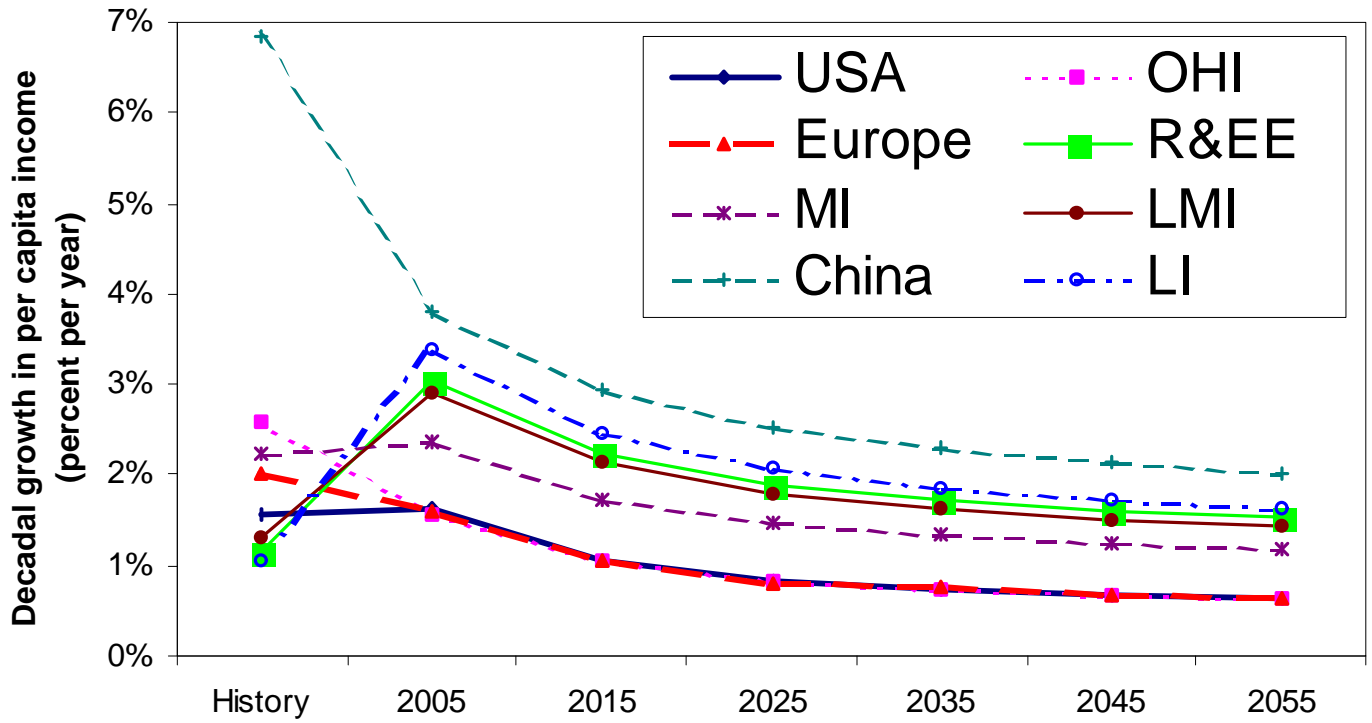
Part A, column [2], and Part B are the result of the MAGICC model  
(Wigley, Solomon, and Raper [1994]) taking emissions from IPCC  
Scenario B2 as implemented in IIASA's MESSAGE model  
as of Jan 11, 1999

Part B is from the same source as Part A, column [2]

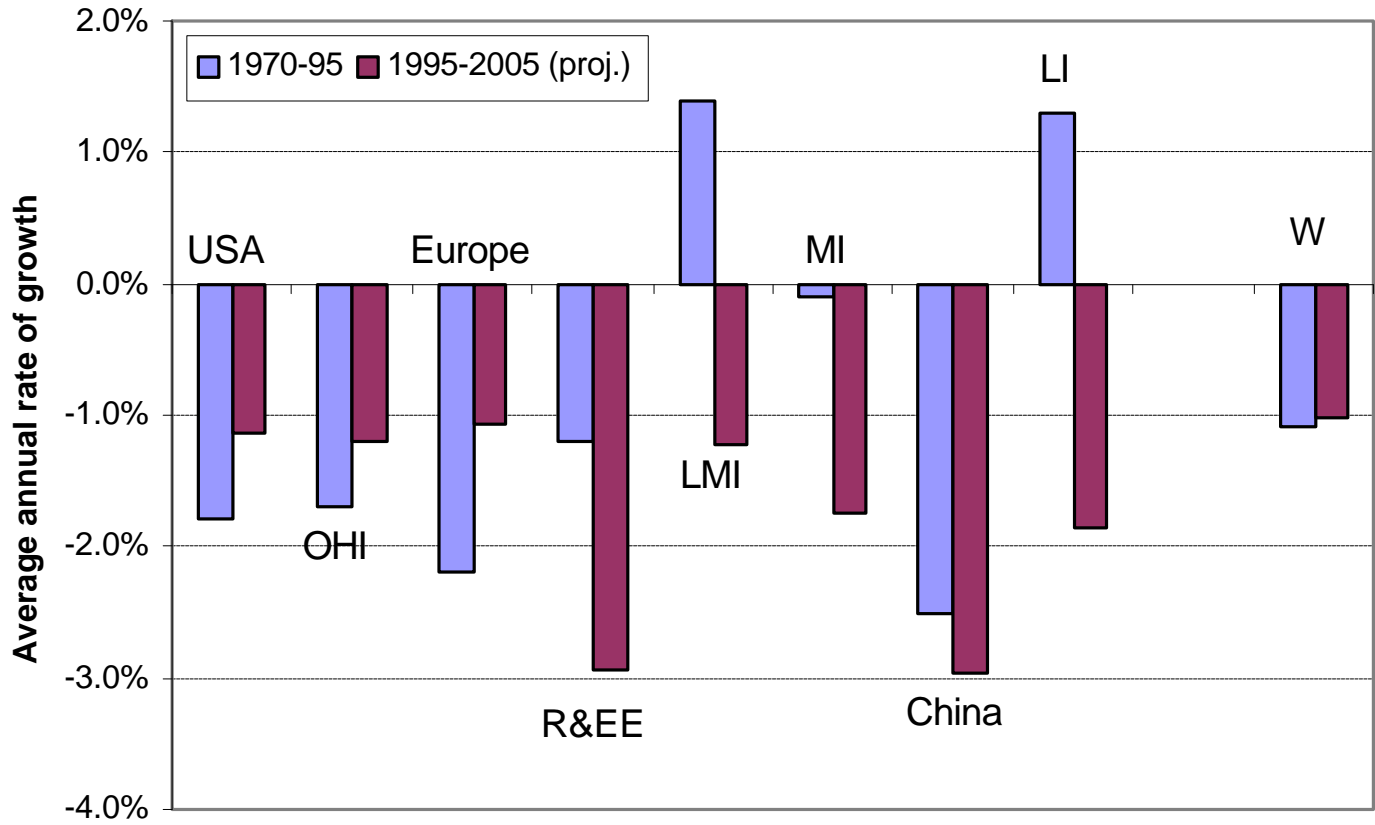
Figure 3-1



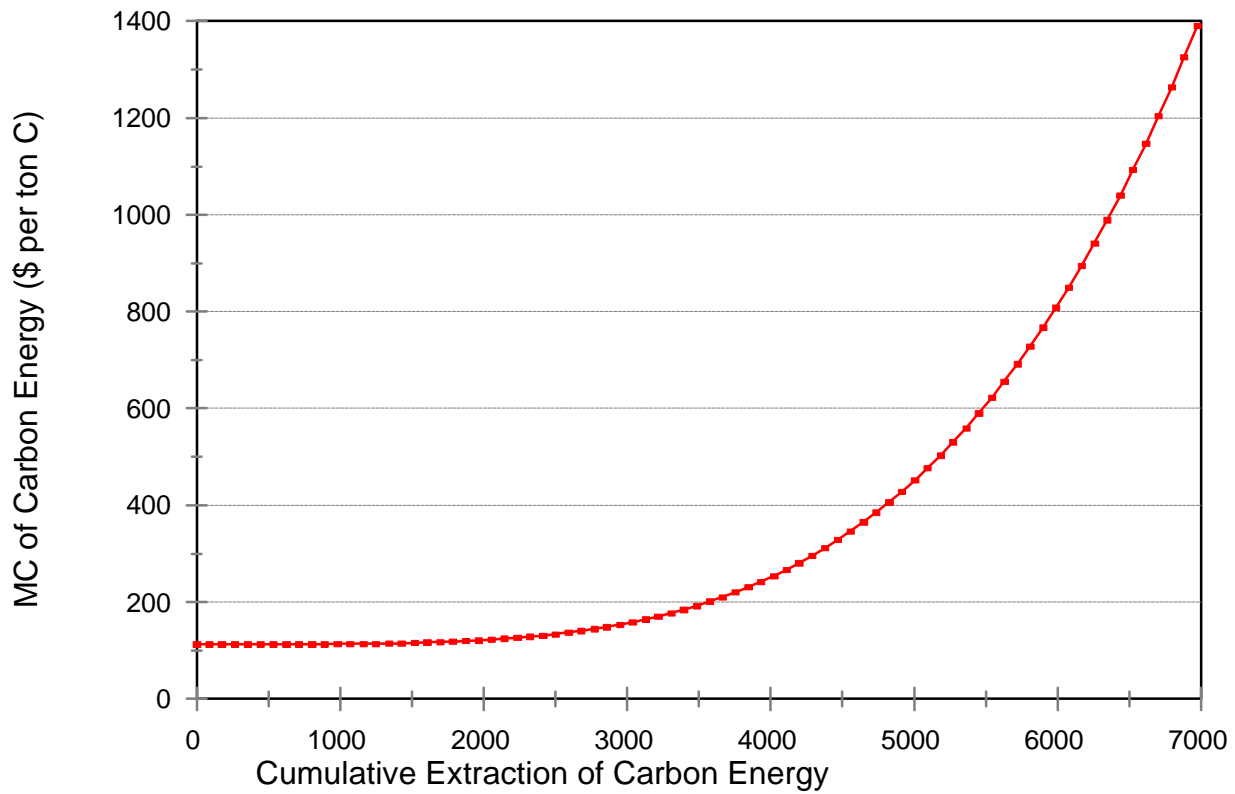
**Figure 3-2. Growth in Per Capita Output**



**Fig. 3-3. Growth in CO<sub>2</sub> Emissions/GDP Ratio**

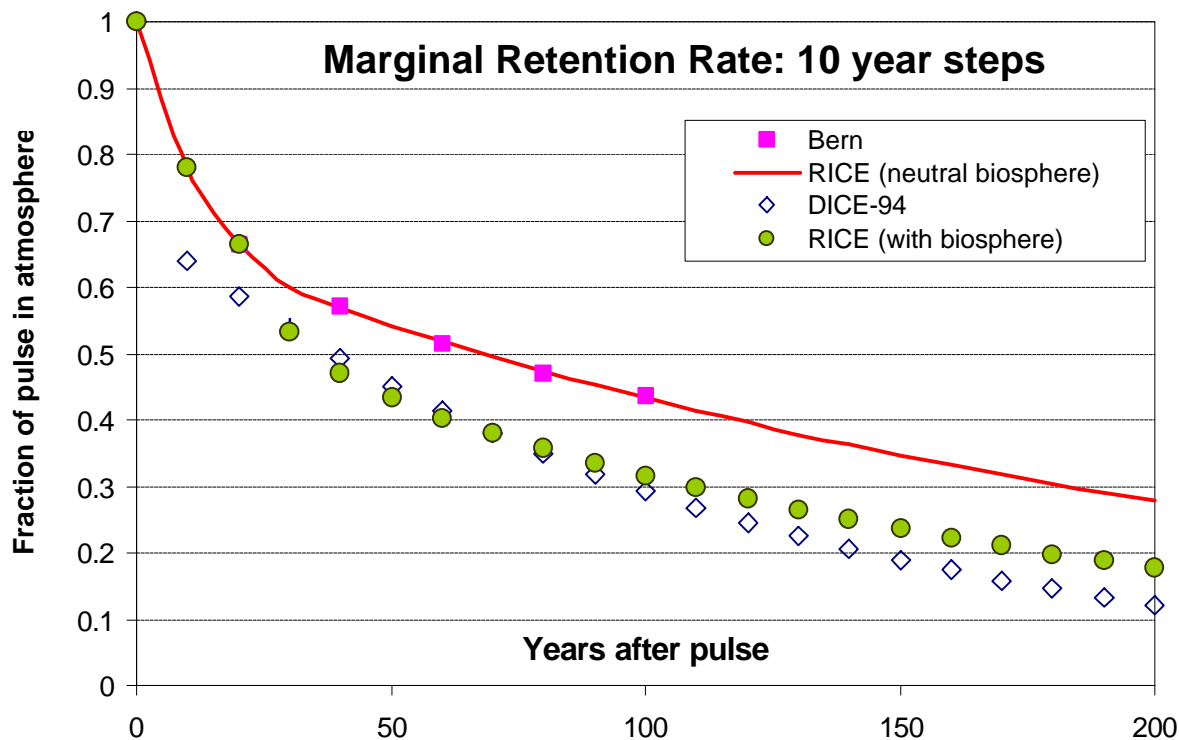


**Figure 3-4.**  
**Carbon Supply Function**  
**in RICE-99 Model**



Note: Cumulative extraction is measured as the carbon content of fossil fuels in billions of tons. MC is marginal cost in 1990 U.S. dollars per ton of carbon equivalent.

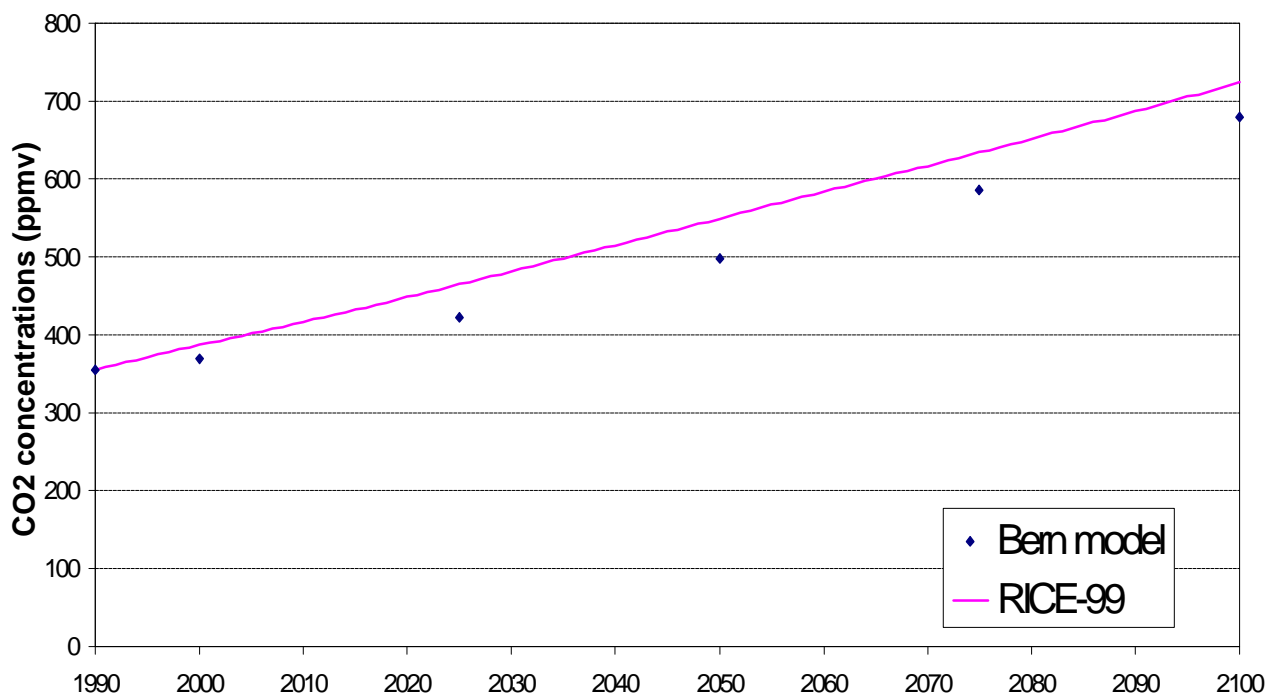
**Figure 3-5**  
**Impulse Response Functions for Different Models**



Note: Solid line is projection from RICE-99 model assuming a neutral biosphere (that is, no effect of changing concentrations on mass of carbon in biosphere). This matches closely the simulation of the Bern model with a neutral biosphere, shown as squares. The bottom two lines show the RICE-99 and DICE-94 models with active biospheres.

**Figure 3-6**

**Comparison of Projections of CO<sub>2</sub> Concentrations from RICE-99 and Bern Models for IPCC 92a Emissions Projection**

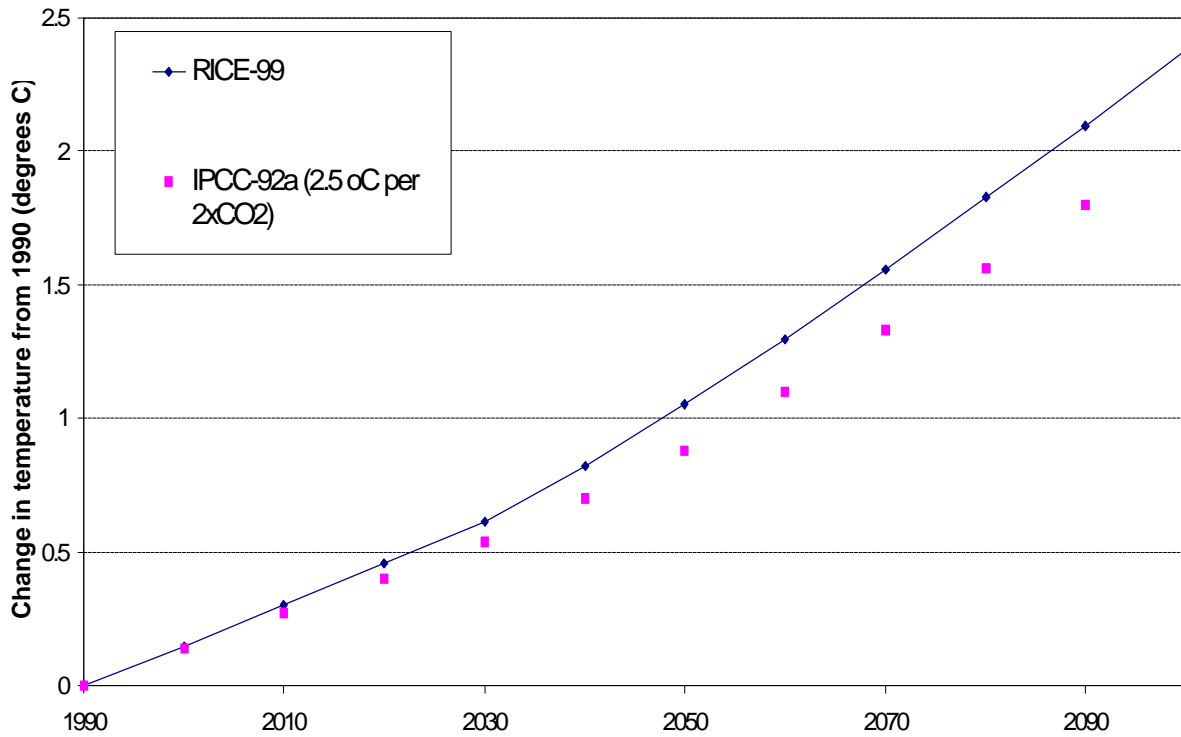


Note: Solid line is projection of CO<sub>2</sub> concentrations using IPCC 92a emissions projection. Diamonds are projections using Bern model. Emissions and the Bern simulation are from IPCC [1996c], p. 23.

Source: carbon calibrate ipcc a 111198.xls

**Figure 3-7**

**Comparison of Temperature Simulation  
of RICE-99 Model with IPCC-96**



Note: Both calculations use the radiative forcings with aerosols and emissions according to IPCC 92a from IPCC [1996c], pp. 321. The IPCC calculation has an equilibrium temperature increase of 2.5 °C for an equilibrium CO<sub>2</sub> doubling, whereas the RICE model has an equilibrium temperature increase of 2.9 °C for an equilibrium CO<sub>2</sub> doubling.

Endnotes:

1. In the tables and text throughout the book, we will occasionally use the following abbreviations: United States – “USA,” Other High Income – “OHI,” OECD Europe – “Europe,” Russia and Eastern Europe – “R&EE,” Middle Income – “MI,” Lower-Middle Income – “LMI,” Low Income – “LI.”
2. For the fourth equation, we measure the change in emissions assuming the initial carbon tax is 0.
3. The Hotelling rent is calculated to be \$0.39 per ton carbon-energy in the first period in the RICE base case, which is essentially zero as compared with  $q(0) = \$113$  per ton.
4. To get the left-hand side of (3.2d) for a given region, we first delete from the data set all countries for which we do not have complete data. We then calculate the change in emissions from each country due to the imposition of the \$50 carbon tax, using (3.3) and (3.4). We then sum these up and multiply by the ratio of total industrial carbon emissions in the region (including the countries dropped from the calculation) to the sum of the left-hand side of (3.3) across countries in the restricted data set.
5. See EIA [1996].
6. The RICE-99 projections in the tables in this chapter come from the base case. See Chapter 2, section 5 for explanation.
7. Carbon intensity is the ratio of industrial carbon emissions to GDP.

8. See Cline [1992a].

9. See Schultz and Kasting [1997].

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

11. By pre-industrial times, we mean the year 1750.

12. 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  $\epsilon$  to  $x$  at  $t = 0$ , so  $x(t) = \epsilon \exp(-\delta t)$ . Therefore, when  $T = 1/\delta$ ,  $x$  has declined to  $x(T) = \epsilon/e$ . Hence the “e-folding time” is the time required for an exponential process to decay to  $1/e = 0.37$  of its equilibrium value after a shock.