Formulation Experiments with a Simple Climate/Economy Model

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Abstract

Much of the science and policy debate around global climate change has focused on models. Most models focus on a single aspect of climate change - atmospheric physics and chemistry, macroeconomic effects of abatement policies, or impacts on land cover from changing temperature and rainfall for example. Only a few models attempt to make climate change fully endogenous by including both the influence of human activities on climate and the impact of climate change on human activity.

The best-known climate-economy model is William Nordhaus' DICE model. The model is a conventional macroeconomic Ramsey growth model with simple carbon and temperature subsystems added. These create a negative feedback loop which tends to reduce economic output due to climate impacts on economic activity. Experiments with the model suggest that only limited effort should be addressed to CO_2 emissions abatement. While the DICE model meets some of the expectations of a system dynamics model, in other ways it falls short. Key variables are exogenous, such as the growth of population and emissions reduction technology. Output is generated by optimization, rather than by simulation with explicit decision rules.

This paper explores the impact of structural changes to the model specification that attempt to bring it closer to the system dynamics paradigm. The impact of exogenous population and technology drivers is explored. Carbon flows are made more explicit, to demonstrate the importance of sink constraints and temperature feedbacks to the carbon cycle. A path dependent energy sector with endogenous technology is tested. Boundedly rational decision rules are substituted for optimization. These tests generally yield results suggesting substantially higher abatement levels than Nordhaus concludes are necessary.

Copies of the DICE model and the revisions described in this paper are available in Vensim format from the author at the address above.

Many energy and economic models have been used to evaluate the cost of reducing greenhouse gas emissions (Beaver 1993; OECD 1993; Wilson and Swisher 1993). Some models also incorporate damage functions for evaluating the costs of climate change (Rotmans 1990; Hope 1993). Few make climate change fully endogenous, closing a feedback loop between the global economy and climate (Hatlebakk and Moxnes 1992; Nordhaus 1992; Nordhaus 1992; Peck and Teisberg 1993; Nordhaus 1994).

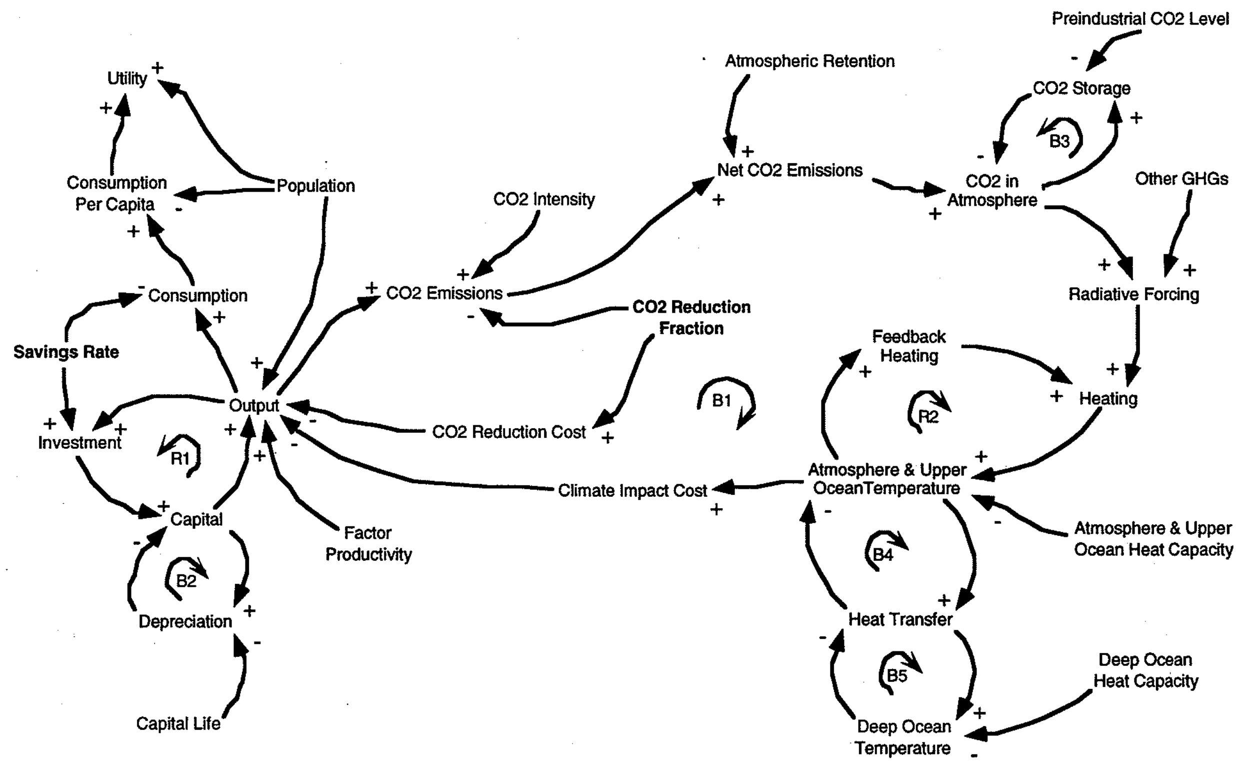
The DICE model shares much with a typical system dynamics model. It incorporates stocks and flows, nonlinearities, and disequilibrium, and is problem-oriented. However, it differs from a typical system dynamics model in several important ways. The time paths of decision variables in the model are determined by optimization, rather than explicit behavioral rules. Exogenous variables play a large role in the model behavior. Sources and sinks are treated less thoroughly. While the model is expressed in continuous equations, the simulation interval is long enough that it effectively runs in discrete time, and integration error is significant. The level of aggregation is higher than the level at which recognizable policy levers operate, so some supplementary analysis is necessary when experimenting with the model.

Table 1. Features of the DICE model

Endogenous	Exogenous	Excluded
Capital	Population	CO_2 in ocean, biota, soils
Output	Factor productivity (technology)	Temperature feedback to carbon cycle
Investment	Emissions reduction technology	Spatial and regional dynamics
Consumption	Other greenhouse gas emissions	Energy sector
CO_2 emissions		Pollutant interactions
Emissions abatement costs		Trade
Atmospheric CO_2		Agriculture
Temperature		
Climate change damage		

The DICE model is probably the simplest of the integrated climate-economy models. The causal structure of the model is shown in figure 1. There are 2 positive and 5 negative feedback loops. Three other sets of feedback loops - population growth, factor productivity increase, and the decline of CO_2 intensity of economic output - may be considered exogenous inputs to the model, as their rates of change are specified by fixed parameters. It has a one-sector economy with a single stock of capital. Economic output is generated by inputs of labor, capital, and technology. Economic activity drives the emission of CO_2, which contributes to an increase in the atmospheric stock. The CO_2 intensity of economic activity decreases autonomously and may be further reduced by costly policies. Over time, CO_2 is removed from the atmosphere by storage and transport processes. Elevated concentrations of CO_2 and other greenhouse gases (GHGs) in the atmosphere increase radiative forcing, which warms the atmosphere and upper layers of the ocean. Positive feedback strengthens the warming, but much of the excess heat absorbed by the atmosphere and upper ocean is transferred to the deep ocean. Temperature changes in the atmosphere and upper ocean cause climate damage costs which reduce economic output.

Figure 1. Causal Structure of the DICE Model



Positive feedback or Reinforcing loops are labeled R#, while negative feedback or Balancing loops are labeled B#. The structure of the utility discounting process is omitted. The decision variables in the optimization are shown in boldface.

The gross behavior of the model arises from the positive feedback in population growth and factor productivity (exogenous) and capital accumulation (loop R1), which leads to exponential growth of output. This growth can be attenuated as increasing economic activity leads to accumulation of greenhouse gases in the atmosphere, which reduces output through climate change damage after a long delay (loop B1). The action of this balancing loop is weak and delayed, because there are large accumulations and negative feedback loops that intervene between GHG emissions and their consequences.

Policies that reduce greenhouse gas emissions reduce the gain around both the strong positive loop of capital growth and the weak, delayed loop of climate change. The costs of weakening the economic growth loop generally outweigh the benefits of avoided climate change. Because of this fact, and time discounting, emissions reductions indicated by the model are very modest - on the order of 10%. It is preferable to grow the economy to pay for the cost of future climate damages than to reduce emissions to avoid them.

This paper explores assumptions and formulations of the model and proposes some structural revisions, which alter the preferred balance between growth and emissions reductions. These issues can be grouped into three areas: discounting and utility in the objective function, the capital growth loop, and the climate change loop. Each will be considered in turn.

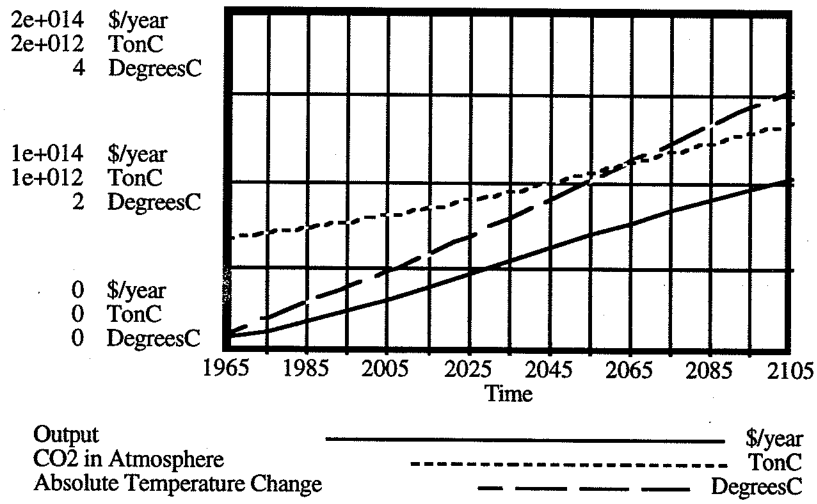


Figure 2. Standard Run of the DICE Model

Output, the stock of carbon in the atmosphere, and the temperature of the atmosphere and upper ocean all grow substantially over the next century. Time paths for the savings rate and greenhouse gas abatement fractions are from Nordhaus (Nordhaus 1992).

Objective Function

The objective of the optimization performed in the DICE model is to maximize cumulative discounted utility over the simulation period. Cumulative discounted utility is given by:

$$CDU = \int e^{-\rho t} P(t) \left\{ \left[C(t)/P(t) \right]^{1-\alpha} - 1 \right\} / (1-\alpha)\, dt,$$

where P is population, C is consumption, ρ is the pure rate of time preference (or discount rate on utility), and α is the rate of inequality aversion (or marginal utility of consumption). The reference value of the rate of inequality aversion is 1, in which case the objective function reduces to $CDU = \int e^{-\rho t} P(t) \ln(C(t)/P(t)) dt$. This implies that the fractional increase in utility for a given fractional increase in consumption is constant, so that an American would benefit proportionally as much from a doubling of income as a Somalian would.

The choice of rate of time preference is motivated by the desire for correspondence between the model and observed behavior. In particular, Nordhaus seeks to reconcile the discount rate and marginal product of capital (net of depreciation) in the model with observed interest rates. In steady state in the Ramsey model, the real interest rate (r) is equal to the sum of the discount rate and the growth rate (g) multiplied by the rate of inequality aversion, $r = \alpha g + \rho$. Thus observed rates of return and growth in the vicinity of 6% and 3% respectively are consistent with a 3% rate of time preference and a rate of inequality aversion of 1.

With these values, the present value of utility decreases by half every 23 years. The choice of rate of time preference thus weights current outlays for abatement more heavily than future avoided damage. It effectively sets a time horizon for concern some time in the late 21st century. Since the discount rate is greater than the rate of growth of per capita consumption, after that time further changes are unimportant. By the end of the 21st century, a year of consumption contributes less than 25% as much to cumulative discounted utility as consumption in 1990, and the discounted value of consumption of an individual in 2100 is 10% of that of an individual in 1990, in spite of growing wealth.

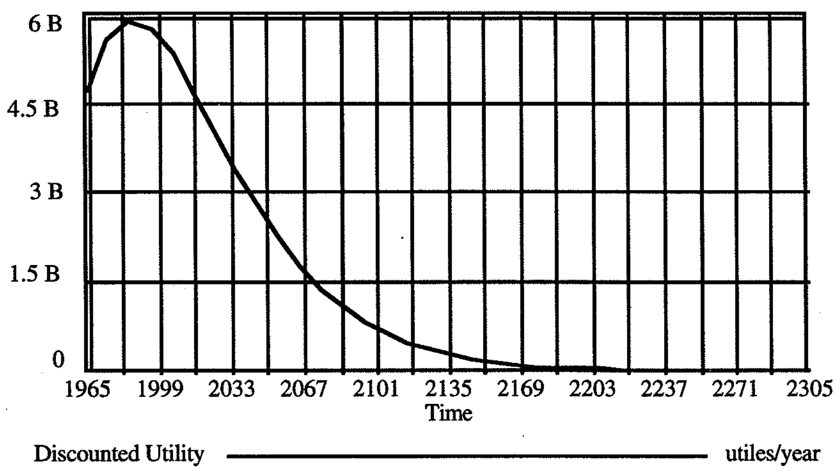


Figure 3. Discounted Utility

Discounted utility measures the annual contribution of the world population's utility to the objective function (cumulative discounted utility). Dimensions of the vertical axis are unimportant; only the relative values matter. As can be seen from the graph, by 2100, further contributions to cumulative discounted utility are negligible.

Assuming for the moment that observed investment behavior is even relevant to the essentially ethical choice of a utility function, rates of time preference and inequality aversion of 0% and 2, respectively, would be equally consistent with the observed rates of interest and growth. Then the welfare of individuals in all generations is weighted equally, but there is a bias towards current consumption when the economy is growing, as the marginal utility of a unit of consumption is lower to wealthier future generations. Given the ethical absurdity of discounting away the welfare of future generations when making social decisions about an intergenerational problem, these values seem much more appropriate, and will be tested below. An alternative approach would be to select a rate of time preference that diminishes over time, as suggested by Rothenburg (1993). Cline (1992) provides a thorough discussion of discounting and climate change policy.

Table 2. Impact of Discounting

Simulation	**Optimal Carbon Tax** $/Ton C		**CO_2 Emissions** 10^9 Ton C/year	
Year	2005	2105	2005	2105
DICE, $\rho = .03, \alpha = 1$	8	22	9.8	20
DICE, $\rho = 0, \alpha = 2$	44	202	8.6	14

Eliminating pure time preference dramatically increases the optimal abatement level. The carbon tax reported here and elsewhere is the implicit marginal productivity of carbon in the production function. Note that the optimal carbon tax and emissions levels vary slightly in the standard runs of the DICE model reported in this paper, as some changes required simulating the model with a shorter time step than Nordhaus uses. In all cases results reported in a single table are comparable, however.

Nearly as important as the issue of discount rate selection is the fact that utility is purely a function of consumption. This means that health and environmental services are excluded from consideration insofar as they are not reflected in the value of goods and services in the economy. Though Nordhaus points out that the model is intended only to address economic considerations, and that policy decisions must take ethical, aesthetic, or other concerns about the environment into account by other means, the issue is more subtle than this. The environment provides free services which are arguably not represented in current prices or national accounts. Tol (1994) addresses these issues by transferring a portion of climate damages into the utility function. This reduces the ability of changes in investment to allow substitution of goods for intangible or non-market services of the environment, and raises the indicated emissions abatement levels.

Capital Growth Loop

The core of the DICE model is a Ramsey growth model. Capital is aggregated to a single capital sector. Capital and labor are combined using a Cobb-Douglas production function to generate output. A fraction of output each year is saved and reinvested in capital, and the remainder is consumed. The savings rate varies over time according to the optimization. Capital depreciates with a fixed lifetime, stated to be 10 years. However, because the model is simulated with a time step of 1 decade, Nordhaus corrects the capital life to account for compounding, using a fractional depreciation rate of .65 per decade. This is simply incorrect; the stock of capital has an inflow as well as an outflow, and the two may not be compounded in isolation from one another. The appropriate way to correct for integration error in this case would be to use a smaller time step. Nordhaus' correction yields an effective capital life of 15.38 years, which is not implausible and is retained for comparability.

Population

Population increase is driven by an exogenous growth rate. The rate of population growth is assumed to decline, so that population stabilizes at a level near 10.5 billion in the second half of the 21st century, 3.15 times its initial value. This equilibrium population estimate is consistent with the lower bound of projections of population increase. This is an optimistic assumption; it requires that the rate of population growth decline faster in the coming decades than has been observed in the last three decades (Population Reference Bureau 1991).

There is no feedback from the economic or environmental sectors of the model to the population growth rate; birth and death rates are decoupled from economic conditions (income, health services) and environmental conditions (pollution, disease). If increasing wealth is an important factor determining the declining rate of population growth, Nordhaus' formulation may understate the importance of avoiding costs of greenhouse gas abatement now. Expenditures which reduce consumption or growth in the short term lead to a larger population, greater emissions, and lower per capita consumption in the long term. At the same time, policies that reduce population growth may offer high economic leverage (though they may be politically difficult to implement).

As a test, population can be made endogenous by linking it to wealth, as in World3, for example (Meadows 1972). This highlights the fact that the objective function is only appropriate when population is an exogenous input to the model. Otherwise, it behaves perversely (figure 4), as it rewards policies that favor population growth at the expense of per capita consumption. The objective function implies that having a population of 10 billion with a per capita income of $5000/year is better than having a population of 5 billion with a per capita income of $10000/year.

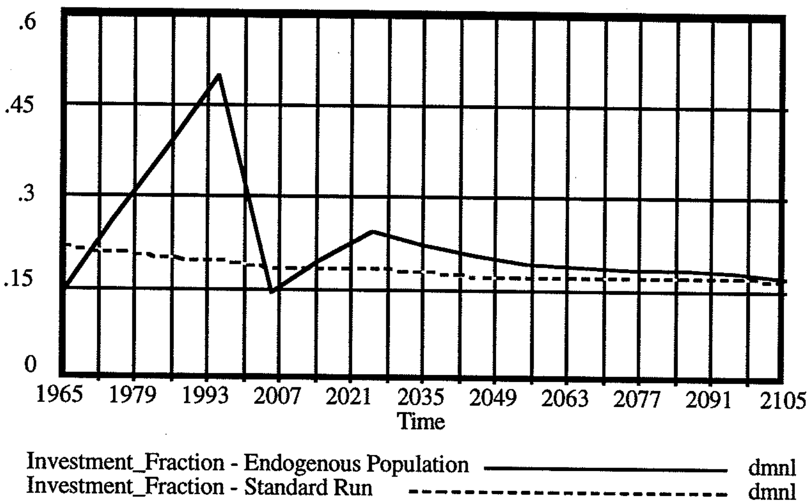


Figure 4. Endogenous Population

Endogenous population growth leads to unrealistic investment behavior with the standard objective function. A high rate of investment early in the simulation reduces consumption, so that population grows larger before stabilizing. While per capita incomes are then lower, the larger population outweighs its effects.

Factor Productivity

The output for a fixed level of capital and labor inputs increases over time due to an exogenous increase in factor productivity (technology). The rate of technological improvement declines from 1.5% per year in the late 20th century to 0.5% per year in the late 21st century, and saturates at a level 3.91 times greater than its initial value. As a result, consumption per capita roughly triples over the next century, and levels off at about six times the initial (1965) value. It's unclear what real-world feedback loops are responsible for the decline, but it would be preferable if they were explicit in the model.

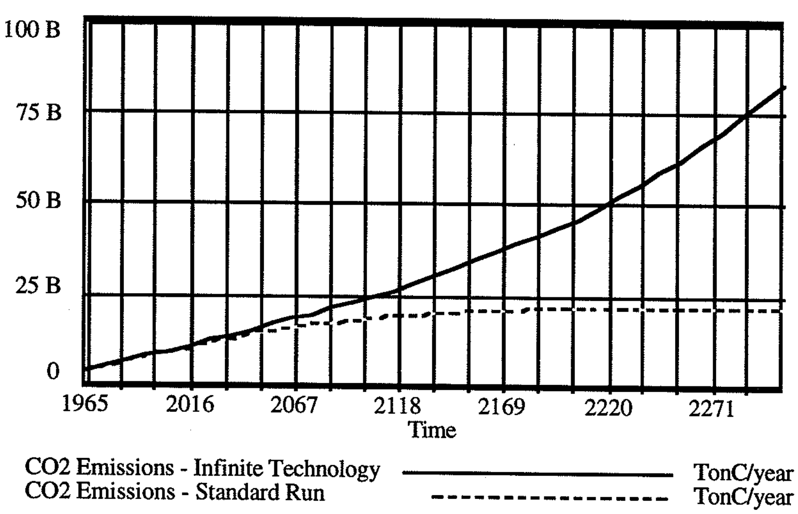


Figure 5. CO_2 Emissions

When the rates of growth of factor productivity and emissions technology do not decline, CO_2 emissions rise far higher than in the standard run.

The assumptions of declining technology and population growth reduce economic output and emissions, so that there is less pressure on the climate system. This is dramatically evident when one removes the assumption of declining factor productivity growth (see figure 5 and table 3). In spite of continually improving emissions technology, emissions rise to more than 10 times current levels in two centuries.

Table 3. Impact of Continuos Technological Progress

Simulation	Optimal Carbon Tax $/Ton C		CO_2 Emissions 10^9 Ton C/year	
Year	2005	2105	2005	2105
DICE, declining technology growth rate	6	20	9.5	19
DICE, constant technology growth rate	7	59	9.6	25

Eliminating the assumption of a declining rate of technological progress in factor productivity and emissions intensity leads to much higher emissions, necessitating stronger controls.

Investment

The choices in the utility function described above are especially crucial in the DICE model because the investment and greenhouse gas abatement decisions explicitly maximize utility. This is an extremely strong assumption, requiring that economic agents make investment decisions that maximize cumulative discounted utility over an infinite horizon for the global population, acting with perfect foresight in a system with fully internalized costs and benefits. It means that investment behavior in 1965 is already changing to compensate for the consequences of climate change occurring late in the 21st century (in Nordhaus severe climate damage run this adjustment to investment is about $3 billion per year).

While optimization is useful for finding effective policies, it is preferable to have decisions in the model use reasonable cognitive resources and rely on information which is actually available to individuals. To allow for the possibility of imperfectly functioning markets and institutions and imperfect individual action in pursuit of long-term goals, the social objective function should be decoupled from the decision making process. While many investment formulations exist in the system dynamics literature, it would be useful here to choose one which maintains close correspondence with the optimal investment path of the Ramsey model.

Table 4. Impact of Behavioral Investment Rule

Simulation		Optimal Carbon Tax $/Ton C		Savings Rate fraction of output	
Year		2005	2105	2005	2105
DICE:	$\rho = .03, \alpha = 1$	9	25	.20	.18
Objective:	$\rho = .03, \alpha = 1$	9	22	.19	.18
Behavior:	$\rho = .03, \alpha = 1$				
Objective:	$\rho = 0, \alpha = 2$	58	106	.19	.18
Behavior:	$\rho = .03, \alpha = 1$				

ρ and α are the rate of time preference and rate of inequality aversion, respectively, for the objective function and investment rule. The behavioral investment rule prevents changes in the objective function from affecting savings behavior.

This can be accomplished by using the optimal growth path, $r = \alpha g + \rho$, to produce a simple heuristic in which investors form a desired rate of return on capital based on the perceived growth rate of wealth, compare it to the prevailing rate of return, and adjust their investment behavior accordingly. If the parameters ρ and α describing observed behavior are identical to the parameters of the utility function, this rule produces decisions identical to the optimization in steady state. When population and factor productivity are growing, the decision heuristic underinvests slightly, but the path is hard to distinguish from the optimal path. This rule uses no information about the future, and allows the possibility of investment behavior different from what is socially optimal. It prevents intertemporal reallocation of investment without explicit signals from policy levers like a carbon tax.

CO_2 Emissions Reduction

Greenhouse gas emissions in the DICE model are separated into two components, CO_2, and other greenhouse gases (such as methane or NO_X). CO_2 is assumed to be controllable; the latter group is assumed to be difficult to assess and control, and is therefore taken as an exogenous impact on total radiative forcing. To the extent that these emissions are controllable, this is a restrictive assumption. Much of the methane emitted by gas production, municipal landfills, and ruminant animals may in fact be controllable, for example. The atmospheric chemistry of these pollutants is very complex, so that linkages among them may be important as well (White 1989). The focus on CO_2 means that the model is concerned almost entirely with the energy system and forestry.

CO_2 emissions are driven by increasing economic output and the intensity of CO_2 emissions per unit of output. The CO_2 intensity declines over time at an exogenous, diminishing rate. This decrease corresponds with observed decreases, principally in the developed world, and is attributed to autonomous technological change and sectoral shifts. Since technological change is not autonomous in reality, there is a significant possibility that the trend will not continue in the future. This will be especially true if the depletion of low-carbon gas and oil resources leads to a shift toward use of carbon-intensive coal, and if economic growth accelerates in the developing world. The estimated rate of change relies mainly on data from the developed countries, and may be biased by the shift of energy intensive industries to locations in the developing world (Rosa and Tolmasquim 1993).

The cost of reducing emissions is embedded in a single curve in the DICE model. The cost curve is derived from estimates by Nordhaus and other top-down model-based analyses. It is assumed that the first half of emissions reductions can be obtained at minimal cost - roughly 1% of output. Eliminating all emissions, which requires halting deforestation and converting the energy system to higher efficiency and non-carbon technology, requires roughly 7% of output. This implies that non-carbon emitting energy technologies can replace fossil fuels at three to four times the current cost of the energy system.

Nordhaus' estimates of the cost curve are comparable to the estimates produced by a variety of energy/economy models (Nordhaus 1991). It assumes that the present level of CO_2 intensity in the economy is optimal - that is, there are no free or negative-cost emissions to be had. Other studies indicate substantial opportunities for negative-cost emissions reductions (Lovins 1977; Lovins and Lovins 1991; Wilson and Swisher 1993). In considering this possibility, Nordhaus justifies the omission of such reductions by assuming that they will happen anyway, without intervention. However, he neglects to make corresponding reductions in absolute emissions levels (Wilson and Swisher 1993).

The cost of reducing emissions is based on the absolute level of emissions reductions, rather than on the rate of change of emissions reductions. This means that rapid changes in carbon intensity may be achieved at the same cost as gradual changes. In reality, long delays in technology development, exploration, and capital lifetimes impose substantial constraints on the energy system. In this respect, the DICE model is optimistic about the potential for abatement. However, the abatement cost curve is fixed over time, and thus insensitive to future technological developments.

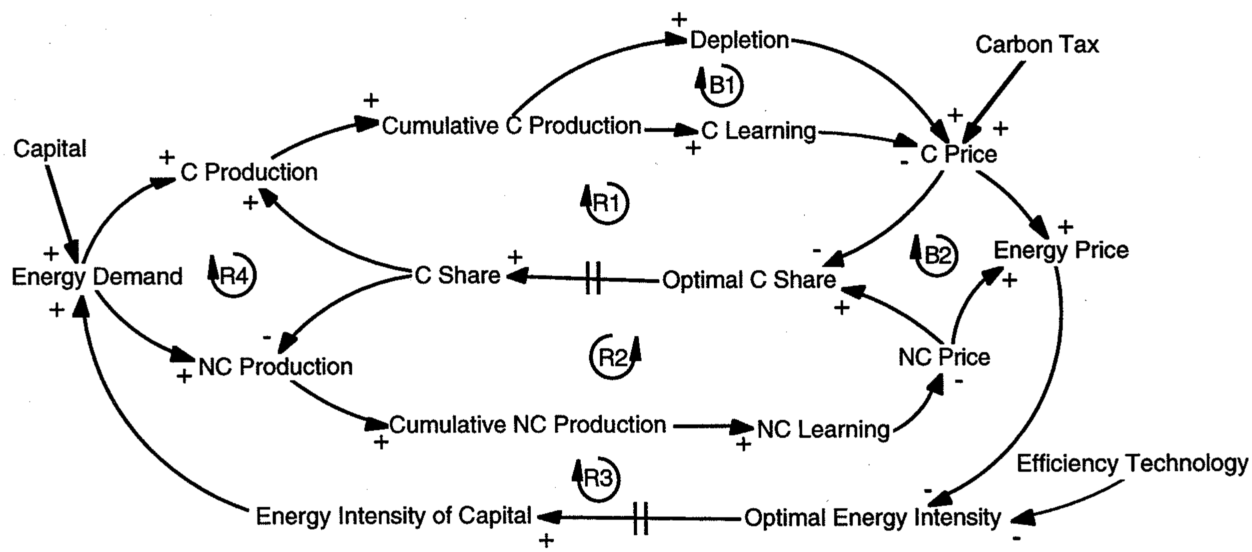
England (1994) cites three reasons for promoting fossil fuel alternatives which are relevant to the estimation of emissions abatement costs: negative social externalities, institutional factors, and technology lock-in. Negative social externalities from fossil fuel use include the cost of acid rain and other pollutants as well as the cost of maintaining stability in the Middle East. Hohmeyer (1990) identifies externalities of -.0284 to -.0769 DM/kWh for fossil fuel electricity generation in Germany, and +.051 to +.168 DM/kWh for solar and photovoltaic electricity. Hall (1990) identifies zero external costs for conservation, wind, and solar energy, and significant external costs of coal, gas, oil, and nuclear energy . The presence of externalities to fossil fuel use could be represented in the DICE model by shifting the CO_2 emissions reduction cost curve downward, creating some additional negative-cost emissions reductions.

Technological lock-in in the energy system is dynamically more interesting than externalities. Lock-in arises from positive-feedback processes that reinforce the position of dominant energy supply and use technologies. Principal among these are learning-by-doing, revenue-driven research and development, economies of scale, and network or bandwagon effects. If one assumes that actors or markets behave with sufficient foresight and understanding, the energy system will follow the socially optimal path, and lock-in is not an issue. However, Arthur (1989) shows that under some conditions, actors' anticipation of lock-in enhances lock-in. If current decisions result in development along differing energy technology paths, there is no reason to believe that the underlying parameters of the DICE cost curve will remain stable.

To the author's knowledge, no detailed energy sector models with empirically parameterized endogenous energy technology exist, though some are under development (DOE 1995). A variety of technology models have been explored in the optimal depletion literature, but they tend to be highly abstract (Davison 1977; Kamien and Schwartz 1977; Hung and Quyen 1993). This paper draws on a simple model of a path-dependent energy system by Moxnes (1992) and a model of nonconventional gas exploitation by Rowse (1994) to create a simple example of the consequences of path dependence for GHG policy. It focuses on energy supply because that portion of the system is easier to aggregate and parameterize, though the opportunities for emissions reductions from energy conservation are generally more extensive and attractive. In this respect the model underestimates the importance of path dependence.

To implement path dependence, it is necessary to replace the cost curve for CO_2 emissions reductions in the DICE model with an explicit energy sector. The structure of the added energy system is shown in figure 6. The capital term in the economic production function is replaced with a composite capital-energy good described by a CES production function in capital and energy. The energy intensity of capital is a stock that adjusts to the optimal intensity with a delay; there is implicitly some costless retrofit potential. Similarly, the effective energy delivered to the capital-energy aggregate is a composite of carbon and non carbon energy inputs, so that the optimal share of each energy source is given by the relative prices and an interfuel substitution elasticity. The actual share adjusts to the optimal share with a delay. Since fossil fuels represent only about two thirds of recent CO_2 emissions, the remaining nonenergy emissions are treated with the abatement cost curve from the DICE model. Autonomous technological progress reduces the energy and CO_2 intensity of output, as in the DICE model.

Figure 6. Energy System Added to the DICE Model



C and NC refer to carbon and noncarbon energy sources, respectively. The key loops added to the model are R1 and R2, which represent the learning curve effect. Associated with these are R3 and R4, which represent increasing energy demand with falling prices, but they are dominated by the impact of efficiency technology. Loops B1 and B2 represent the effects of rising prices from depletion of fossil fuels on the market share of carbon energy sources and overall energy demand. Two energy sources are shown here for simplicity, though the model includes a third, nonconventional carbon resource.

Energy is supplied by three sources: conventional carbon, nonconventional carbon (representing shale oil or coal liquefaction, for example), and noncarbon (renewable or nuclear). The cost of each source is determined by technology, depletion, and the carbon tax rate. Initially, nonconventional and noncarbon energy are four and six times more expensive than conventional carbon energy, respectively. Technology for each source is endogenous and implemented by a standard learning curve (Towill 1990). The learning rate selected, 10% per doubling of experience, is identical for fossil and non-fossil energy. The rate is lower than those reported for the thermal efficiency of coal electricity generation (Sharp and Price 1990) and nuclear electricity construction costs (Cantor and Hewlett 1988). Depletion affects only the conventional carbon source.

The alternative energy costs and substitution elasticities are chosen so that the model roughly reproduces the cost curve in the DICE model, leading to results similar to its standard run when the effects of learning and depletion are switched off. When learning and depletion are active, the conventional carbon source is dominant initially. As it is depleted, its cost rises, and the nonconventional carbon resource begins to gain market share. The cost of nonconventional carbon energy then falls rapidly with accumulating experience, until it becomes the dominant source. Noncarbon energy never becomes important, as it does not move down the learning curve quickly enough.

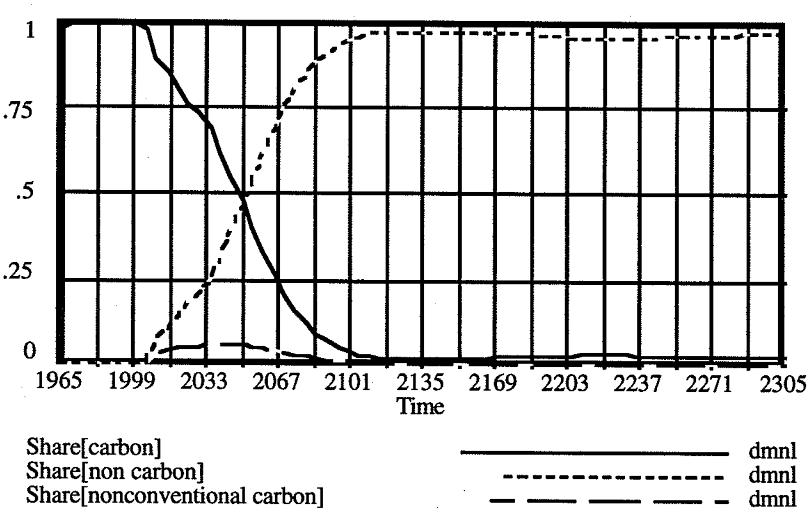


Figure 7. Energy Transition

With a strong carbon tax, the energy system shifts from carbon to noncarbon energy sources, which achieve a dominant cost position as they accumulate experience. Were it not for the need to control nonenergy emissions, the carbon tax could be reduced substantially toward the end of the simulation.

Table 4. Impact of Path-Dependent Energy Sector

Simulation	Carbon Tax $/Ton C		Energy CO_2 Emissions 10^9 Ton C/year	
Year	2005	2105	2005	2105
Static, no tax	0	0	8.5	16
Static, optimal tax	20	30	8.3	13
Path dependent, no tax	0	0	8.8	10
Path dependent, optimal tax	45	43	8.1	8.1
Path dependent, optimal tax, no discounting	176	228	7.6	0.4

A path-dependent energy sector increases the optimal abatement effort and the sensitivity of the emissions response. Carbon taxes in this version of the model are only roughly comparable to those in other runs presented in this paper, as the carbon tax is an explicit policy affecting energy prices rather than estimated from the implicit marginal productivity of carbon in the economy.

Introducing the energy sector replaces the CO_2 emissions reduction fraction decision in the DICE model with two decisions: the energy intensity capital and the share of carbon vs. non-carbon energy. While it is possible to use optimization to find the paths for these decisions, this model assumes instead that agents respond only to price, so that abatement efforts must be driven by an explicit carbon tax. A sufficiently large carbon tax causes the energy system to adopt the noncarbon energy source rather than the nonconventional carbon source. Because it accumulates more learning, the noncarbon energy source then establishes permanent dominance (see figure 7).

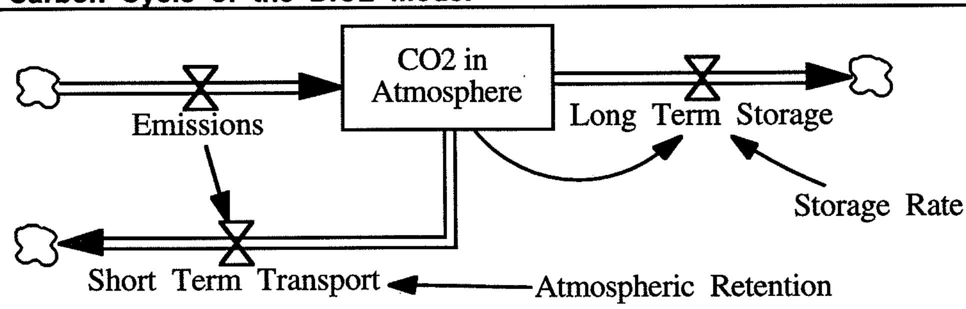
Climate Change Loop

Emissions from the human/economic system drive the behavior of the carbon cycle and climate in the DICE model. The key state variables in this part of the model represent the stock of greenhouse gases in the atmosphere, the heat stored in the atmosphere and upper ocean, and the heat stored in the deep ocean. The major feedback loop between the economic and climate systems (B1 in figure 1) is relatively weak and delayed. The large stock of atmospheric CO_2 and negative-feedback CO_2 storage processes buffer changes in emissions. Radiative forcing of the climate system from CO_2 is proportional to the logarithm of its concentration, so the loop gain decreases as the CO_2 stock rises. While feedback warming boosts the response of the climate to radiative forcing, the large thermal mass of the earth introduces long delays.

Carbon Cycle

The carbon cycle model in the DICE model is extremely simple (see figure 8), with a single stock of atmospheric carbon, an inflow of emissions (net of short-term storage), and an outflow of long-term storage. It is assumed that the atmosphere and the surface layer of the ocean are well mixed, so that only a fraction of emissions, given by an Atmospheric Retention parameter, remain in the atmosphere. This is somewhat misleading, as very little carbon actually remains in the mixed layer of the ocean; it instead is transported deeper. The Atmospheric Retention parameter is misleadingly named; it does not describe the actual fractional retention of emissions in the atmosphere, as the storage of carbon must be accounted for as well. To avoid confusion, the proportion of emissions remaining in the atmosphere, net of short- and long-term storage processes, will be referred to as the airborne fraction.

Figure 8. Carbon Cycle of the DICE model



The flow of short-term transport is not included in the model, but it is implicit in the assumption that only a fraction of emissions remain in the atmosphere. The remainder must be removed by a short term transport flow proportional to emissions.

A more detailed carbon sector model is desirable, as the variation of atmospheric retention may have policy implications. As Firor (1988) notes, the effect of reductions in emissions may be amplified by transient effects of carbon transport in the ocean. This means that stabilization of the atmospheric concentration of CO_2 may be easier than anticipated. Adding a more detailed carbon cycle to the DICE model, based on classic models by Oeschger (1975) and Goudriaan (1984), with temperature feedback from Fung (1991), demonstrates this fact. In a partial model test against a scenario in which emissions are reduced substantially, the airborne fraction of emissions falls more quickly in the more detailed model, leading to a slightly lower steady-state CO_2 concentration (figure 9).

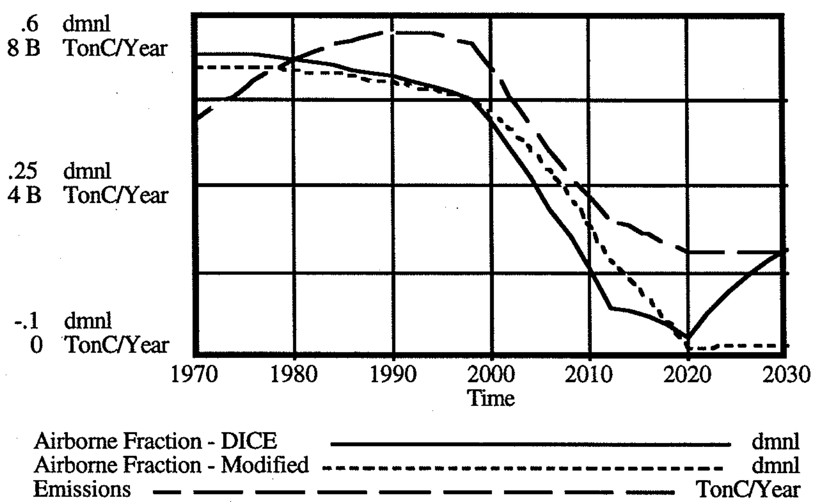


Figure 9. Airborne Fraction

When subjected to a hypothetical declining emissions path, the airborne fraction drops more quickly in the modified model, which has more sensitive transient behavior..

The transient differences between the models affect the results only slightly. There are two reasons for this. First, the climate system has long delays in temperature adjustment, so that transient effects in the carbon cycle tend to be filtered out. Second, the response of radiative forcing and hence temperature to the concentration of CO_2, unlike minor trace gases, is roughly logarithmic (Rotmans 1990; Nordhaus 1994). Thus large changes to the stock of carbon are necessary before changes in radiative forcing are significant.

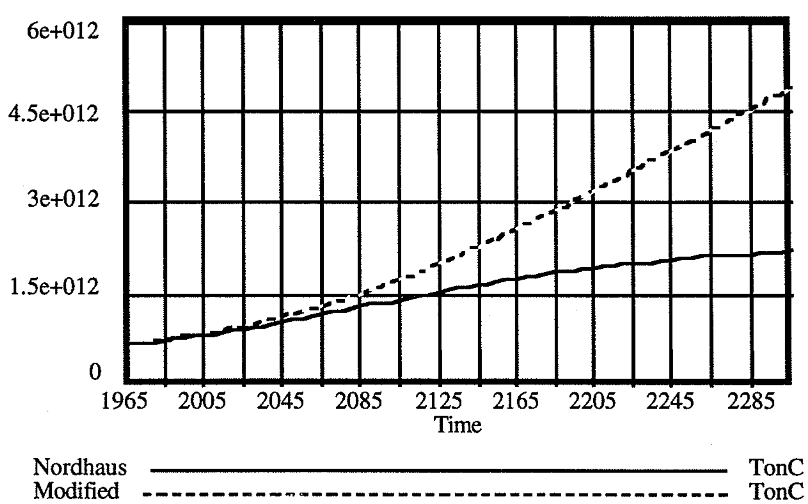


Figure 10. Nordhaus and Modified Carbon Cycles

When subjected to the emissions of Nordhaus' standard run, the stock of atmospheric carbon in the modified model is nearly identical to that of the DICE model over the historical period. However, the stock grows much larger in the future, due mainly to saturation of the oceanic sink for carbon.

Comparison with the modified model highlights a more important problem with the DICE model carbon cycle, though: the sources and sinks of carbon are assumed to be infinite. At first this would seem to be a reasonable assumption, given that the initial stock of carbon in the deep ocean is roughly 60 times as large as that in the atmosphere. The chemistry of carbon in the oceans renders the effective size of the sink only 6 times as large as the atmosphere, though. Cumulative emissions of carbon through the year 2305 are nearly as large as total estimated resources of fossil fuels and larger than the combined total current stock of carbon in the atmosphere, surface ocean, biomass, and soils (Bolin 1986). The revised model incorporates explicit sinks for carbon in the ocean and biosphere; saturation of these sinks reduces the rate of storage and transport, so that the atmospheric concentration rises much higher.

Table 5. Impact of Realistic Carbon Cycle

Simulation	Optimal Carbon Tax $/Ton C		CO_2 in Atmosphere 10^9 Ton C		
Year	2005	2105	2005	2105	2305
DICE	8	24	820	1430	2280
Modified carbon cycle	11	36	840	1740	4870
Modified carbon cycle, constant tech. growth rate	14	121	840	2060	14920

Incorporation of a realistic carbon cycle suggests modest increases in the optimal tax policy. If one assumes continuing economic growth, (see table 3), the impact is much more dramatic.

Climate System

The final element of the climate change loop is the climate system itself. The atmosphere and oceans are divided into two cells: the atmosphere and surface layers of the ocean, and the deep ocean. Radiative forcing from increasing GHG concentrations initiates warming, which is augmented by positive feedback processes. The central issue here is the estimation of the temperature feedback parameter, which determines the amount of additional warming from a given increase in atmospheric temperature (loop R2 in figure 1), and the heat capacity of the atmosphere and upper ocean, which determines the delay in the warming effect.

In the DICE model, these two parameters are estimated by regression. As Nordhaus notes, because the observed temperature change in recent decades, when most of the cumulative emissions have occurred, has been relatively small, either the estimated temperature feedback of the system will be small or the estimated time delay will be large (Nordhaus 1992). Some physical models suggest that some other factor, such as sulfate aerosol emissions, may be masking the actual temperature trend, leading estimates based on historical data to underestimate the actual temperature sensitivity of the system. Like the carbon sector model, this illustrates the danger of estimating parameters from time series data when the model structure is substantially incomplete.

Climate Change Damages

The impact of climate change on the economic system is represented by a climate damage cost curve similar to the emissions reduction cost curve. The impact of climate change is a quadratic function of temperature. It is parameterized so that a 3° change would impose 1.3% decrease in output, while a 6° change would cost four times as much.

This formulation of the impact of climate change suffers from some of the same difficulties as the abatement cost curve. The economic impact of climate change depends on the absolute change rather than the rate of change of temperature. If temperature change is slow and human and natural systems can adapt at low cost over long time frames, the actual cost may be less than the estimates. But if temperature change is rapid and adaptation involves protecting or abandoning long-lived infrastructure capital, the rate of change may be very important. The instantaneous rate of change is not the issue (indeed, it is not even observable); rather it is the gap between the current temperature and the temperature to which the economy or biosphere are adapted (Hatlebakk and Moxnes 1992). The rate of temperature change and the temperature gap are more responsive to policy changes than the absolute temperature; Nordhaus demonstrates that the optimal abatement effort is much higher when damages are rate-dependent (Nordhaus 1994).

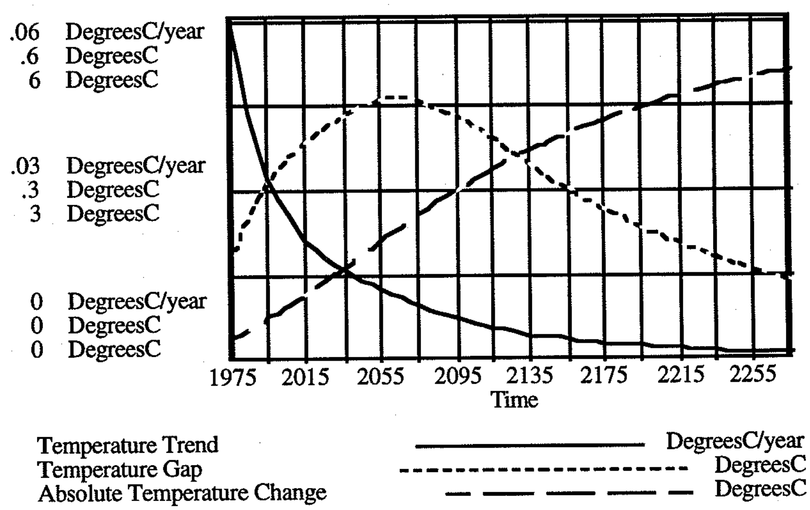


Figure 11. Possible Drivers of Climate Impacts

The temperature trend reflects the instantaneous rate of change in the model, which oddly declines throughout the simulation. The temperature gap is the difference between the current temperature and the temperature to which human or biological systems are adapted (a 20-year adaptation delay is assumed here). The absolute temperature change is the difference between the current temperature and the preindustrial temperature.

The damage cost function is estimated on the basis of current conditions. Climate change impacts, changes in consumer preferences, or other factors may produce structural changes in the economy, such as an increasing share of agriculture in economic activity, which would alter the estimates. This is particularly important in developing countries, where population pressure forces the use of increasingly marginal land. Since agriculture comprises a larger share of national income in the developing nations, it can be expected that they will bear proportionately larger costs. At the same time they have fewer resources. This raises important equity issues which must be considered outside the framework of the model. The transfer of large sums of capital to the developing countries to ensure equity can be expected to be problematic.

Conclusions

The general conclusion of the DICE model is that only modest emissions abatement efforts are necessary. This is so because abatement efforts are costly in the short term, restricting economic growth, and have only marginal effects on the costs of climate change in the long term. This conclusion rests on three features of the model: emissions which are limited by declining growth and autonomous technology but are resistant to policy, insensitivity of the climate system to marginal changes in emissions, and time discounting.

The objective function in the DICE model effectively discounts the consumption of future generations twice; once because they are richer than us (inequality aversion) and once out of pure impatience (time preference). Eliminating time preference to yield an objective function which is fair to future generations dramatically increases the indicated abatement effort. While this produces unrealistic historical investment behavior in the DICE model, decoupling investment from the objective function by creating a behavioral investment rule solves this problem. This amounts to recognition of the fact that cognitive limitations, market failures, and imperfect knowledge of the future may cause observed behavior to deviate from the path which would actually maximize social welfare.

The impact of the human and economic system on the carbon cycle and climate is limited by the assumption of declining population growth and factor productivity, which causes emissions to eventually stabilize with no intervention. While it is clear that population will stabilize, it is not so clear that this is true of factor productivity. The assumption of limited factor productivity seems to internalize the argument of the *Limits to Growth* study without acknowledging what feedback loops might be responsible for the achievement of steady state (Meadows 1972). The consequence of limited growth is that the load on natural systems remains tractable, reducing the need for costly interventions.

The potential cost of policy measures to influence CO_2 emissions is overstated. There may be significant negative-cost emissions reductions available from internalizing negative social externalities to energy use and removing institutional barriers to energy efficiency. More importantly, the evolution of energy efficiency and supply technologies is implicitly fixed in the DICE model. The impact of a carbon tax is only to induce substitution of other inputs for CO_2. If, instead, the energy system is path dependent, a carbon tax will change the technological frontier along which substitution decisions are made. This means that abatement efforts may eventually be relaxed, and that there may be policy levers which yield large results for small initial efforts, magnified by positive feedback.

The effect of abatement efforts on climate change is limited by several factors in the DICE model. The large stock of CO_2 buffers the impact of changes in emissions. Because the contribution of CO_2 to radiative forcing is logarithmic, the marginal effect of an increasing CO_2 concentration in the atmosphere decreases. The large thermal mass of the oceans and upper atmosphere delays the impact of increased radiative forcing several decades. While sluggish stocks and long delays are realistic characteristics of the climate system, the DICE model understates the strength of the climate feedback to the economy in several ways. The carbon cycle model assumes infinite carbon sinks and no nonlinear or feedback effects of rising temperature and CO_2 concentrations. Treating the carbon cycle in a more realistic manner demonstrates that carbon concentrations in the atmosphere could rise to much higher levels than predicted by the DICE model. In this case, abatement efforts should be stronger, and we can have less confidence that the global system will remain in an operating regime which we understand.

While the impact of the modified carbon cycle is limited by the logarithmic relation of radiative forcing to the atmospheric CO_2 concentration, this may not be true of the climate system or the complex interactions among other atmospheric trace gases. There is a possibility of relatively rapid events, such as cessation of the Atlantic thermohaline circulation, large-scale release of high-latitude methane hydrates, or breakup of the Antarctic ice sheet, that have extreme consequences (Cline 1992; Kutzbach 1992; Townsend, Frolking et al. 1992). While there may be mitigating feedbacks as well (Lindzen 1990), it would be preferable to represent them explicitly and explore them in more detail than parameter sensitivity analysis in the DICE model permits.

The economic and biogeophysical systems in the DICE model are necessarily highly aggregated. Many speculative feedback loops are omitted. This allows thorough analysis of the model and makes it practical to conduct the hundreds of simulations necessary for optimization. However, it reduces the ability of the model to represent real-world policy levers explicitly. More importantly, it increases the range of uncertainty of the model. Nordhaus conducts a thorough Monte Carlo analysis of the model by assigning subjective probability distributions to a variety of variables to get a sense of the uncertainties, but because important feedback loops are missing (as in the carbon cycle), this analysis is likely to understate the true level of uncertainty. It is important to test the structural uncertainties as well. While the structural revisions here are tested in isolation, it appears possible to construct a model with parameter values and historical behavior very similar to the DICE model that generates very different conclusions about the effort which should be allocated to greenhouse gas emissions abatement.

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