COWLES FOUNDATION FOR RESEARCH IN ECONOMICS
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COWLES FOUNDATION DISCUSSION PAPER NO. 1019

Rolling the "Dice": An Optimal Transition Path for Controlling Greenhouse Gases

by

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June 1992

ROLLING THE "DICE": AN OPTIMAL TRANSITION PATH FOR CONTROLLING GREENHOUSE GASES

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[aaas0602.mss; June 2, 1992, 17:00pm]

I. INTRODUCTION

The possibility of greenhouse warming has received growing attention in recent years. Climatologists and other scientists have warned that the accumulation of carbon dioxide (CO_2) and other greenhouse gases (GHGs) is likely to lead to global warming and other significant climatic changes over the next century. Many scientific bodies, along with a growing chorus of environmentalists and governments, are calling for severe curbs on the emissions of greenhouse gases, as for example the reports of the Intergovernmental Panel on Climate Change (IPCC [1990]) and the Second World Climate Conference (October 1990). Governments have recently approved a "framework treaty" on climate change to monitor trends and national efforts, and this treaty forms the centerpiece of the "Earth Summit" held in Rio in June 1992.

To date, the calls to arms and treaty negotiations have progressed more or less independently of economic studies of the costs and benefits of measures to slow greenhouse warming. Over the last few years, however, a growing body of evidence has pointed to the likelihood that greenhouse warming will have only modest economic impacts in industrial countries, while programs

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to cut GHG emissions will impose substantial costs. Like two ships passing in the night, the economic studies and the treaty negotiations seems to be proceeding independently under their own steam.

Notwithstanding the difficulties of marrying the economic analysis with the policy process, the need to address the potential issues raised by future climate change is daunting for those who take policy analysis seriously. It raises formidable issues of data, modeling, uncertainty, international coordination, and institutional design. In addition, the economic stakes are enormous, involving investments on the order of hundreds of billions of dollars a year to slow or prevent climate change.

In earlier studies, I developed a simple cost-benefit framework for determining the optimal "steady-state" control of CO_2 and other greenhouse gases.[2] This earlier study came to a middle-of-the-road conclusion that the threat of greenhouse warming was sufficient to justify modest steps to slow the pace of climate change, but I found that the calls for draconian cuts in GHG emissions by 50 percent or more were not warranted by the current scientific and economic evidence on costs and impacts.

The earlier studies had a number of shortcomings, but one of the most significant from an analytical point of view was the inadequate treatment of the dynamics of the economy and the climate. The earlier work examined a "resource steady state," one in which all physical flows are constant (e. g., in which population, emissions, concentrations, and climate change have all stabilized in their steady state) although there might be improvements in real incomes because of technological change. It

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[2] The latest version appears in abbreviated form in Nordhaus [1991a] and in greater detail in Nordhaus [1991b].

then went on to examine the optimal control strategy in the resource steady state.

The steady-state approach is unsatisfactory primarily because of the extraordinarily long time lags involved in the reaction of the climate and economy to greenhouse gas emissions. Current scientific estimates indicate that the major GHGs have an atmospheric residence time over 100 years; moveover, because of the great thermal inertia of the oceans, the climate appears to have a lag of several decades behind the changes in GHG concentrations; and there are long lags in introduction of new technologies in human economies to changing economic conditions. It would appear, therefore, that the dynamics are of the essence and that an examination of the steady state may provide misleading conclusions for the steps that we should take at the dawn of the age of greenhouse warming.

The plan of the present study is to develop a dynamic, global model of both the impacts of and policies to slow global warming. It is an integrated model that incorporates both the dynamics of emissions and impacts and the economic costs of policies to curb emissions. We call it the <u>DICE model</u> as an acronym for an "Dynamic Integrated Climate-Economy model."[3] This new model is an advance over earlier studies in that it allows for different policies in the transition path from those in the ultimate steady state. It does this through the extension of the standard tools of modern optimal economic growth theory and adding to this analysis both a climate sector and a closed-loop interaction between the climate and the economy. The model is

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[3] The complete model is presented in a background paper Nordhaus [1992a]. In addition, the theoretical underpinnings of the model are developed in a companion paper, Nordhaus [1992], which developed an optimal growth model in which to analyze the issue of the optimal response to the threat of climate change under conditions of certainty.

sufficiently small as to be transparent (or at least translucent), to allow a range of sensitivity analyses, and to be available for a number of further extensions.

The purpose of this paper is to lay out in detail the structure of the model and the nature of the assumptions. The first section lays out the algebra of the model in simplified form. The following sections derive the parameters of the model in detail. The final sections then show some empirical runs of the model and provide estimates of the optimal policy along with some sensitivity runs of alternative assumptions.

II. METHODOLOGY

Existing empirical studies of the interaction between climate change and economic growth have generally been of a partial-equilibrium or static nature. Much economic work has to date analyzed the costs of different GHG restrictions. Estimating the economic and other impacts of greenhouse warming has proved extremely difficult. I have attempted to summarize the results of studies for the United States (see Nordhaus [1991]), but these remain incomplete in a number of respects.

The present study constructs a dynamic optimization model for estimating the optimal path of reductions of GHG gases. The basic approach is to use a Ramsey model of optimal economic growth with certain adjustments and to estimate the optimal path for both capital accumulation and GHG-emission reductions. The resulting trajectory can be interpreted as either (i) the most efficient path for slowing climate change given initial endowments or (ii) as the competitive equilibrium among market economies where the externalities are internalized using the appropriate social shadow prices for GHGs. We first describe the approach verbally and then present the model in equation form.

In intuitive language, the approach is the following. Begin with the "traditional" sector of the economy, that is, the economy without any incorporation of climate change. The global economy is assumed to produce a composite commodity. It is not necessary that the countries actually be identical. Rather the goods produced must be perfect substitutes and the production functions must be identical except for multiplicative differences in productivity. In plain language, this means that countries can differ in their quantitative attributes, but there cannot be large differences in the composition or relative proportions of different commodities. While this is a restrictive assumption, preliminary work with a more complete multi-country model suggests that aggregation does not affect the major conclusions.

Our composite economy is endowed with an initial stock of capital and labor and an initial level of technology, and all industries behave competitively. Each country maximizes an intertemporal objective function, identical in each region, which is the sum of discounted utilities of per capita consumption times population. Output is produced by a Cobb-Douglas production function in capital, labor, and technology. Population growth and technological change are exogenous, while capital accumulation is determined by optimizing the flow of consumption over time. There is no need for international trade since the outputs of the different countries are perfect substitutes.

Turning to the "non-traditional" part of the model, we introduce a number of relationships that attempt to capture the major forces affecting climate change. This part includes an emissions equation, a concentrations equation, a climate equation, a damage relationship, and a cost function for reducing emissions. Emissions represent all GHG emissions, although they are most easily viewed as CO_2. Uncontrolled emissions are a slowly declining fraction of gross output, which is consistent with a complex set of assumptions about the underlying production functions. GHG emissions can be controlled by increasing the prices of factors or outputs that are GHG-intensive.

Atmospheric concentrations are increased with emissions, with concentrations reduced with an atmospheric residence time of 120 years. Climate change is represented by realized global mean surface temperature, which uses an equilibrium relationship drawn from the consensus of climate modelers and a lag given by a recent coupled ocean-atmospheric models. The economic impacts of climate change are assumed to be increasing in the realized temperature increase.

We note that this model has one major shortcoming as a representation of economic and political reality. It assumes that the public goods nature of climate change is somehow overcome. That is, it assumes that, through some mechanism, countries internalize in their national decision making the global costs of their emissions decisions. This seems unlikely, but the current solution has the virtue of calculating the equilibrium that would emerge were each country to behave in such a farsighted and altruistic fashion.

III. **MODEL**

A. Basic outline

In estimating the general-equilibrium solution for an efficient path of capital accumulation and emissions reduction, we use the following model and assumptions. We treat the world as a single economic entity. The different regions of the world are aggregated together and we analyze the optimal policy for the mythical "average" individual. Clearly, this assumption misses much of the current dilemma and debate between developed and poor countries, and it also averages out the losers and the winners from climate change. The defense of this assumption is that this study is concerned with the efficient intertemporal policies not with the issues concerning the distribution of income across countries or people.

The model operates in steps of 10 years centered on 1965, 1975, 1985,...2095,.... The model is calibrated by fitting the solution for the first three decades to the actual data for 1965, 1975, and 1985 and is then optimizing for capital accumulation and GHG emissions in the future. This approach assumes that it is desirable to maximize a social welfare function that is the discounted sum of the utilities of per capita consumption. The major decision is about the level of consumption today, where abstaining from consumption today increases consumption for future generations. In technical language, we desire to maximize the objective function:

$$(0) \qquad \max_{\{c(t)\}} \quad \sum_t U[c(t),P(t)](1+\rho)^{-t}$$

which is the discounted sum of the utilities of consumption, $U[c(t),P(t)]$, summed over the relevant time horizon. Here U is the flow of utility or social well-being, $c(t)$ is the flow of consumption per capita at time t, $P(t)$ is the level of population at time t, and ρ is the pure rate of social time preference.

The maximization is subject to a number of constraints. The first set represents economic constraints, while the second is the novel set of climate-emissions constraints.

B. Economic Constraints[4]

The first set of constraints is those relating to the growth of output. Economists will recognize these as a standard model of optimal economic growth known as the "Ramsey model."[5] The first

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[4] This section presents a summary of a more extensive analysis of the DICE model. The full documentation is given in Nordhaus [1992a].

[5] See Ramsey [1928] and Solow [1988].

equation is the definition of utility, which is equal to the size of population [P(t)] times the utility of per capita consumption u[c(t)]. We take a power function to represent the form of the utility function:

$$(1) \qquad U[c(t)] = P(t)\{[c(t)]^{1-\alpha} - 1\}/(1-\alpha)$$

In this equation, the parameter α is a measure of the social valuation of different levels of consumption, which we call the "rate of inequality aversion." When $\alpha = 0$, the utility function is linear and there is no social aversion to inequality; as α gets larger, the social becomes increasingly egalitarian. In the experiments reported here, we take $\alpha = 1$, which is the logarithmic or Bernoullian utility function.

Output [Q(t)] is given by a standard Cobb-Douglas production function in capital in technology [A(t)], capital [K(t)], and labor, which is proportional to population. The term $\Omega(t)$ relates to climatic impacts and will be described in equation (11).

$$(2) \qquad Q(t) = \Omega(t)A(t)K(t)^{\gamma}\ P(t)^{1-\gamma}$$

where γ is the elasticity of output with respect to capital. We assume constant returns to scale in capital and labor.

The next equation shows the disposition of output between consumption [C(t)] and gross investment [I(t)]:

$$(3) \qquad C(t) = Q(t) - I(t)$$

This simply notes that output can be devoted either to investment or to consumption.

The next equation is the definition of per capita consumption:

(4) $c(t) = C(t)/P(t)$

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

(5) $K(t) = (1-\delta_K)K(t-1) + I(t)$

where δ_K is the rate of depreciation of the capital stock.

C. Climate-Emissions-Damage Equations

The next set of constraints will be unfamiliar to most economists and consists of a simple representation of the relationship between economic activity, emissions, concentrations, and climate change. As with the economic relationships, these equations are highly aggregated.

Emissions. The first equation links greenhouse-gas emissions to economic activity. In the analysis that follows, we translate each of the GHGs into its CO_2 equivalent. To aggregate the different GHGs, we use a measure of the total warming potential, which is the contribution of a GHG to global warming summed over the indefinite future. Approximately 80 percent of the total warming potential is due to CO_2, and we therefore put most of our effort into analyzing that gas.

In modeling GHG emissions, I assume that the ratio of uncontrolled GHG emissions to gross output is a slowly moving parameter represented by $\sigma(t)$. In what follows, we assume that the exogenous decline in σ is 1.25 percent per annum.

GHG emissions can be reduced through a wide range of policies. We represent the rate of emissions reduction by an "emissions control factor," $\mu(t)$. This is the fractional reduction of emissions relative to the uncontrolled level. One of the key questions investigated here is the optimal trajectory of emissions control. The emissions equation is given as:

$$(6) \qquad E(t) = [1- \mu(t)]\sigma(t)Q(t)$$

In this equation, E(t) is GHG emissions, $\sigma(t)$ is determined from historical data, and it is assumed that GHG emissions were uncontrolled through 1990. The variable $\mu(t)$ is determined by the optimization.

<u>Concentrations</u>. The next relationship in the economy-climate nexus represents the accumulation of GHGs in the atmosphere. For the non-CO_2 GHGs, the issues are relatively straightforward issues of estimating the atmospheric lifetimes or chemical transformations. We concentrate here on CO_2 because that is likely to be the most important gas for greenhouse warming. I assume that CO_2 accumulation and transportation can be represented as a n-box system, in which each of the boxes is well mixed. Some manipulation will show that this can be represented by the following equation:

$$(7) \qquad M(t) = \beta E(t) + (1-\delta_M)\ M(t-1)$$

where M(t) is the change in concentrations from pre-industrial times, β is the marginal atmospheric retention ratio, and δ_M is the rate of transfer from the quickly mixing reservoirs to the deep ocean. This equation is the GHG analog of the capital accumulation equation. Atmospheric concentrations in a period are determined by last period's concentrations [M(t-1)] times (1-δ_M), where δ_M is the rate of removal of GHGs. We have estimated this relationship on historical data (1860-1985) and derived the following equation:

$$(7') \quad M(t) = \underset{(.015)}{.64}\ E(t) - .9917\ M(t-1) \qquad R^2 = .803 \quad SEE = .519$$

This is the equation we use in the model.

Climate change. The next step concerns the relationship between the accumulation of greenhouse gases and climate change. Climate modelers have developed a wide variety of approaches for estimating the impact of rising GHGs on climatic variables. On the whole, existing models are, unfortunately, much too complex to be included in economic models. Another difficulty with current general circulation models (GCMs) is that they have generally been used to estimate the equilibrium impact of a change in CO_2 concentrations upon the level of temperature and other variables. For economic analyses, it is essential to understand the dynamics or transient properties of the response of climate to GHG concentrations.

The basic approach is to develop a small model that captures the summary relationship between GHG concentrations and the dynamics of climate change. In what follows, we represent the climate system by a multi-layer system; more precisely, there are three layers--the atmosphere, the mixed layer of the oceans, and the deep oceans--each of which is assumed to be well mixed. The accumulation of GHGs warms the atmospheric layer, which then warms the mixed ocean, which in turn diffuses into the deep oceans. The lags in the system are primarily due to the thermal inertia of the three layers. We can write the model as follows:

$$\begin{aligned} T_1(t) &= T_1(t-1) + (1/R_1)\ \{F(t) - \lambda T_1(t-1) - (R_2/\tau_2)[T_1(t-1) - T_2(t-1)]\} \\ T_2(t) &= T_2(t-1) + (1/R_2)\ \{(R_2/\tau_2)[T_1(t-1) - T_2(t-1)]\} \end{aligned} \tag{8}$$

where $T_i(t)$ = temperature of layer i in period t (relative to the pre-industrial period); i = 1 for the atmosphere and upper oceans (rapidly mixed layer) and = 2 for the deep oceans; F(t) = radiative forcing in the atmosphere (relative to the pre-industrial period); R_i = the thermal capacity of the different layers; τ_2 = the transfer rate from the upper layer to the lower layer; and λ = feedback parameter.

The next step is to find the appropriate numerical representation of the simplified climate model in (8). We estimate the parameters in (8) by calibrating the smaller model to transient runs from larger GCMs and by comparing the predictions with historical data. Unfortunately, the models disagree by a wide margin, and the historical data are even further at variance from the climate models. In the study here, we use the results from a study by Schlesinger and Jiang [1990] for calibration purposes. This study has a temperature-CO_2 sensitivity of 3 degrees C for CO_2 doubling, which is close to that of the scientific consensus (see National Academy of Science [1991]), and an e-fold time for reaching .63 of the equilibrium temperature of 19 years.

<u>Impacts.</u> The next link in the chain is the impact of climate change on human and natural systems. Estimating the damages from greenhouse warming has proven extremely difficult, and I have reviewed some of the issues in Nordhaus [1991b]. The overall assessment of the cost of greenhouse warming in the U. S. is that the net economic damage from a 3°C warming is likely to be around ¼ percent of national income for the United States in terms of those variables we have been able to quantify. This figure is clearly incomplete, for it neglects a number of areas that are either inadequately studied or inherently unquantifiable. As a rough adjustment, I increased this number to around 1 percent of total U. S. output to allow for these unmeasured and unquantifiable factors. Making adjustments for output composition in different countries, I further raised the estimated impact to 1.33 percent of global output for all countries. In addition, there is evidence that the impact increases nonlinearly as the temperature increase, and we assume that the relationship is quadratic. Therefore, the final relationship between global temperature increase and income loss is:

$$(9) \qquad d(t) = .0133\ [T(t)/3]^2\ Q(t)$$

where d(t) is the loss of global output from greenhouse warming.

Cost of emissions reduction. The last major link in the chain is the costs of reduction of greenhouse gases. This is the one area that has been extensively studied and, while not without controversy, the general shape of the cost function has been sketched on a number of occasions. There are numerous estimates, particularly for CO_2, of the cost of reducing GHGs (see the extensive survey in EPA [1989] and the survey in Nordhaus [1991]). Using current annual emissions of 8 billion tons of CO_2 equivalent, my survey suggested that a modest reduction of GHG emissions can be obtained at low cost. After 10 percent reduction, however, the curve rises as more costly measures are required. A 50 percent reduction in GHG emissions is estimated to cost almost $200 billion per year in today's global economy, or around 1 percent of world output. This estimate is understated to the extent that policies are inefficient or are implemented in a crash program. The final form of the equation used in the model is:

$$(10) \quad TC(t)/GNP(t) = b_1\mu(t)^{b2} = .0686\mu(t)^{2.887}$$

where μ is the fractional reduction in GHG emissions and TC/GNP is the total cost of the reduction as a fraction of world output.

Combining the cost and damage relationships, we have the Ω relationship in the production function as follows:

$$(11) \qquad \Omega(t) = [1 - b_1\mu(t)^{b2}]/[1 + d(t)]$$

$$= \ [1 - .0686\ \mu(t)^{2.887}]/[1 + .00144\ T(t)^2]$$

III. DATA AND CALIBRATION[6]

This section describes briefly the sources of the data used for the model and the calibration of the model to the data. Data on the major variables were collected for three years, 1965, 1975, and 1985, while future periods are estimated by the calculations described above. Data on population, GNP, consumption, and investment are obtained from existing data sources of the World Bank, UNESCO, the OECD, and the U. S. and other national governments.

The parameters of the Cobb-Douglas production function are obtained by assuming that the output-elasticity of capital is 0.25 and then by estimating the level and rate of Hicks-neutral technological change directly as a residual. The utility function is assumed to be logarithmic, and the rate of social time preference is taken to be three percent per year. This preference function leads to predictions of the rate of return on capital and the gross savings rate that are close to observed levels.

Assumptions about future growth trends are as follows: The rate of growth of population is assumed to decrease slowly, stabilizing at 10.5 billion people in the 22nd century. The rate of growth of total factor productivity is calculated to be 1.3 percent per annum in the 1960-89 period. This rate is assumed to decline slowly over the coming decades.

The model has been run using the 486 version of the GAMS algorithm on various 386 compatible machines. The canonical runs presented below use a 40-period calculation with terminal valuations (or transversality conditions) on carbon, capital, and atmospheric temperature; these terminal valuations were obtained from a 60-period run and are sufficient to stabilize the solution for the first 20 periods. The canonical 40-period run can be solved in about two minutes on an Intel 486/33 processor.

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[6] The details of the data are described in Nordhaus [1992a].

Optimization models of the kind analyzed here have proven extremely resistant to conventional econometric estimation. In principle, it would be possible to form a likelihood function over the observations and to estimate the uncertain parameters of the model through an iterative procedure wherein each model run would give a value of the likelihood, and through a search algorithm the maximum-likelihood estimates would be determined. In practice, this procedure has never to my knowledge been undertaken even for small optimization models.

In the place of a formal statistical procedure, we have simply chosen parameters so that the values taken by the model in the first three periods are tolerably close to actual data. The current solution matches global GNP, emissions, GHG concentrations, and even estimates of global temperature change reasonably well for the historical periods.

IV. **POLICY EXPERIMENTS**

We now describe the different scenarios or policy experiments to which the model is applied.

1. No controls ("baseline"). The first run is one in which there are no policies taken to slow or reverse greenhouse warming. Individuals would adapt to the changing climate, but governments would take no steps to curb greenhouse-gas emissions or to internalize the greenhouse externality. This policy is one which has been followed for the most part by nations through 1989.

2. Optimal policy. The second case undertakes to construct economically efficient or "optimal" policies to slow climate change. This run maximizes the present value of economic welfare; more precisely, this case maximizes the discounted value of utility in (0) subject to the constraints and relationships in (1) to (11). This policy can be thought of as one in which the

nations of the world gather to set the efficient policy for internalizing the greenhouse externality. It is assumed that the policy is efficiently implemented, say through uniform carbon taxation, in the decade beginning 1990.

3. Ten-year delay of optimal policy. This policy is one which delays implementing the optimal policy for ten years. This policy examines the issue of the costs and benefits of delaying implementing policies until our knowledge about the greenhouse effect, along with its costs and benefits, is more secure. This approach has been advocated by the U. S. government during the Bush administration. In this scenario, we assume that sufficient information is in hand so that the optimal policy is implemented beginning in the decade beginning in 2000.

4. 20 percent emissions reductions from 1990 levels. Many environmentalists and some governments are proposing a substantial cut in CO_2 or GHG emissions. One target that has been prominently mentioned is a 20 percent cut in emissions. This is interpreted here as a 20 percent cut of the combination of CFC and CO_2 emissions from 1990 levels, where these are converted to a CO_2-equivalent basis. In quantitative terms, this represents an emissions limitation of 6.8 billion tons per year of CO_2 equivalent. This policy has no particular analytical, scientific, or economic merit, but it has the virtue of simplicity; it implies a growing percentage reduction in the future given a growing uncontrolled emissions path.

5. Geoengineering. A final policy would be to determine the benefit of a technology which would provide costless mitigation of climate change. This could occur, for example, if some of the geoengineering options proved technically feasible and environmentally benign. Two interesting proposals include shooting smart mirrors into space with 16-inch naval rifles or

seeding the oceans with iron to accelerate carbon sequestration.[7] An alternative interpretation would be that the greenhouse effect has no harmful economic effects. This scenario is useful as a baseline to determine the overall economic impact of greenhouse warming and of policies to combat warming.

V. RESULTS AND CONCLUSIONS

We now summarize the overall results for the five scenarios described above. A longer description of the model and a presentation of the numerical results is contained in Nordhaus [1992a].

Overall results

Table 1 shows the overall evaluation of the different policies. The first column shows the discounted value of consumption for the five paths. This is calculated as the present value of consumption after 1990 discounted at the market rate of return on capital (discounted back to 1990 in 1989 prices).

The optimal policy in row 2 has greater value than the three other policies in rows 1, 3, and 4.[8] The optimal policy has a net benefit of $271 billion relative to a policy in which no controls are undertaken. This number is absolutely large, although it is only .039 percent of the discounted value of consumption. The cost of delaying the optimal policy by 10 years is estimated to be $28 billion.

The environmentalist policy of reducing emissions 20 below 1990 levels is extremely costly. We estimate that this policy

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[7] The issues of geoengineering are discussed in National Academy of Sciences [1991].

[8] The values in column 3 for run i are equal to the present value of consumption for run 1 plus the algebraic difference in the attained value of the objective function from run i to run 1.

will cost $10.9 trillion in present value terms. This constitutes 4.7 percent of the total discounted value of consumption.

The last row shows the overall economic impact of climate change. The net damage from global warming is estimated to be $5.9 trillion relative to the optimal policy and $5.6 trillion relative to a policy of no controls. These represent .81 and .77 percent of the discounted value of consumption.

In general, these numbers are mind-numbing in absolute size -- largely because we are considering global output over the indefinite future. On the other hand, with the exception of the policy of stabilizing emissions, the numbers are modest relative to the total size of the global economy.

Emissions and Concentrations

We next show some of the details of the model runs. Figures 1 and 2 shows the emissions control rates in different scenarios. These show the extent to which GHG emissions are reduced below their uncontrolled levels. In the optimal path, the rate of emissions reduction is approximately 10 percent of GHG emissions in the near future, rising to 15 percent late in the next century. (Recall that this is primarily CO_2 emissions.) The environmental path of a 20 percent cut in emissions from the 1990 level shows steeply rising control rates, with the rate of control reaching 70 percent by the end of the next century.

Figure 3 shows projected CO_2-equivalent atmospheric concentrations in billions of tons CO_2 equivalent (again, this includes both CO_2 and CFCs). The impact of the optimal control strategy is noticeable, reducing concentrations by a little more than 100 billion tons at the end of the next century. Note that even with emissions stabilized at 80 percent of 1990 levels, the atmospheric concentrations of CO_2-equivalent concentrations continue to rise. The 10-year delay in implementing greenhouse gas restraints show virtually no difference from the optimal path and is not included in the graph.

Global temperature

Figure 4 shows the resulting projected increase in realized mean global surface temperatures (relative to temperatures in the 19th century). The uncontrolled path shows an initial increase of around 0.6 degrees C today, rising to 3.1 degrees C by 2100.

The optimal path shows a modest decline in the growth rate of global temperatures, with a rise of about 0.2 degree C less than the uncontrolled path by the end of the next century. The policy that cuts emissions to 80 percent of the 1990 level shows continued growth in temperatures, rising to 2.25 degrees C by the end of the next century. This surprising result shows that even draconian policies will slow climate change only modestly. The reason is primarily because of the momentum in the system from existing concentrations of GHGs.

Carbon taxes

Figures 5 and 6 show the carbon tax that would be necessary to implement each of the policies. The carbon tax should be thought of as the tax (or its regulatory equivalent) that would be necessary to raise fossil fuel and other prices sufficiently to induce economic agents to substitute other goods and services for carbon-intensive ones.

The optimal path shows a carbon tax of around $5 per ton carbon (or the equivalent in other GHGs) for the first control period, 1990-99. For reference, a $10 per ton carbon tax will raise coal prices by $7 per ton, about 25 per cent at current U.S. coal prices. The carbon tax increases gradually over time to around $20 per ton carbon by the end of the next century. The rising tax primarily reflects the rising level of global output rather than increasingly stringent control efforts.

The 10-year delay has a zero-tax in the fourth period, but then is virtually indistinguishable from the optimal policy. The policy of no mitigation obviously has a zero carbon tax. Figure 6 shows the trajectory of the policy that cuts emissions 20 percent from 1990 levels. This tax reaches about $100 per ton early in the 21st century and climbs to almost $500 per ton by the end of the next century. Clearly, very substantial fiscal or regulatory steps are necessary to bring about a trajectory with constant CO_2 emissions.

Output

Figures 7 and 8 show the impact of different policies on output. The first shows the estimates for the entire period while the second zooms in on the first few periods. For these calculations, the value of output is "green" gross world output (GGWP). Conceptually, GGWP equals output less the flow of damages from climate change less the costs of mitigation. The surprising result of these figures is that the difference between a policy of no controls and the optimal policy is relatively small through the next century. The flow impact, relative to the optimum, is somewhat less than one percent of real output at the maximum. Of course, the actual damage (equal to the difference between the "no controls" and the "geoengineering") is much larger than the cost of no controls relative to the optimum. But the latter appears small because a fair amount of economic cost would occur even in the optimal trajectory.

While the difference between the no-controls and the optimal policies is small, there are big stakes in both the geoengineering option and in the environmental option. The impact of a geoengineering solution would be quite substantial--because it would cut the costs of both climate damage and of mitigation.

There is also potential for a major waste of resources if the greenhouse policies go too far. Figure 7 shows the impact on green world output of going too far in the control of greenhouse gases--leading to <u>net</u> losses in output of over $3 trillion annually by the end of the next century.

Finally, Figure 9 shows the trajectory of real consumption per capita in the four cases. The striking feature of this figure is that, even though there are differences among the cases studied here, the overall economic growth projected over the coming years swamps the projected impacts of climate change or of the policies to offset climate change. In these scenarios, future generations may be worse off as a result of climate change, but they are still likely to be much better off than current generations. In looking at this graph, I was reminded of Tom Schelling's remark a few years ago that the difference between a climate-change and a no-climate-change scenario would be thinner than the line drawn by a number 2 pencil used to draw the curves. Thanks to the improved resolution of computerized graphics, we can now barely spot the difference!

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Table 1

Impact of Alternative Policies on Discounted Consumption

		Discounted Value of Consumption, 1990 on		
Run No.	Description	[Trillions of 1989 US $]	Difference from No Control [Billions of $]	Percent Difference
1	No Controls	731.694	0	0.000 %
2	Optimal policy	731.965	271	0.037 %
3	10-year delay	731.937	243	0.033 %
4	Stabilize Emission	720.786	(10,908)	-1.491 %
5	Geoengineering	737.296	5,602	0.766 %

[\qpro:aaast1]

Figure 1

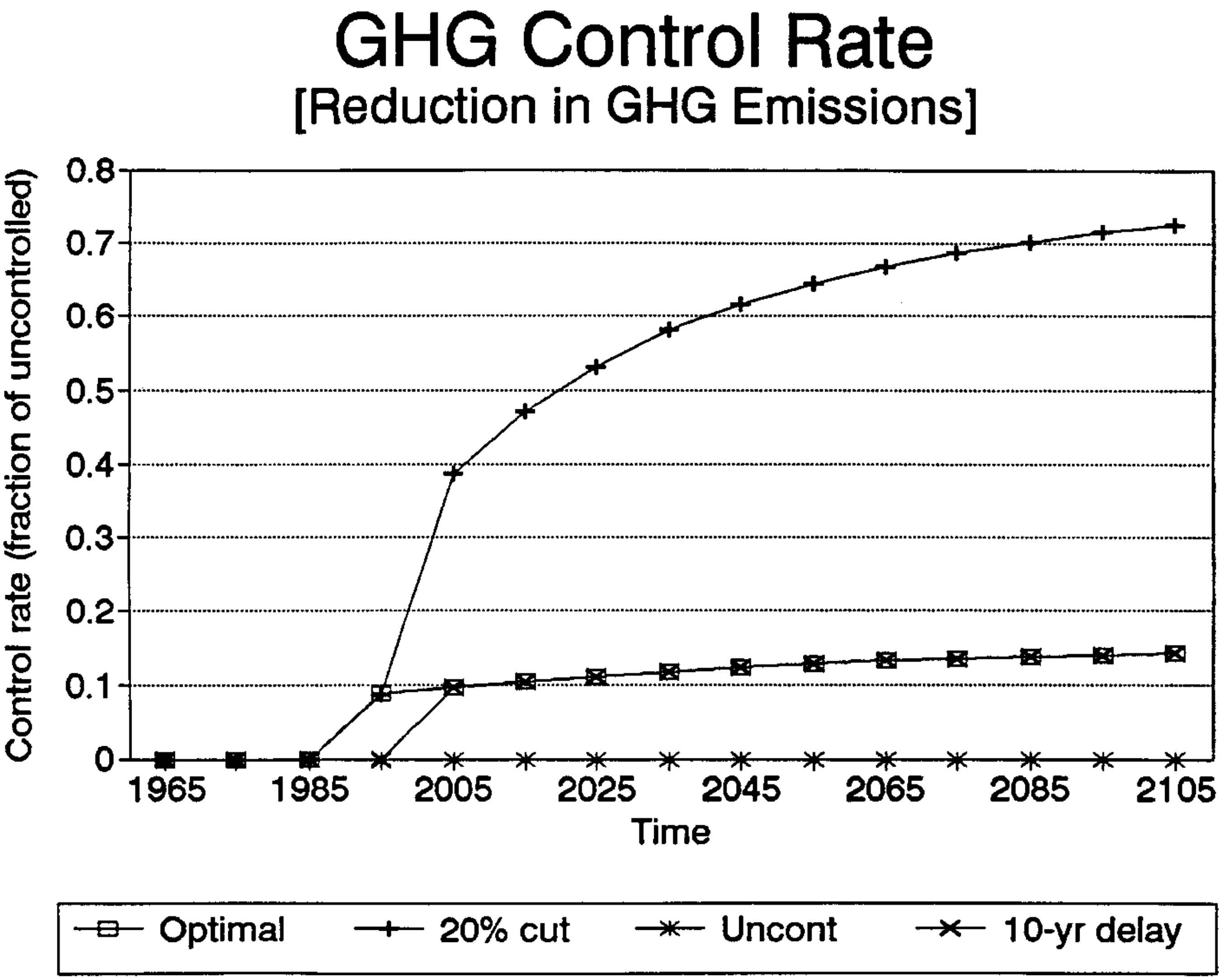
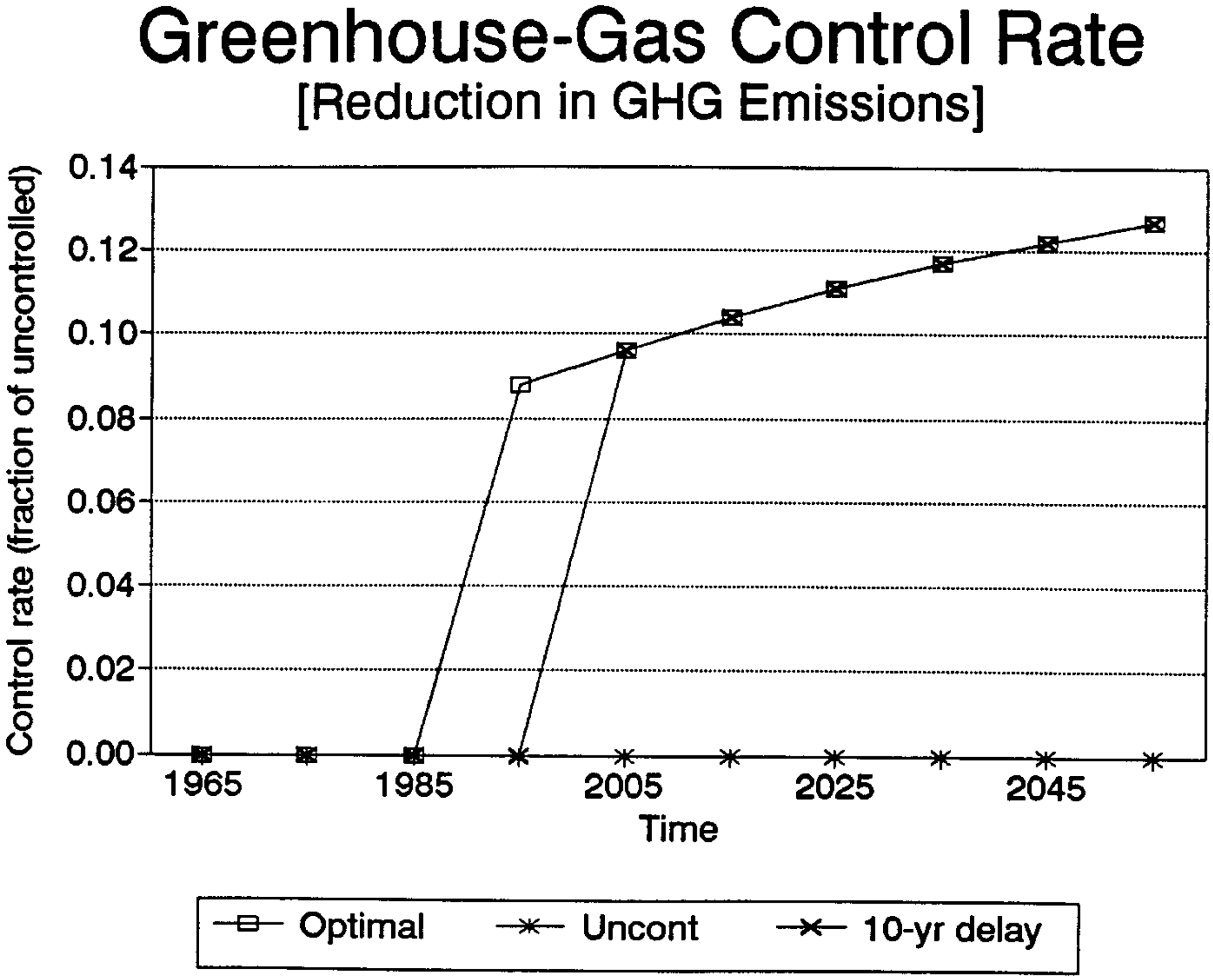

GHG Control Rate
[Reduction in GHG Emissions]
Control rate (fraction of uncontrolled)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1965
1985
2005
2025
2045
2065
2085
2105
Time
Optimal
20% cut
Uncont
10-yr delay

Figure 2



Greenhouse-Gas Control Rate
[Reduction in GHG Emissions]

Figure 3

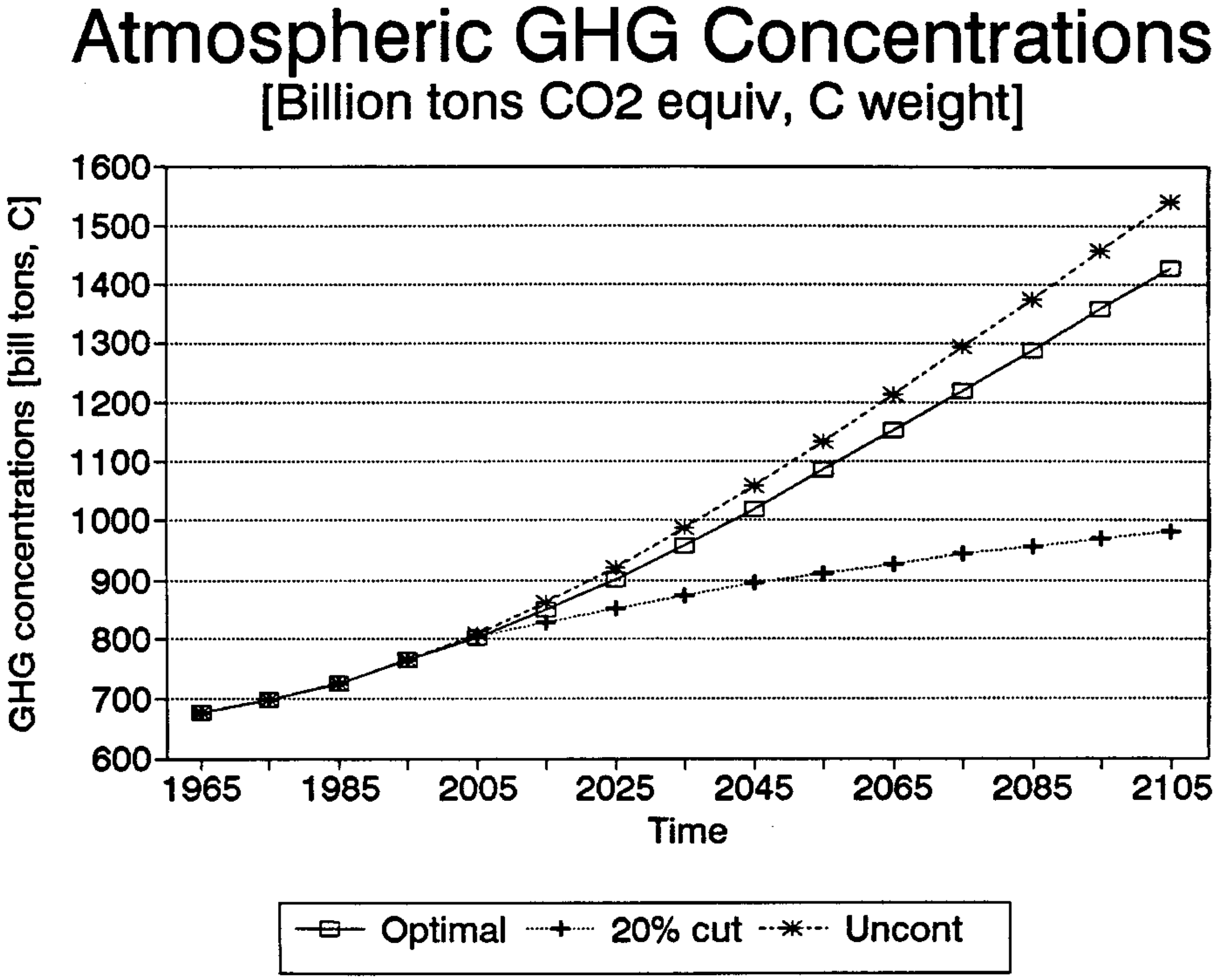

Atmospheric GHG Concentrations
[Billion tons CO2 equiv, C weight]
GHG concentrations [bill tons, C]
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
1965
1985
2005
2025
2045
2065
2085
2105
Time
Optimal
20% cut
Uncont

FIgure 4

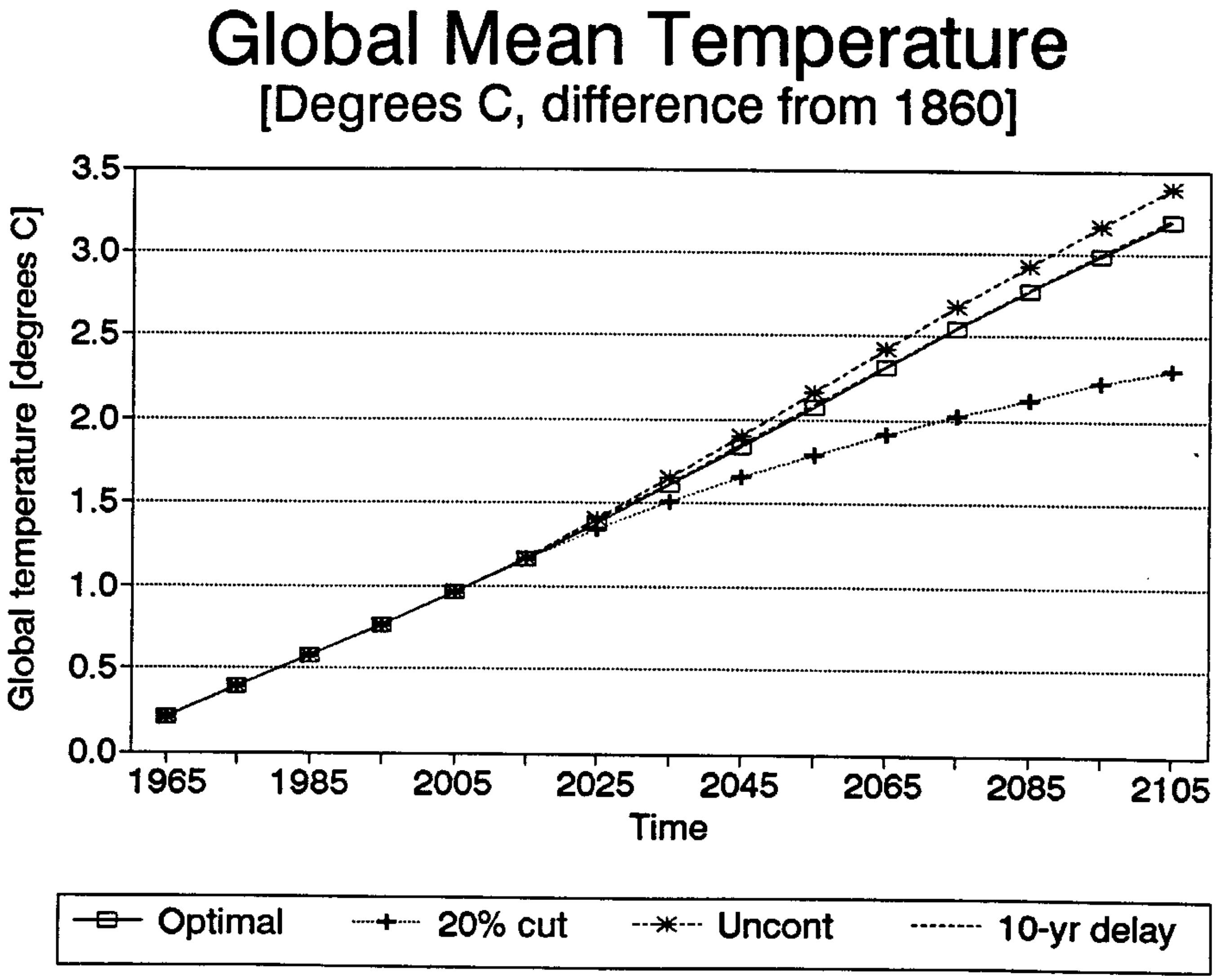

Global Mean Temperature
[Degrees C, difference from 1860]
Global temperature [degrees C]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1965
1985
2005
2025
2045
2065
2085
2105
Time
Optimal
20% cut
Uncont
10-yr delay

Figure 5

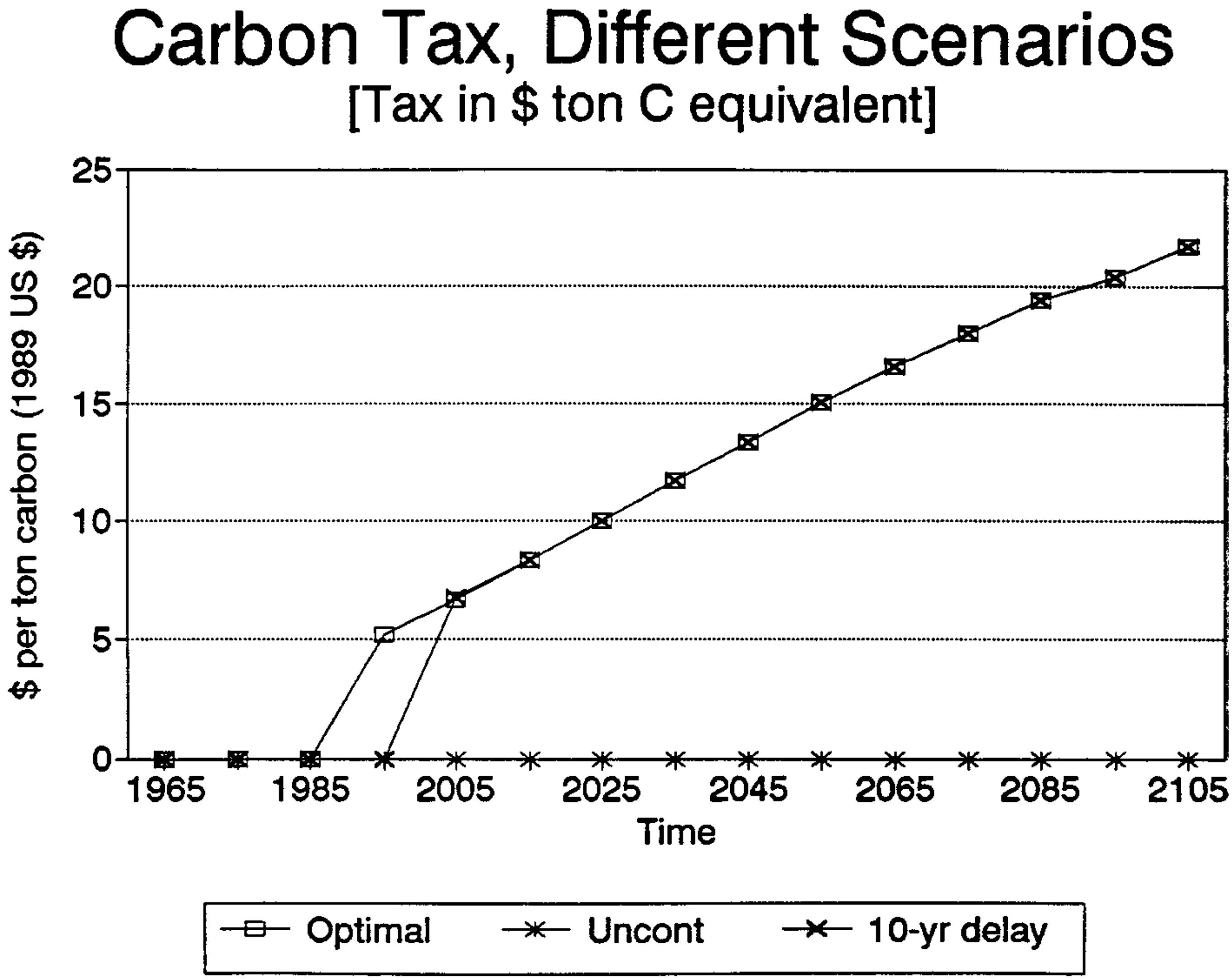

Carbon Tax, Different Scenarios
[Tax in $ ton C equivalent]
$ per ton carbon (1989 US $)
25
20
15
10
5
0
1965
1985
2005
2025
2045
2065
2085
2105
Time
Optimal
Uncont
10-yr delay

Figure 6

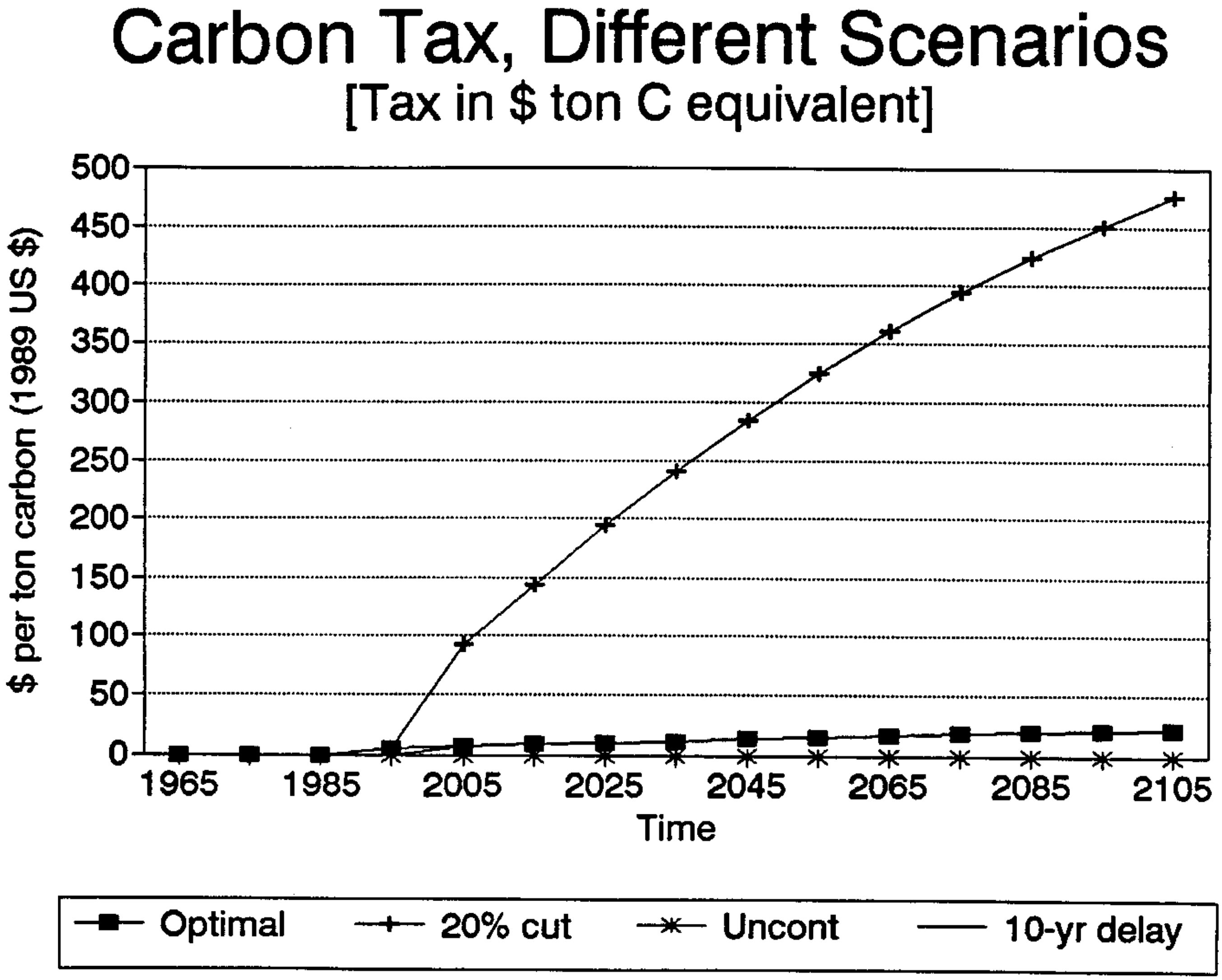

Carbon Tax, Different Scenarios
[Tax in $ ton C equivalent]
$ per ton carbon (1989 US $)
500
450
400
350
300
250
200
150
100
50
0
1965
1985
2005
2025
2045
2065
2085
2105
Time
Optimal
20% cut
Uncont
10-yr delay

Figure 7

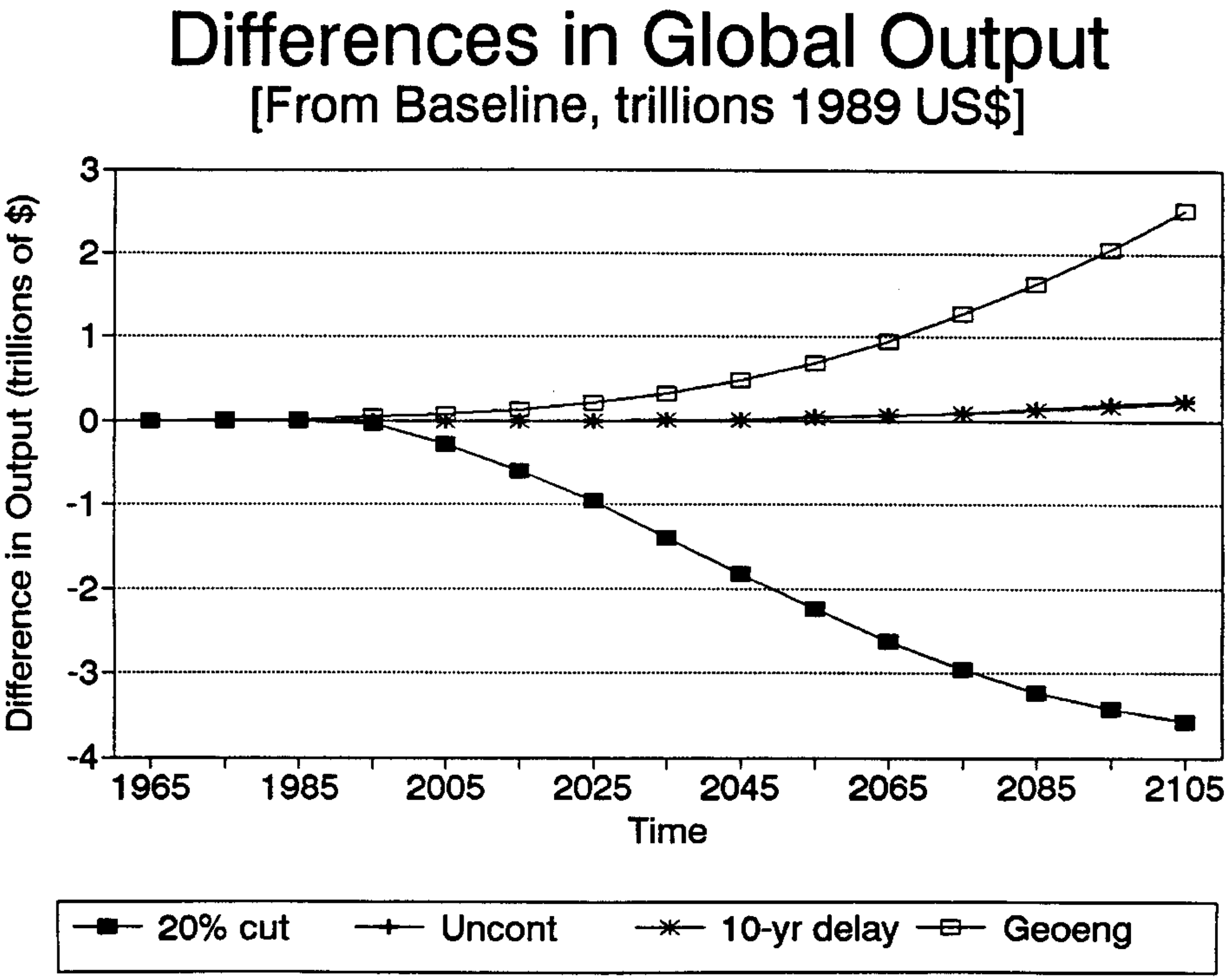

Differences in Global Output
[From Baseline, trillions 1989 US$]

Figure 8

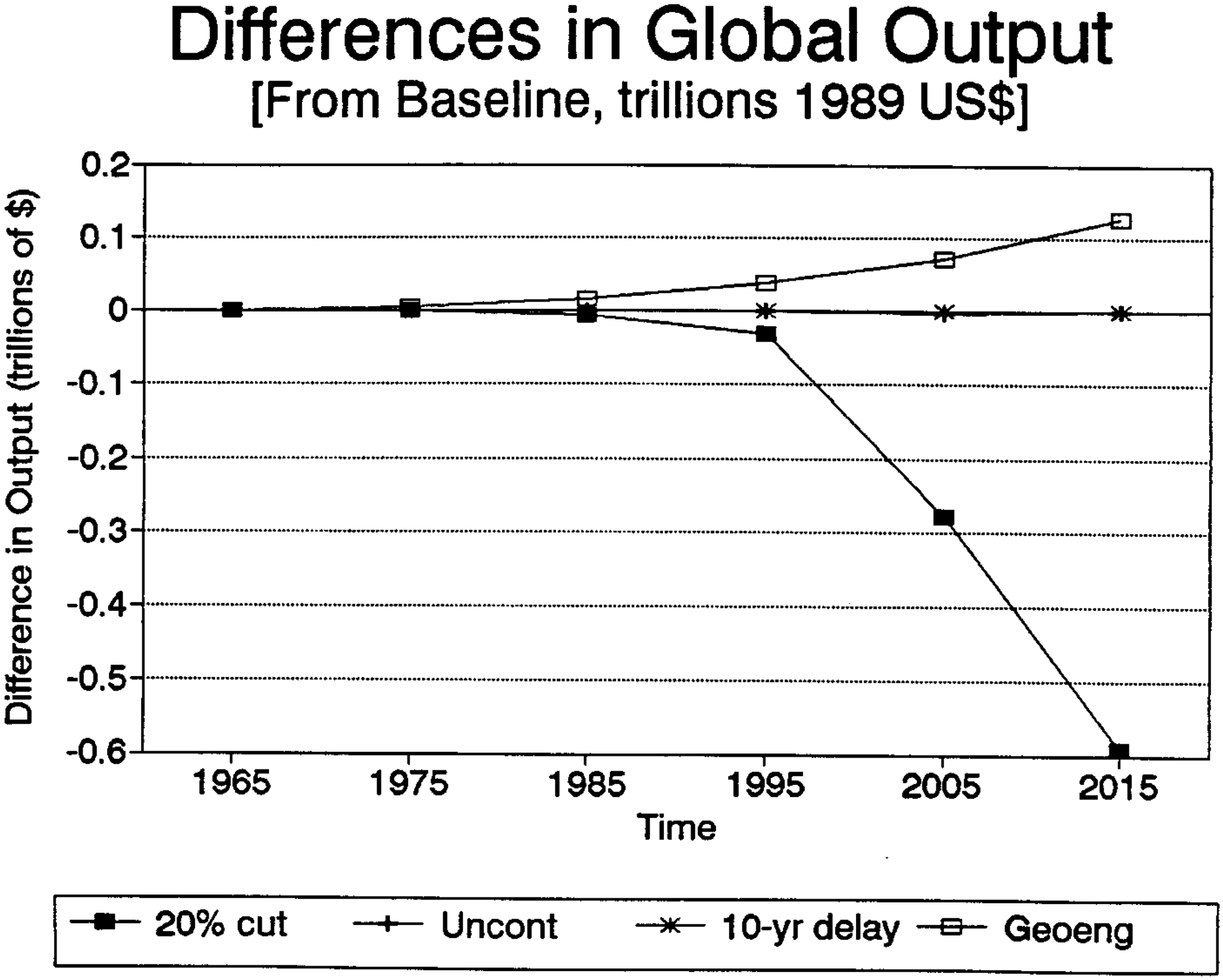
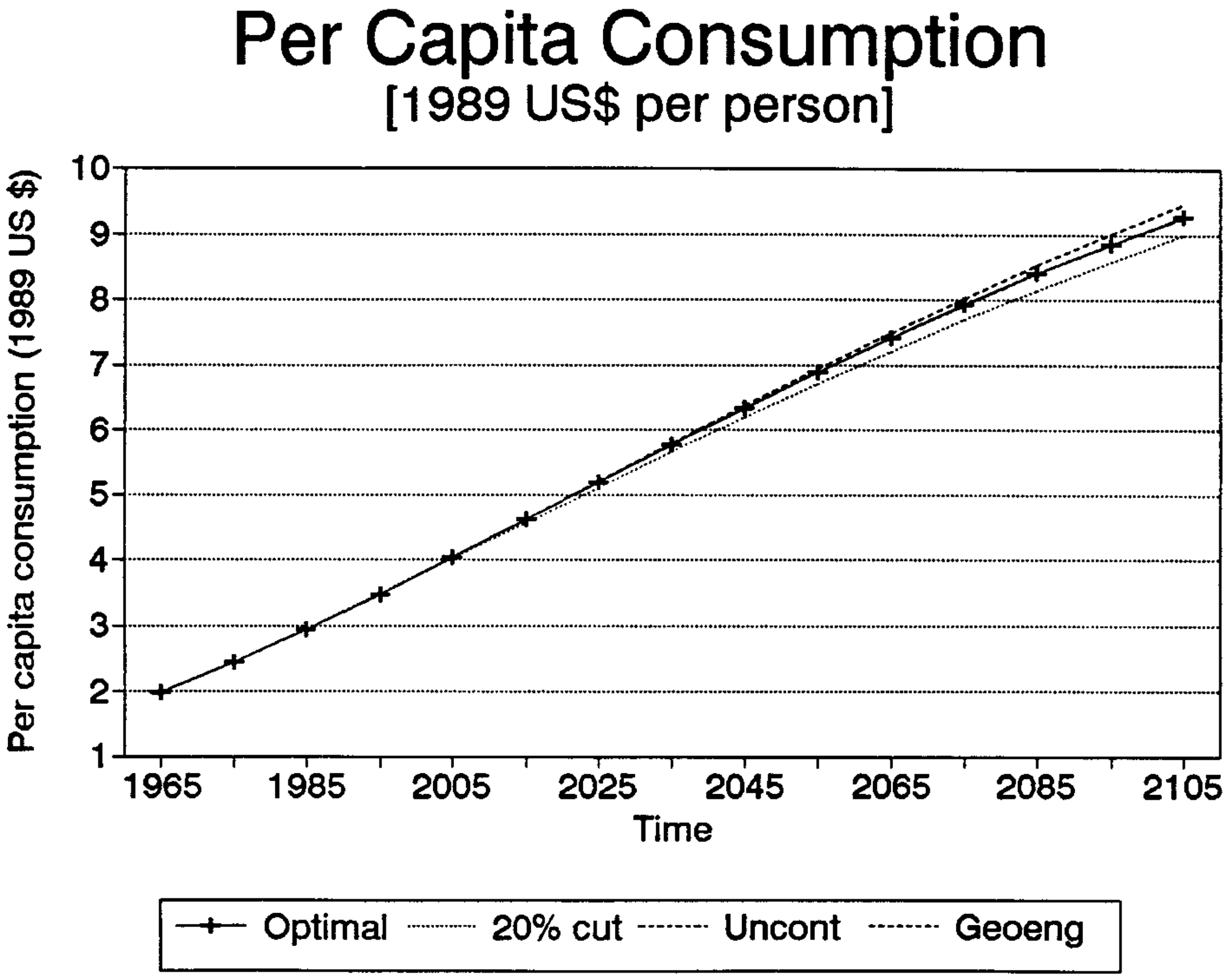

Differences in Global Output
[From Baseline, trillions 1989 US$]
Difference in Output (trillions of $)
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
1965
1975
1985
1995
2005
2015
Time
20% cut
Uncont
10-yr delay
Geoeng

Figure 9


Per Capita Consumption
[1989 US$ per person]
Per capita consumption (1989 US $)
10
9
8
7
6
5
4
3
2
1
1965
1985
2005
2025
2045
2065
2085
2105
Time
Optimal
20% cut
Uncont
Geoeng