To Slow or Not to Slow: The Economics of The Greenhouse Effect

Author(s): William D. Nordhaus

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TO SLOW OR NOT TO SLOW: THE ECONOMICS OF THE GREENHOUSE EFFECT

William D. Nordhaus

I. INTRODUCTION[1]

Over the last decade, scientists have studied extensively the greenhouse effect, which holds that the accumulation of carbon dioxide (CO_2) and other greenhouse gases (GHGs) is expected to produce global warming and other significant climatic changes over the next century. Along with the scientific research have come growing alarm and calls for drastic 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). To date, these call to arms for forceful measures to slow greenhouse warming have been made without any serious attempt to weigh the costs and benefits of climatic change or alternative control strategies.

The present study presents a simple approach for analyzing policies to slow climate change. We begin by summarizing the elements of an economic analysis of different approaches to controlling greenhouse warming. We then sketch a mathematical model of economic growth that links the economy, emissions, and climate changes and summarize the empirical evidence on the costs of reducing emissions and concentrations of greenhouse gases and on the damages from greenhouse warming, relying primarily on data for the United States. The different sections are then integrated to provide estimates of the efficient reduction of greenhouse gases, after which the final section summarizes the major results.

II. CLIMATE CHANGE: SCIENCE AND ECONOMIC MODELLING

In weighing climate-change policies, the prospects for global warming and the linkage between human activities and the emissions of GHGs form a key building block. This study uses a simplified analytical structure. We have taken existing models and simplified them into a few equations that are easily understood and manipulated.

The scientific basis of the greenhouse effect has been described in the preceding paper by Cline.[2] As a result of the buildup of a number of GHGs, it is expected that significant climate changes will occur over the next century and beyond. The major GHGs are carbon dioxide, methane, nitrous oxides, and chlorofluorocarbons (CFCs). Table 1 shows the important greenhouse

[1] This paper is a revision of earlier versions (see Nordhaus [1989]), and the author is grateful for insightful comments on early drafts from many people, with particular thanks to Jesse Ausubel, Alan Manne, James Sweeney, and an anonymous referee. This research was supported in part by the National Science Foundation.

[2] Excellent nontechnical discussions are also contained in National Research Council (1987), Schneider (1989), and IPCC (1990).

Table 1

Estimated contribution of different greenhouse gases to global warming mid-1980s

	Relative contribution		
Greenhouse gas	Instantaneous (%)	Total (%)	Source of emission
CO_2	53·2	80·3	Largely from combustion of fossil fuels
Methane	17·3	2·2	Poorly known. From a wide variety of biological and agricultural activities
CFC-11 and 12	21·4	8·8	Wholly industrial, from both aerosols and non-aerosols. Being phased out
Nitrous oxides	8·1	8·7	From fertilisers and energy use

Source: Emissions from EPA (1989), vol. 1. Definition of instantaneous and total in text. Estimates of the ratio of total warming potential to instantaneous warming potential from Lashof and Ahuja (1991), with calculations and data explained in Nordhaus (1990). Uses zero discount rate on future warming.

gases along with the sources of emissions and estimates of their contribution to global warming. Current reviews suggest that a doubling of CO_2 or its radiative equivalent, will in equilibrium increase global mean surface temperature by 1° to 5 °C.[3]

A complication in studying climate change arises from the multitude of GHGs. In the analysis that follows, we translate each of the GHGs into its CO_2 equivalent. We also use a measure of the total warming potential, which is the contribution of a GHG to global warming summed over the indefinite future. A complete dynamic analysis would also incorporate discounting to take into account that the cost of warming is different depending upon the time at which the warming occurs, but this complication is of second-order importance and is ignored here.

Table 1 shows a comparison of the instantaneous (i.e. the relative impact upon warming per unit of concentration) and total warming potential of major GHGs in the mid-1980s.[4] This shows the dominance of CO_2 in long-term warming from GHG emissions over the next century. Table 2 shows the estimates of CO_2-equivalent emissions of each of the major GHGs in 1985. The first column (production or emissions) shows the CO_2 equivalent of the total production or gross emissions in 1985, while the second column (emissions weighted by change in concentrations) reflects the fact that the increase in atmospheric concentrations is less than production or emissions. For both estimates, CO_2 is approximately 80 percent of the total global CO_2-equivalent emissions of around 8 billion tons. In this study, we measure CO_2 in terms of its carbon content. The ratio of CO_2 weight to carbon weight is $(12+16+16)/12 = 3{\cdot}67$.

A final element in estimating the climatic impact of rising GHGs involves the time delay in the reaction of climate to increasing atmospheric concentrations.

[3] The sources of uncertainty about future climate change focussing on CO_2 are systematically analysed in Nordhaus and Yohe (1983).

[4] A non-technical discussion is provided in Nordhaus (1990). The estimates used here rely on the more complete analysis of Lashof and Ahuja (1991).

Table 2

CO_2-equivalent emissions 1985 (millions of metric tons, carbon content of CO_2 per year, total warming potential)

	Emission weights	Concentration weights
Carbon dioxide	6500	6500
Methane	612	181
Nitrogen oxides	549	703
Chlorofluorocarbons	261	714
Total, CO_2 equivalent	7922	8098

Source: Emissions and changes in concentrations are from EPA (1989). Estimates of total warming potential are described in text and use a zero discount rate.

The average climate responds slowly to increases in radiative inputs, chiefly because of the thermal inertia of the oceans. Estimates of the delay to equilibrium range from 6 to 95 years. In the model used here, we simplify by assuming that the temperature adjustment process takes the following form:

$$\dot{T}(t) = \alpha\{g[M(t)] - T(t)\} \quad (1)$$

$$\dot{M}(t) = \beta E(t) - \delta M(t) \quad (2)$$

where dots over variable represent time derivatives and t = time

$T(t)$ = increase in global mean surface temperature due to greenhouse warming since mid-19th century (°C)

$M(t)$ = anthropogenic atmospheric concentration of CO_2 equivalent GHGs (billions of tons of CO_2 equivalent)

$E(t)$ = anthropogenic emissions of CO_2 equivalent GHGs (billions of tons of CO_2 equivalent per year)

$g[.]$ = equilibrium increase in global mean temperature in response to increasing CO_2 equivalent concentration

α = delay parameter of temperature in response to radiative increase (per year)

β = fraction of CO_2 equivalent emissions that enter the atmosphere

δ = rate of removal of CO_2 equivalent from the atmosphere (per year)

The interpretation of these equations is as follows. Equation (1) states that the increase in global temperature rises in response to the difference between the equilibrium temperature increase and the actual increase. Equation (2) is a simplified two-box diffusion model in which a fraction β of emissions goes into the atmosphere and the fraction δ of the quantity in the atmosphere diffuses into the deep ocean, which is a very large sink for CO_2.

We estimate the climate-equation parameters from existing climate models. Hansen estimates a time delay parameter (α), of 0·0181 for a box-diffusion ocean model with a temperature-CO_2 coefficient of 3 °C per doubling, while calculations by Stouffer *et al.* in a coupled atmosphere-deep ocean model (1990) have a time delay parameter of 0·013. These are slightly lower than other estimates and we use α = 0·02 in our calculations. For the factor β (the airborne fraction of GHGs), we estimated the equation with ordinary least squares using data on concentrations and emissions of CO_2 from 1850 to 1986. We use the conventional estimate for δ of 0·005 (representing a residence time of 200 years), and estimate β to be 0·49 with a standard error of 0·0125. We round this to $\beta = 0{\cdot}50$ for the calculations that follow.

III. ECONOMIC APPROACHES TO CONTROL OF THE GREENHOUSE EFFECT

The economics of the greenhouse effect is a classic case of a public good, in which emissions of GHGs involve a global externality. We can analyse the costs and benefits of the greenhouse effect and policies in terms of two fundamental functions. The *greenhouse damage function* describes the costs to society of the changing climate. This damage function would incorporate, for example, the impact of changing crop yields, land lost to oceans, and so forth. The *abatement cost function* describes the costs that the economy undergoes to prevent or slow the greenhouse effect. The cost function would include the cost of changing from fossil to non-fossil fuels, the substitution of different substances for CFCs, raising coastal structures, and so on.

In what follows, we will concentrate upon *efficient* strategies to reduce the costs of climate change. An efficient strategy is one that maximises overall net economic welfare (call it 'green GNP'), which includes all goods and services, whether or not they are metered by markets, and includes all externalities from economic activity.

Figure 1 depicts the analysis graphically in a static framework. The upward sloping curve is the efficient marginal cost of abatement function, showing the incremental cost of reducing CO_2 or other GHGs by one unit. The wavy line is the marginal damage from greenhouse warming associated with an additional unit of GHGs. The horizontal axis measures GHG emissions as a percent of the uncontrolled quantity. This variable has a value of 0% when GHGs are uncontrolled (i.e. in an unregulated environment). We can derive from economic theory certain properties about the shape of the marginal abatement cost function in a competitive economy with no other externalities and where controls are efficiently designed. First, we know that it has a minimum of zero at the uncontrolled point: *The first units of GHG reduction are virtually free. This is the result of the zero market price on the GHG emissions.* Second, we know that the cost function increases in the level of abatement. Third, society can always do worse than the abatement cost function by inefficiently designing regulations.

Next examine the greenhouse damage function, which measures the cost to the economy of higher levels of GHGs (measured relative to some baseline). In contrast to the cost function, we know little about the shape of the damage function – for this reason, we draw the damage function as a wavy line. We suspect that higher levels of greenhouse gases will hurt the global economy, but because of the fertilization effect of CO_2 or the attractiveness of warm climates, the greenhouse effect might on balance actually be economically advantageous.

Figure 1 uses the marginal cost and damage concepts to describe different

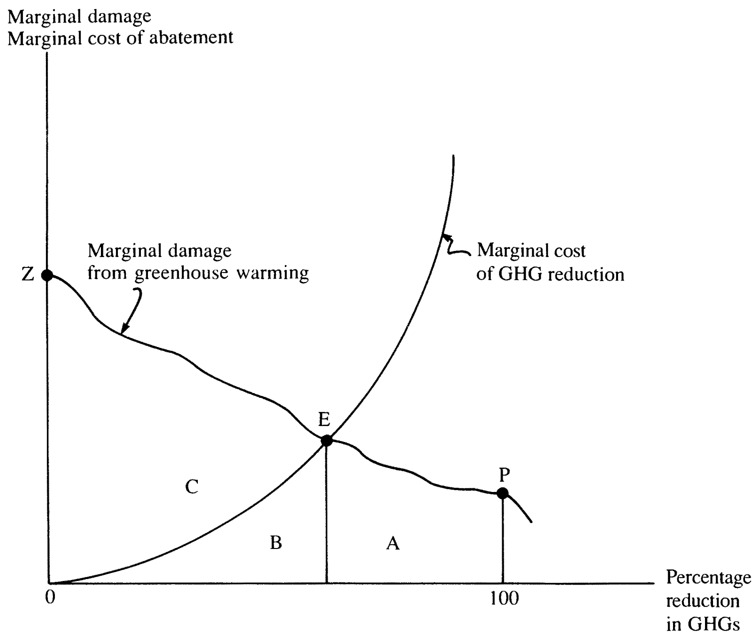

Fig. 1. Marginal costs of GHG reductions and marginal damage from GHG emissions.

policies along with their costs and benefits. We can measure the total cost of an uncontrolled greenhouse effect as the area under the damage curve over the entire range [0, 100]; this area is the sum of regions A+B+C in Figure 1. Reducing GHG levels by one unit from the laissez-faire point Z produces a net gain equal to the reduction of damage of amount Z minus the increase of cost of zero. The efficient level of control is at point E, where the marginal cost of abatement equals the marginal damage of emissions. Relative to the laissez-faire equilibrium, the damages at the optimal-control point E have been reduced by the sum of areas B+C, while the increased abatement costs are given by B, so the net economic gain is given by the area C.

IV. MODELLING OF ECONOMIC AND CLIMATIC DYNAMICS

Because greenhouse policies involve investing today to reduce damages in the distant future, we present a stylised model of the relationship between economic growth and climate change that incorporates the dynamics of climate change and of investing in slowing climate change. The model includes three components: (1) a simplified model of the cycle of greenhouse gases; (2) an economic model that incorporates the tradeoffs involved in reducing greenhouse gases; and (3) a framework for describing how society chooses between alternative consumption paths.

Following Section II's analysis, it will be convenient to linearise equation (1) as follows:

$$\dot{T}(t) = \alpha\{\mu M(t) - T(t)\} \tag{3}$$

where all variables were defined above except for μ, which is the linearised equilibrium sensitivity of temperature to concentrations of CO_2-equivalent emissions (i.e., $g'(M) = \mu$).

In examining the economics of greenhouse warming, we rely upon a simple general equilibrium model of inputs, outputs, climate, emissions, and consumption. We study the impact of policies upon an economy in the middle of the next century. The key assumption is that the economy is in *resource steady-state*. This signifies that all physical flows in the global economy are constant although the real value of economic activity may be increasing. All emissions and concentrations of greenhouse gases are therefore constant, and the climatic impacts of industrial activity have stabilised. We allow for 'balanced resource-augmenting technological change' at rate h; that is, the useful goods and services produced by the economy will be assumed to grow uniformly in each sector even though the physical throughputs are constant.

In the steady state, per capita consumption is given by

$$c(t) = y^* e^{ht}\{g[E^*] - \phi[T^*]\}. \tag{4}$$

In this equation, the new variables are $c(t)$ = per capita consumption at time t; y^* is a constant; $y(t) = y^* e^{ht}$ = output before any emissions reduction and with no climate damage; E^* = steady-state emissions; T^* = steady-state temperature increase; $g(E^*)$ = steady state cost function from reduction of emissions; and $\phi(T^*)$ = steady state damage from climate change. The production function is undated to indicate that we are considering a resource steady-state.

We assume that it is desirable to maximize a social welfare function that is the discounted sum of the utilities of per capita consumption. An optimal program for allocating resources over time maximizes the following:

$$V = \int_0^\infty u[c(t)]\, e^{-\rho t}\, dt. \tag{5}$$

The fundamental policy question involves how much reduction in consumption society should incur today to slow the consumption damages from climate change in the future.

The choice of discount rate is a thorny issue in studies of investment, and this is particularly the case for investments over a century or more. Assuming that the rate of return on investment has been determined appropriately, in our resource steady-state, the real discount rate on goods will be given by $r = \rho + \alpha h$, where ρ = the pure rate of social time preference, $-\alpha$ = the elasticity of the marginal utility with respect to per capita consumption, and h is the growth rate of per capita consumption. In the model used here, the critical parameter is $r - h$, which is the difference between the discount rate on goods and the growth rate of the economy. This will be relevant because, while we discount future damages at r, in our resource steady state the damages will be growing at the rate of economic growth (h). With slow economic growth (h near zero), or with a utility function close to logarithmic (α near 1), $r - h$ will be close to the pure rate of time preference. In advanced countries today, the real rate of return on capital is estimated to be between 4 and 10% per year while the growth of real output is around 3% per year, so $r-h$ is between 1 and 7% per year. In the calculations that follow, we use estimates of $(r-h)$ that are very low (either 0 or 1% per year) to reflect the possibility that the future equilibrium will come in a low- or no-growth economy with a low rate of time preference; and a case of $r-h = 4\%$ per year estimate to reflect the approximate real rate of return in advanced economies today.

To calculate the optimal level of emissions reduction we perform a variational experiment. Starting from the resource steady state, consider a one-shot increase in emissions by ΔE in period 0. This will lead to an increase in concentrations in the future by $\beta \Delta E e^{-\delta t}$. In our stylised economy-climate system, this will lead to an increase in temperature of

$$\Delta T(t) = \Delta E \mu \beta \alpha [e^{-\delta t} - e^{-\alpha t}]/(\alpha - \delta) \tag{6}$$

The present and future impact upon consumption is given by:

$$\Delta c(t) = \begin{cases} y^* g'(E^*)\,\Delta E, & \text{for } t = 0 \\ -y^* e^{ht} \phi'(T^*)\,\Delta T(t) & \text{for } t > 0 \end{cases} \tag{7}$$

where $y^* g'(E^*)\,\Delta E$ is the increase in consumption from allowing higher emissions at time 0 and $y^* e^{ht} \phi'(T^*)\,\Delta T(t)$ is the damage from the higher concentrations of GHGs in the future. Starting from the reference path that is a resource steady state, with $r-h > 0$, if the original path was optimal, the present value of the change in the emissions path should be zero for small variations. This implies:

$$y^* g'(E^*)\,\Delta E = \int_0^\infty [y^* e^{ht} \phi'(T^*)\,\Delta T(t)]\, e^{-rt} dt$$

Using (6), some manipulation will show that this reduces to

$$g'(E^*) = \mu \beta \phi'(T^*)\, \alpha [1/(r+\delta-h) - 1/(r+\alpha-h)]/(\alpha-\delta) \tag{8}$$

or

$$g'(E^*) = \mu \beta \phi'(T^*)\, \Gamma \tag{9}$$

where Γ = the present-value factor $= \alpha/[(r+\delta-h)(r+d-h)]$. Equations (8) and (9) state that the optimal degree of reduction of GHGs comes where the current cost of reducing GHG emissions equals the present value of the damage from higher concentrations. Γ can be interpreted as the number of years, in present value, of equilibrium-CO_2-doubling climate damage, which occurs when a one-shot concentration increase, equal to the initial CO_2 concentration, occurs at time zero. For example, say that a doubling of CO_2 in equilibrium reduces world output by 1%. Then a CO_2 emission equal to the initial concentration would produce impacts over the indefinite future whose present value is equal to Γ percent of world output. Column (2) of Table 3

Table 3

Value of present-value factor, and present value of CO_2 emissions

(1) Difference between real interest rate on goods and growth rate $(r-h)$, % per year	(2) Present-value factor (Γ)	(3) Present value of climate damages from CO_2-equivalent emissions (1989 \$ per ton CO_2 equivalent, carbon weight) for damages as percentage of world output $[\mu\beta\phi'(T^*)\Gamma]$ 2	(4) 1	(5) $\frac{1}{4}$
		\$	\$	\$
0	200.0	65.94	32.97	8.24
1	44.4	14.65	7.33	1.83
4	7.41	2.44	1.22	0.31

Note: For these calculations, we assume that the lag of temperature behind GHG concentrations is $\alpha = 0.02$ (for a mean lag of 50 years), and that the rate of disappearance of GHGs is 0.005 per year (for an atmospheric residence time of 200 years).

Present-value factor in column (2) is defined in the text. Calculation of present value of climate damages is defined in the text (Section VI) and is made as follows: Damage is percent of output per year, where 1989 world output is equal to \$20,000 billion US dollars. Total CO_2 equivalent emissions in 1989 are estimated to be 8.0 billion metric tons of CO_2, carbon weight. Therefore the total damage is the present value factor from column (2) times the damage in the upper column divided by initial value of atmospheric concentrations, measured in present value of future damages per ton CO_2 equivalent emission.

shows numerical values of the present-value factor Γ for different values of the underlying parameters. To find the efficient or optimal amount of reduction of GHGs, we return to equation (9), which shows that the optimal degree of steady-state control comes where $g'(E^*) = \mu\beta\phi'(T^*)\Gamma$.

V. EMPIRICAL ESTIMATES OF THE COSTS OF SLOWING WARMING

This section presents the estimates of the costs of GHG reduction while the next estimates the damages that may arise from warming. The experiment that is conducted below examines a 'snapshot' of emissions, concentrations, and economic costs and damages at a point in time.[5] They are then converted into the relevant economic magnitudes using the tools introduced in the last section. More precisely, for *impacts* we examine the consequences of doubling of the CO_2-equivalent concentrations of GHGs in the atmosphere. For the *costs* we estimate the costs of reducing the emissions of CO_2 in today's economy. The rationale for these two snapshots is that the lag of impacts behind emissions is in the order of 30 to 80 years, so we need to understand the impacts in the future of changes in GHG emissions today.

Clearly, this economic calculation is oversimplified. First, it abstracts from the intricate economic and climatic dynamics by considering the resource steady state in which the economy is growing while the physical flows are remaining constant. Second, in extrapolating the sectoral composition of the United States economy, there are two problems with opposite signs. On the one

[5] A preliminary analysis of a non-steady-state trajectory incorporating several regions and growth of emissions is contained in Nordhaus (1990*a*).

Table 4

Alternative responses to the threat of greenhouse warming

1. Slow or prevent greenhouse warming: reduce emissions and concentrations of greenhouse gases.
Reduce energy consumption
Reduce GHG emissions per unit of energy consumption or GNP
Shift to low-CO_2 fuels
Divert CO_2 from entering atmosphere
Shift to substitutes for CFCs
Remove greenhouse gases from atmosphere
Grow and pickle trees
2. Offset climatic effects.
Climatic engineering
Shoot particles into the stratosphere
Fertilise the ocean with trace iron
3. Adapt to warmer climate.
Decentralised/market adaptations
Movement of population and capital to new temperate zones
Corn belt migrates toward Canada and Siberia
Central/governmental policies
Build dikes to prevent ocean's invasion
Land-use regulations
Research on drought-tolerant crops

hand, the sectoral composition of developing countries is generally more resource-intensive than the United States; on the other hand, during the process of economic growth economies tend to become less resource intensive. The net effect of these two forces is unclear. Third, the calculations omit other potential market failures, such as ozone depletion or air pollution; these complementary market failures are particularly important for the CFCs, which have already been severely curbed for reasons unrelated to greenhouse warming. While these oversimplifications are necessary at this stage, they have the virtue of allowing greater transparency than would be possible in a model with full spatial and temporal resolution.

How can nations cope with the threat of greenhouse warming? Table 4 lays out some of the options. A first option, taking preventive policies to slow or prevent greenhouse warming, has received the greatest public attention. Most policy discussion has focussed on reducing energy consumption or switching to non-fossil fuels. A second option is to offset the climatic warming through climatic engineering. Among recent proposals are putting trace iron in the North Pacific and Antarctic oceans and shooting particulate matter into the stratosphere. One estimate finds that 100,000 kilograms of carbon can be offset by 1 kilogram of particles. Careful analysis of these proposals is only just beginning, but a number of cost-effective ones have already been identified. A final option is to adapt to the warmer climate. This could take place gradually on a decentralized basis through the automatic response of people, institutions, and markets as the climate warms and the oceans rise. If particular areas become unproductive, labour and capital would migrate to more productive regions. If sea level rises, settlements would gradually retreat upland unless protected. In addition, governments could take steps to pre-empt possible harmful climatic impacts by land-use regulations or investing in research on living in a warmer climate.

In what follows, I will examine mainly the first strategy, slowing greenhouse warming through reduction of atmospheric concentrations of greenhouse gases. This option is most relevant for policy because preventive steps must be taken today while adaptive steps and climate engineering can be taken later as climate changes. Clearly, a complete policy analysis would need to investigate the entire range of responses.

There are numerous estimates of the cost of reducing GHGs, and for this purpose I present the results of a recent survey.[6] This survey examines the cost of GHG reductions through three of the most discussed and significant strategies: (1) reducing CFC emissions, (2) reducing CO_2 emissions, and (3) increasing the carbon locked up in trees.

There are at this time more than a dozen different estimates of the costs of reducing CO_2. These often differ by a factor of two or three, although the general shapes of the cost curves are similar. The costs of CFC reduction are not terribly controversial. By contrast, the estimates of reforestation options are highly controversial and not well documented. In addition, a number of other possible options, such as treatment of methane-producing ruminants or rice paddies, are ignored here.

We show in Figure 2 the estimates of the marginal cost curve for each option and a total marginal cost curve for reducing GHGs. The curve marked 'Marginal cost: All GHGs' in Figure 2 is calculated as the (efficient) marginal

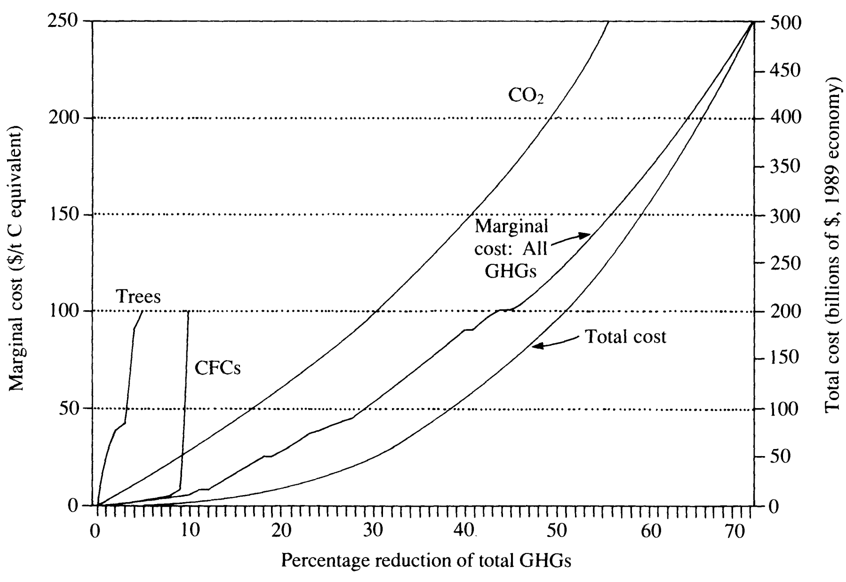

Fig. 2. Marginal and total costs of GHG reduction.

[6] See Nordhaus (1991).

cost curve of all options. We also show the same result in terms of the *total* global cost of GHG reduction (in billions of 1989 dollars at the 1989 level of world economic activity) for different levels of reduction of GHG emissions. Columns (2) and (3) of Table 7 show our estimates of the marginal and total costs of reducing GHGs. These suggest that a modest reduction of greenhouse gas emissions can be obtained at low cost. After 10% reduction, however, the curve rises as more costly measures are required. A 50% reduction in GHG emissions is estimated to cost almost $200 billion per year in today's economy, or around 1% of world output. This estimate is understated to the extent that the implementing policies are inefficient or that they are implemented in a crash program.

VI. ESTIMATING THE DAMAGES FROM GREENHOUSE WARMING

We now move from the *terra infirma* of climate change to the *terra incognita* of the social and economic impacts of climate change. Studies of the impacts of climate change are in their infancy, and at this stage we can only hope to obtain an order-of-magnitude estimate of impact of greenhouse warming upon the global economy. Before presenting the estimates, two points should be noted. First, it must be recognised that human societies thrive in a wide variety of climatic zones. For the bulk of economic activity, non-climate variables like labour skills, access to markets, or technology swamp climatic considerations in determining economic efficiency. Second, although this analysis focuses primarily upon globally averaged surface temperature, this variable is chosen because it is a useful *index* (in the nature of a sufficient statistic) of climate change that tends to be associated with most other important changes rather than because it is the most important factor in determining impacts.

Table 5 shows a sectoral breakdown of United States national income, where the economy is subdivided by the sectoral sensitivity to greenhouse warming. The most sensitive sectors are likely to be those, such as agriculture and forestry, in which output depends in a significant way upon climatic variables. At the other extreme are activities, such as cardiovascular surgery or microprocessor fabrication in 'clean rooms', which are undertaken in carefully controlled environments that will not be directly affected by climate change. Our estimate is that approximately 3% of United States national output is produced in highly sensitive sectors, another 10% in moderately sensitive sectors, and about 87% in sectors that are negligibly affected by climate change. In the damage estimates that follow, we will make the simplifying assumption that the damage applies to world GNP in 2050, and that the composition of 2050 world GNP is the same as United States GNP in 1981. Table 6 presents a rough set of estimates of the impact of greenhouse warming upon United States national income. The major findings are:

☐ Most studies suggest that greenhouse warming will lower yields in agriculture. This impact is, however, offset by the fertilisation effect of higher levels of CO_2. An assessment in the EPA report (1988) finds an overall impact

Table 5

Breakdown of economic activity by vulnerability to climatic change, U.S. 1981

Sector	National income	
	Value (billions)	Percentage of total
Total national income	2415·1	100·0
Potentially severely impacted		
Farms	67·1	2·8
Forestry, fisheries, other	7·7	0·3
Moderate potential impact		
Construction	109·1	4·5
Water transportation	6·3	0·3
Energy and utilities		
Energy (electric, gas, oil)	45·9	1·9
Water and sanitary	5·7	0·2
Real estate		
Land-rent component	51·2	2·1
Hotels, lodging, recreation	25·4	1·1
Negligible effect		
Manufacturing and mining	627·4	26·0
Other transportation and communication	132·6	5·5
Finance, insurance, and balance real estate	274·8	11·4
Trade and other services	674·6	27·9
Government services	337·0	14·0
Rest of world	50·3	2·1

Sources and notes: Data are based on the United States National Accounts, *Survey of Current Business*, July 1984.

on all crops for the United States is plus or minus $10 billion, with the difference between these estimates arising from the magnitude of the climate change.

☐ There is great uncertainty about the impact of climate change upon sea-level change. Recent scientific views are in the range of 30 to 60 cm over the next century. EPA (1988) estimates the cost of a 50 cm sea-level rise for the United States will fall in three categories: land loss of around 4000 square miles, protection costs (by levees and dikes) of high-value property, and miscellaneous protection of open coasts. The total capital value is in the order of $50 billion, which is approximately 0·05 % of projected cumulative gross private domestic investment over the period 1985–2050.

☐ Many other sectors are likely to be affected, although numerical estimates of the effects are incomplete. Greenhouse warming will increase the demand for space cooling and decrease the demand for space heating, with but a small net impact on the energy sector. The forest products industry may benefit from CO_2 fertilisation. Water systems (such as runoff in rivers or the length of ice-free periods) may be significantly affected, but the costs are likely to be determined more by the rate of climate change than the new equilibrium climate. Construction in temperate climates will be favourably affected because of a longer period of warm weather. For recreation and water transportation, the outlook is mixed depending upon the initial climate. Cold regions may gain while hot regions may lose; investments in water skiing will appreciate while those in snow skiing will depreciate. But for the bulk of the economy – manufacturing, mining, utilities, finance, trade, and most service industries – it is difficult to find major direct impacts of the projected climate changes over the next 50 to 75 years.

□ A wide variety of non-marketed goods and services escape the net of the national income accounts and might affect the calculations. Among the areas of importance are human health, biological diversity, amenity values of everyday life and leisure, and environmental quality. I am aware of no studies that point to major costs, but further analysis will be required to determine whether these omitted sectors will significantly affect the assessment of the cost of greenhouse warming. An important area for future research is to use broader measures of national output, such as those in Nordhaus and Tobin (1972) and Eisner (1985), to determine whether the conclusions for the market sector would be modified. One particular area of importance is the amenities of everyday life; one thorough study suggests major amenity benefits from global warming.[7]

The overall assessment of the cost of greenhouse warming in the United States is shown in the bottom of Table 6. We estimate that the net economic

Table 6

Impact estimates for different sectors, for doubling of CO_2, U.S. (positive number indicates gain; negative number loss)

Sectors	Billions (1981 $)
Severely impacted sectors	
Farms	
Impact of greenhouse warming and CO_2 fertilisation	−10·6 to +9·7
Forestry, fisheries, other	Small + or −
Moderately impacted sectors	
Construction	+
Water transportation	?
Energy and utilities	
Energy (electric, gas, oil)	
Electricity demand	−1·65
Non-electric space heating	1·16
Water and sanitary	−?
Real estate	
Land-rent component	
Estimate of damage from sea level rise	
Loss of land	−1·55
Protection of sheltered areas	−0·90
Protection of open coasts	−2·84
Hotels, lodging, recreation	?
Total	
Central estimate	
Billions, 1981 level of national income	−6·23
Percentage of national income	−0·26

Sources for Table 6: Underlying data on impacts are summarised in EPA (1988). Translation into national-income accounts by author. Details are available on request.

[7] See National Research Council (1978).

damage from a 3° warming is likely to be around $\frac{1}{4}\%$ 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. We might raise the number to around 1% of total global income to allow for these unmeasured and unquantifiable factors, although such an adjustment is purely *ad hoc*. It is not possible to give precise error bounds around this figure, but my hunch is that the overall impact upon human activity is unlikely to be larger than 2% of total output.

A full assessment of the impact of greenhouse warming must, of course, include regions outside the United States. To date, studies for other countries are fragmentary, and is not possible to make any firm conclusions at this time. A preliminary reading of the evidence is that other advanced industrial countries will experience modest impacts similar to those of the United States. On the other hand, small and poor countries, particularly ones with low population mobility in narrowly restricted climatic zones, may be severely affected. Much more work on the potential impact of climate change on developing countries needs to be done.

These remarks lead to a surprising conclusion. Climate change is likely to produce a combination of gains and losses with no strong presumption of substantial net economic damages. This is not an argument in favour of climate change or a laissez-faire attitude to the greenhouse effect. Rather, it suggest that a careful weighing of costs and damages will be necessary if a sensible strategy is to be devised.

VII. AN EFFICIENT POLICY FOR SLOWING GREENHOUSE WARMING

We can now provide estimates of an efficient policy for slowing greenhouse warming,[8] where this is described in equations (7) through (9). In this analysis, we assume a baseline in which there are no greenhouse policies in place. This approach is taken because few countries have actually decided upon their greenhouse policies and because we are attempting to determine a 'zero-base', most efficient policy.

We begin by tabulating in Table 7 the calculated costs and damages that are drawn from the findings above. Column (1) shows the percentage reduction in GHGs from an uncontrolled level. Columns (2) and (3) show the costs of GHG reductions from Figure 2. The final column displays the estimated total discounted damages associated with the given level of reduction of GHG emissions, this figure being derived from the estimates in Table 3.

The efficient level of GHG reduction is shown in Table 7 for the middle level of damages and for a discount rate that is 1% above the growth rate (that is,

[8] In order to make the damage estimates comparable with the cost estimates, we need to put them into the same units. The conversion is made using the analysis of section IV. Recall that the present value of damages from a unit of GHG emissions is given by the relationship that marginal damage per unit of GHG emission $= \mu\beta\phi'(T^*)\,\Gamma\,\Delta E$, where the variables are defined in section (IV). Table 3 shows alternative estimates of the damage from CO_2-equivalent emissions for different values of the discount rate and the damage function.

Table 7

Calculation of costs and benefits for different levels of reduction of greenhouse gas emissions

(1) Reduction of GHG emissions (as percentage of base level)	(2) Marginal cost of reduction ($ per t C)	(3) Total cost of reduction ($ billion/yr)	(4) Total benefit of reduction ($ billion/yr)
0	0·0	0·0	0·0
1	0·5	0·04	0·6
2	1·0	0·12	1·2
3	1·5	0·24	1·8
4	2·0	0·40	2·4
5	2·6	0·61	3·0
10	5·3	2·2	5·9
* 11	8·0	2·9	6·5
15	16·3	6·8	8·9
20	28·0	16·3	11·9
25	40·2	30·7	14·8
30	53·3	49·5	17·8
40	89·9	108·0	23·7
50	120·0	191·0	29·6
60	171·0	309·0	35·6
75	285·0	581·0	44·4

* Most efficient level of control of GHG emissions for medium damage level.
Source: For both costs and benefits, calculations use 1989 levels of world greenhouse gas emissions and world output. Cost estimates shown in Fig. 3. Estimates of benefits assume parameters given in Table 3.

$r-h = 0{\cdot}01$ per year). This estimate corresponds to the middle damage estimate in column (4) of Table 3 of $7·33 per ton of CO_2 equivalent. Equating the marginal damage with the marginal cost leads to an efficient level of control, shown with the asterisk in Table 7, of 11 % of GHG emissions. At the efficient control level, the total cost of reducing emissions is around $3 billion per year while the total benefit is estimated to be around $6 billion per year.

The same outcome is illustrated in Figure 3, which puts together the empirical marginal costs and damage curves. The horizontal axis shows the reduction in GHGs. The curve marked 'MC: All GHGs' is our estimate of the marginal cost of GHG reduction shown in Figure 2. The horizontal curves marked Low, Medium, and High Damage correspond to damage estimates in Table 3 of $1·83, $7·33, and $66 per ton of CO_2 equivalent. The low, medium, and high damage curves are, respectively, (i) economic costs actually identified in this study ($\frac{1}{4}$% of total output), (ii) the costs raised to 1 percentage point to allow for a significant amount of potential unmeasured damage, and (iii) an estimate of 2 % to allow for maximum plausible damages. The first two figures use the middle discount rate of $(r-h)$ equal to 1 %, while the third uses a value of $r-h$ of 0.

The efficient policy is found at the intersection of the relevant damage curve with the marginal cost curve. The medium case was shown in Table 7 and leads to a current reduction of 11 % of GHG emissions. At the low damage estimate,

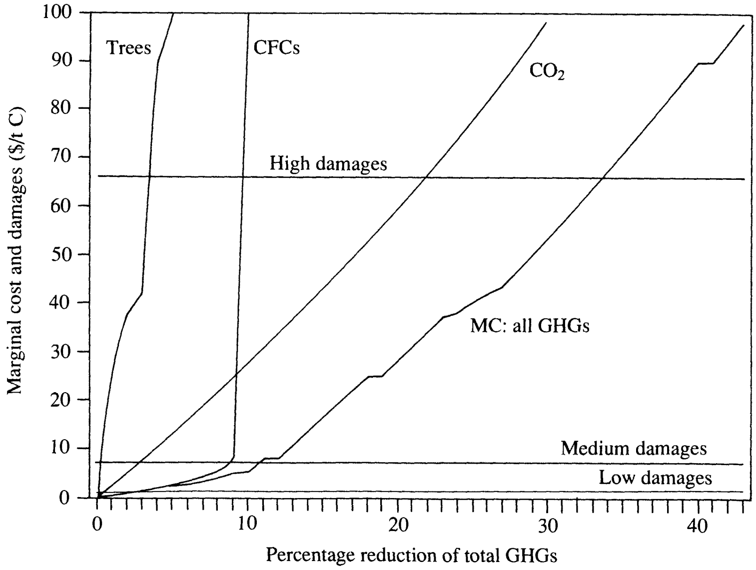

Fig. 3. Marginal cost and damages.

there is very little GHG emission reduction for its own sake. At the extreme end the high damage estimate, about one-third of total GHG emissions would be reduced.

The same figure also presents the results for the high and medium policies in a manner that allows us to determine the contribution of different GHGs to the total reduction. For the medium damage estimate, the efficient policy totals about 11% reduction in CO_2-equivalent emissions. Of this virtually none comes from trees, 2% from the reduction of CO_2, and 9% comes from the reduction in CFC emissions. All options suggest a significant reduction in the use of CFCs and that little can be realised through forestry options. The main difference among the policies is the extent to which CO_2 emissions are reduced.[9]

VIII. CONCLUSIONS

The present study has investigated strategies for coping with the likelihood of significant greenhouse warming over the coming century. It has focussed primarily upon data based on the United States and extrapolated to the rest of the world. The principal conclusions are as follows.

First, an efficient strategy for coping with greenhouse warming must weigh the costs and benefits of different policies. We have surveyed the economic literature on the costs of abatement and the damages from greenhouse warming. Estimates of both costs and damages are highly uncertain and

[9] This study assumes that damages are linear in concentrations; this assumption makes the optimal policy independent of the steady-state concentrations. A more plausible approach, for which there is some evidence, would be that increases in marginal damages are rising in the extent and rate of climate change. If the damage function is quadratic, then the marginal damage would be proportional to concentrations. The estimates in this paper are then easily adjusted by multiplying the damage estimates in columns (3) to (5) of Table 3 by the ratio of steady-state temperature increase to the CO_2-doubling temperature increase.

incomplete, and our estimates are therefore highly tentative. We investigate the impact of climate change coming from an equilibrium doubling of CO_2-equivalent atmospheric concentrations, which we take to be a 3 °C rise in global mean surface temperature along with the associated changes in climate. The flow of damages identified from this climate change is estimated to be about $\frac{1}{4}$% of output for today's United States economy. There are clearly unmeasured and unmeasurable impacts, which might raise this impact to 1%, or at most 2% of total global output, although these higher figures are no more than an informed hunch.

Second, we examined three different policy measures (reducing CO_2 emissions, CFC reduction, and afforestation), and have calculated an overall marginal cost of GHG reduction. We find that about 10% of GHG emissions can be reduced at extremely low cost; above that level, the marginal cost of abatement rises sharply. Using today's economy as a base, the long-run marginal cost of reducing GHG emissions is estimated to be $40 per ton C for a 25% reduction and $120 per ton for a 50% reduction. The total global costs of these reductions are about $2 billion per year for a 10% reduction, $31 billion for a 25% reduction, and $191 billion per year for a 50% reduction.

Third, putting together our marginal cost and marginal damage schedules, we can calculate the efficient greenhouse policy. For the low damage function – which includes only identified costs and uses a middle discount rate – we estimate the marginal damage of greenhouse gases to be about $1·83 per ton of C in CO_2 equivalent, which suggests very little CO_2 abatement. For the medium damage function, which assumes damage from greenhouse warming of 1% of GNP, the cost is reckoned at $7·33 per ton carbon; in this case, the efficient reduction is 11% of total GHG emissions. In this case, CFCs are substantially reduced, and CO_2 emissions are reduced by about 2%. In the high damage case, with damages taken to be 2% of total output and with no discounting, GHG emissions are reduced by about one-third.

Fourth, the appropriate level of control depends critically upon three central parameters of the climate-economic system: the cost of control of GHGs, the damage to the human societies from greenhouse warming, and the time dynamics as reflected in the rate of discount of future goods and services along with the time lags in the reaction of the climate to emissions. The efficient degree of control of GHGs would be essentially zero in the case of high costs, low damages, and high discounting; by contrast, in the case of no discounting and high damages, the efficient degree of control is close to one-third of GHG emissions.

Finally, it should be emphasised that this analysis has a number of important oversimplifications. It simplifies enormously many of the intricate economic and climatic complexities by taking a global view of economic activity and a simple dynamic specification of emissions, concentrations, and economic growth. It also bases the economic damage assumptions upon the 1981 sectoral composition of the United States economy and assumes that this composition will hold for the global economy in the mid-21st century. In addition it ignores other routes for investing society's resources – such as factories, education, research, and health – and focusses on a single tradeoff between future and present consumption. Moreover, the calculations omit other potential market failures, such as ozone depletion or air pollution, which might reinforce or weaken the logic behind greenhouse gas reduction. And finally, it ignores the issues of uncertainty, in which risk aversion and the possibility of learning may modify the stringency and timing of control strategies.

Notwithstanding these simplifications, the approach laid out here may help clarify the questions and help identify the scientific, economic, and policy issues that must underpin any rational decision. Once the fundamental concepts are clear, it is relatively straightforward to move to a more detailed disaggregated approach so as to fine tune the calculations. But whether we use simple approaches like the present one or more elaborate models, we must balance costs and damages if we are to preserve our precious time and resources for the most important threats to our health and happiness.

Yale University and the Cowles Foundation.

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