

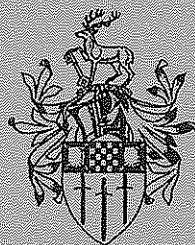
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**Economics and the Environment:
The Shadow Price of
Greenhouse Gases and Aerosols**

David Maddison

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Enquiries about Surrey Energy Economics Centre may be made to:

Director of SEEC: Peter Pearson

E-mail: P.Pearson@surrey.ac.uk

Secretary: Isobel Hildyard

E-mail: I.Hildyard@surrey.ac.uk

SEEC, Economics Dept, University of Surrey, Guildford GU2 5XH, UK.

Telephone: +44-1483-259379

Fax: +44-1483-303775

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**ECONOMICS AND THE ENVIRONMENT: THE SHADOW
PRICE OF GREENHOUSE GASES AND AEROSOLS**

David Maddison
University College London

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ABSTRACT

This paper describes a model which integrates economic growth assumptions and GHG emissions assumptions with a model of the global climate. The model may be used for the purpose of calculating the business as usual path of global warming over the very long term. Furthermore; given an abatement cost function for Carbon emissions and a temperature dependent damage function culled from the literature the model may also be used to determine the optimal reduction in GHG emissions and the implied shadow price of GHG emissions. The shadow prices are important for determining the cost effectiveness of projects aiming to reduce GHG emissions. The paper calculates the marginal rate at which different GHG emissions can be traded whilst holding the present value of damages constant. In general this rate is different from that suggested by the global warming potential of the different gases. The currently optimal tax on carbon emissions is estimated to be \$5.87 per tonne.

The paper also deals with sulfate aerosols which are thought to backscatter incoming solar radiation and help to mask the onset of climate change. In some perverse sense sulphur emissions possess an economic value in their ability to fend off global warming. Large scale desulphurisation measures could accelerate global climate change.

Using exogenous input assumptions based on the IPCC's best guess scenario and parameter assumptions which have found support in the literature the paper calculates the impact of business as usual emissions on global GNP. These are compared with the impacts experienced under an optimal control solution and to what GNP would have been in the absence of a Greenhouse Effect. What emerges is that the Greenhouse Effect does little to reduce economic growth and that virtually nothing can be done to retrieve these losses anyway even by following the optimal abatement strategy. Furthermore protocols involving the

stabilisation of emissions or concentrations at current levels are all much worse than doing nothing.

Although the message seems to be that it matters little whether carbon emissions are cut or not such a view would be premature. Great uncertainty is attached to virtually all the parameters in the model, not least those relating to the damage function and the sensitivity of the climate to heightened radiative forcing. Moreover this analysis proceeds by replacing the uncertain parameters with their expected values. The question models such as this therefore address is what would be the optimal policy to follow if all the parameters were known with perfect certainty. But since it is absolutely not the case that all the parameters are known with perfect certainty the results of these exercises are not strictly policy relevant and may yield poor policy guidance.

THE SHADOW PRICE OF GREENHOUSE GASES AND AEROSOLS

by David Maddison¹

1 INTRODUCTION

This paper introduces a simple model which was built to examine the extent to which different assumptions regarding the costs of abating GHG emissions and the damage from global temperature rise get translated into different policy recommendations. The degree to which using different models of the carbon cycle and making different assumptions regarding the thermal lag and climate sensitivity matter can also be examined. The model can be used to evaluate different protocols covering the emission of GHGs or used to locate the "optimal" strategy in the sense outlined below.

Whatever protocol the model is asked to evaluate, a set of different shadow prices for GHG emissions emerge representing the marginal rate at which different GHG emissions can be traded whilst holding the present value of damages constant. In general this rate will be different from that suggested by considering the Global Warming Potential (GWP) of the various gases. Knowing the rates at which the different gases may be traded off against one another could provide a country with some flexibility in meeting emissions reductions targets. The shadow prices could also form the basis for evaluating the cost effectiveness of projects to reduce GHG emissions in Less Developed

¹ Centre for Social and Economic Research into the Global Environment (CSERGE), University College London. This material may not be cited, reproduced or quoted without the permission of the author. Helpful comments made by members of the Climate Research Unit at the University of East Anglia and other members of CSERGE particularly Samuel Fankhauser are gratefully acknowledged. All errors remain the responsibility of the author.

Countries because the exogenous input assumptions and the parameter assumptions are not without support in the literature.

The salient features of the model are as follows: the model takes baseline economic output and future GHG emissions as given. All these GHG emissions accumulate in the atmosphere and are removed only slowly depending on their atmospheric lifetimes. Using equations reported by the IPCC it is possible to calculate the increase in radiative forcing attributable to each GHG including any indirect effects and overlap effects. The increase in radiative forcing is to some extent offset by the presence of sulfate aerosols causing a back scattering of solar radiation.

Equilibrium warming is proportional to the change in radiative forcing and actual warming adjusts to equilibrium warming via a process of lagged adjustment. This temperature rise is taken as an index of global environmental change leading to a reduction in "green" GNP (GGNP) beneath conventionally measured economic output. This occurs through the need to divert economic resources into combatting the physical effects of global environmental change or providing compensation for the loss of environmental amenities. Such economic losses are quantified in terms of a damage function. The optimal control of Global Warming involves explicitly maximising the sum of discounted GGNP through time by allocating resources between GHG abatement and immediate gratification. The abatement cost function for carbon is an equation linking proportionate reductions in carbon emissions with a proportionate cost in terms of GNP.

A number of other cost benefit analyses of the global warming problem have been undertaken in the literature for example with the CETA model of Peck and Teisberg (1992). In a separate cost benefit analysis of arresting climate change Cline (1992) considers the economic desirability of a 4GtC emissions

ceiling compared with business as usual. Recently Nordhaus (1992) has developed an elegant optimal control model of GHG abatement entitled DICE. This model is based around a Ramsey type model of economic growth in which all climate damage has a market impact cutting income and reducing emissions. This aspect of the DICE model conflicts with the view of many who see climate change as having mainly a non market impact. In contrast to the DICE model the analysis offered below calculates the optimal tax rates on a whole range of GHGs. Recently Fankhauser (1994) has calculated the marginal damage from GHG emissions using a model similar to the one outlined here. But the marginal damage figures presented by Fankhauser are conceptually quite different from the optimal tax rates provided here.

The remainder of the paper is organised as follows: in section 2 the model is described in greater detail. The basis for the abatement and damage cost estimates is discussed and the carbon cycle model and temperature change equation explained. Section 3 describes the input assumptions for baseline economic growth and emissions. These track the IPCC's best guess scenario fairly closely. Section 4 describes the results of the model when it is run using these assumptions. The results describe the impact on GGNP of continuing with BAU and the optimal percentage reduction of GHG emissions. The optimal tax rates necessary to secure the optimal reduction in emissions are computed and contrasted with the marginal damage estimates. Apart from the optimal strategy a variety of other GHG protocols are assessed. Section 5 concludes with a discussion of the role of uncertainty.

2 THE MODEL

The model has the form of a dynamic non-linear programme and takes baseline global GNP and GHG emissions as exogenous. The objective of the model is

to maximise the sum of GGNP up to the year 2200. Green GNP is the same as conventional GNP but with expenditures on pollution abatement costs and the value of environmental damage subtracted. A constant rate of discount equal to 5% is applied over all time periods. The control variable in this model is the percentage reduction in carbon emissions in each time period. Increasing abatement reduces income but also reduces future GHG concentrations reducing warming and avoiding climate change related damage.

The extent to which reducing carbon emissions reduces GNP is determined by the abatement cost function. The cost estimates used to generate this equation are from the GREEN model (Burniaux et al., 1992) and the Edmonds and Barnes (1991) model. Both models assume that emissions trading occurs, so costs are kept to a minimum. The technique used to condense the information contained in these models is to take the published results regarding a percentage reduction in emissions, the associated reduction in GNP and the time at which the cutback occurs. Treating these results as data points summary regression analysis is used to fit an abatement cost curve. This method is a convenient way of summarising the available information on abatement costs since the results from more than one model may be incorporated. A cubic abatement cost curve through the origin appears to provide the best fit to abatement cost estimates after experimentation with more generalised functional forms. The coefficient on the percentage cutback term appears to be time variant and indicates that abatement costs fall modestly over time.

It is important to understand that the estimated equation has no particular statistical significance. In particular; adding the results from many different models does not obviously result in a better cost curve. The abatement cost estimates generated by the equation are displayed in table 1. These estimates

TABLE 1: The Estimated Cost of CO₂ Abatement with Emissions Trading

Percentage Cutback	Percentage Cost in Terms of GNP					
	2000	2020	2050	2100	2150	2200
0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.2	0.2	0.1	0.1	0.1	0.1
50	1.3	1.2	1.1	0.9	0.8	0.6
75	4.3	4.1	3.7	3.1	2.5	1.9
100	10.3	9.7	8.9	7.4	6.0	4.6

Source: See Text

of course refer to the costs of reducing emissions of CO₂ from the consumption of fossil fuel. There has been considerable discussion about the potential for afforestation to sequester carbon from the atmosphere as an alternative to emissions reductions. Although some progress has been made in identifying the potential scope for afforestation and the different management options which might be appropriate much less is known regarding the price of land and how this might change in response to large scale afforestation. This makes it difficult to assess the cost effectiveness of such measures. At this stage it seems best to omit the potential for afforestation from the calculations. In fact, the results of the analysis seem to suggest that measures which involve the slow

absorption of carbon over a number of decades have a low value at least for the scenario dealt with.

There has been surprisingly little discussion regarding the cost of reducing emissions of CH_4 and N_2O . Adams et al (1992) have calculated within the context of a linear programming model deliberate policies to reduce methane emissions from the agricultural sector using market mechanisms. The findings of this study suggest that the marginal cost of abating one ton of methane commences at \$1,166. Michaelis (1992) argues that to reduce emissions of N_2O by one ton through restricting the use of fertiliser costs \$6,500. The model presented here assumes that it is impossible to abate methane or nitrous oxide emissions.

The damage function takes temperature rise as an index of global environmental change and converts it into a proportionate reduction in GNP. The results of a survey of expert opinion conducted by Nordhaus (1994) suggest a loss of 3.6% of GNP for a 3 °C temperature rise. A taxonomy of the impacts of climate change by Cline (1992) points to much smaller losses of 1.1% for a 2.5 °C rise and damage increasing by a power of 1.3 with temperature rise. Fankhauser (1992) arrives at an estimate of 1.5%. Titus (1993) uses an estimate of 2.5% of GNP for a 4 °C rise in temperature. None of these papers indicate the extent to which damage depends upon the rate of warming. The model follows Fankhauser (1993) in assuming a loss of 1.5% for a 2.5 °C temperature rise and a takes damage function exponent of 2.

The model deals with the five main GHGs: CO_2 , CH_4 , N_2O , CFC-11 and CFC-12. The baseline emissions of these gases is exogenous input to the model. The purpose of including so many different GHGs is that their shadow values may be directly inferred from the analysis. The model also considers the

influence of aerosol particles on the Earth's radiative balance. These particles are thought to mask the onset of global warming by scattering and absorbing solar radiation. According to Charlson et al. (1990, 1991, and 1992) the effect of current emission loads corresponds to a negative radiative forcing of $1\text{w}\text{m}^{-2}$ averaged over the northern hemisphere compared with $2.5\text{w}\text{m}^{-2}$ from anthropogenic GHG emissions. This implies that the change in radiative forcing over the Northern hemisphere might have been substantially less than was previously believed to be the case. Aerosols, unlike the GHGs, do not mix perfectly and have an atmospheric lifetime measured in terms of weeks. Perversely attempts to reduce fossil fuel emissions could precipitate global warming depending upon the character of the changes in fossil fuel use and whether they affect the sulphur load (see Wigley, 1991). Large scale desulphurisation measures could also conceivably have an important impact. Given their ability to mask the effects of global warming sulfate aerosols possess an economic value in this model.

The end of period change in the atmospheric concentrations of the non carbon GHGs depends only upon their current atmospheric concentration, the average residence times of the different gases and the quantity of each gas released during that period. The average residency times of the gases are the latest estimates contained in the IPCC (1992) document. The dynamics of CO_2 in the atmosphere are governed by the carbon cycle. The model of the carbon cycle used here is that of Maier-Reimer and Hasselman (1987) although simpler models of the carbon cycle tend to leave the results unchanged. The 1985 concentrations of all these gases as reported in Boden et al., (1991) define the initial state of the system.

In order to determine the change in global temperature brought about by an elevated concentration of GHGs in the atmosphere it is necessary to calculate

the change in radiative forcing relative to pre industrial levels attributable to each gas. Radiative forcing rises less than linearly with concentrations since some spectral bands become effectively saturated. The functional form and parameters of the equations linking radiative forcing to changes in GHG concentrations are those cited by IPCC (1990). Both the direct and indirect forcing from CH₄ emissions are included as are the negative indirect effects of CFCs on stratospheric ozone (itself a potent GHG). The indirect effect of CFCs may reduce their potency as GHGs by up to 80% (Ramaswamy et al., 1992). A function is taken from IPCC (1990) to represent an overlap term between CH₄ and N₂O. The changes in radiative forcing attributable to each of the different gases along with sulfate aerosols are summed to find total change in radiative forcing relative to preindustrial levels.

To calculate the equilibrium temperature rise from the change in radiative forcing it is necessary to multiply by the climate sensitivity parameter (measured in Kw⁻¹m²) and a dimensionless feedback parameter. Taking the IPCC central estimate of 2.5°C warming for CO₂ doubling it is possible to calculate that the product of the feedback and sensitivity parameters is 0.572Kw⁻¹m²¹. Given that the climate sensitivity parameter is widely agreed to be 0.3Kw⁻¹m² the feedback parameter is 1.91 but it could easily be as high as 3.4 or as low as 1.1. Current temperature adjusts to equilibrium warming

1 Dividing the expected temperature change by the equation for the change in direct forcing from CO₂ doubling gives:

$$\lambda = \frac{2.5}{6.3\log(2)} = 0.572$$

via a simple lagged adjustment process exhibiting an e-fold time¹ of 19 years. The observed global temperature record provide the boundary conditions for this equation.

This concludes the specification of the model which is subsequently solved in ten year time intervals using the GAMS software (see Brooke et al, 1992). Further details regarding the structure and parameterisation of the model are available from the author on request.

3 INPUT ASSUMPTIONS

This section describes the construction of the input assumptions which drive the model. The assumptions deliberately reflect key aspects of the IPCC best guess scenario IS92a. Obviously the results contained in the following section correspond to these assumptions.

The production of conventional GNP output tracks population growth, and population is determined by the cumulative logistic function. The parameters of this function are chosen such that the curve passes through the current population of 5.25 billion and the IPCC estimate of 8.41 billion for 2025 and 11.31 billion for 2100. It is assumed that labour productivity continues to grow at an annual rate of 1.6% per annum. This figure matches the average growth in GNP per capita assumed in IS92a.

The emission of GHGs is determined by the growth in income and exogenous GHG intensities. The annual growth rates used for the GHG intensity of output are all implicit in IS92a and point to a uniform decrease in the GHG intensity of output. Given an average rate of economic growth of 2.3% the decline in

1 The e-fold time corresponds to the time required to close the gap between actual and committed warming by a proportion $1-e^{-1}$ (about 63%).

output intensities is insufficient to prevent an increase in total emissions at least over the first half of the next century. In the no controls scenario emissions of carbon increase rapidly in the early part of the next century reaching 10.7GtC annually by the year 2025. Towards the end of the 21st century however the rate of increase slows such that by the year 2095 annual emissions reach 17.4GtC per annum. Beyond that point the decline in the carbon intensity almost matches the increase in economic output such that the growth in carbon emissions virtually stabilises. In contrast methane, nitrogen and sulphur emissions both reach a maximum half way through the 21st century and then turn down modestly as the decline in their output intensities outstrips economic growth. The IPCC has assumed that, with the Montreal Protocol and the amendment to it signed in London, the output intensities of the CFC gases will decline extremely rapidly. CFC-11 intensity falls at 6.85% annually whilst CFC-12 intensity falls by 7.66% annually. These negative growth rates nevertheless permit significant emissions of CFCs to occur even after their planned phase-out since many of these substances are "banked" in refrigerators and aerosols and in any case not all countries have signed the Montreal Protocol.

These trends in economic growth and emissions are projected forward to the year 2200. The resultant scenario is close but not identical to the IPCC's IS92a scenario (see tables 2 and 3).

TABLE 2: Business as Usual Annual GHG and Aerosol Emissions Assumptions

Year	C (Gt)	CH ₄ (Tg)	N (TgN)	CFC-11 (kt)	CFC-12 (kt)	S (Tg)
1995	6.7	544	13.7	248	290	106
2005	8.0	620	15.2	170	183	120
2015	9.4	688	16.4	113	113	133
2025	10.7	743	17.2	74	68	143
2035	12.0	785	17.7	47	40	150
2045	13.1	813	17.8	29	23	155
2055	14.1	830	17.7	18	13	158
2065	15.1	837	17.4	11	7	158
2075	15.9	836	16.9	7	4	156
2085	16.7	830	16.3	4	2	153
2095	17.4	819	15.6	2	1	150

Source: See text.

TABLE 3: Business as Usual Economic Growth Assumptions

Year	GNP (\$tr)	GGNP (\$tr)	% Difference
1995	26.27	26.27	0.0
2005	35.73	35.72	0.0
2015	47.25	47.22	-0.1
2025	60.87	60.82	-0.1
2035	76.67	76.55	-0.2
2045	94.75	94.52	-0.2
2055	115.31	114.89	-0.4
2065	138.65	137.94	-0.5
2075	165.20	164.04	-0.7
2085	195.48	193.68	-0.9
2095	230.15	227.46	-1.2

Source: See Text.

4 RESULTS

This section outlines the results which emerge from the model when it is run using the input values described above. Results are reported only up to the year 2100 to avoid any problems associated with the assumption of a terminal date.

In the BAU scenario global temperature rises to 2.2°C by the end of the 21st century (see table 4) though the committed temperature rise by that time is somewhat higher. This temperature rise has only a limited impact reducing GGNP by just 1.2% below baseline GNP (see table 3). At the same time income has increased tenfold whilst population has only doubled so this loss does not seem to be of much importance. Per capita incomes grow monotonically with the input assumptions used here even if no action is taken to reduce GHG emissions.

To begin with, the marginal damage from these unchecked emissions (see table 5) amounts to \$6.07 per tonne of carbon, \$47 per tonne of methane and \$884 per tonne of Nitrogen. The marginal damage from CFC-11 is \$2,115 and from CFC-12 \$4,194. These figures reflect only the role of CFCs as radiatively important gases and not as agents which deplete the ozone layer. If these concerns were taken into account the optimal tax on CFCs would be very much higher. The optimal tax on these substances is also very sensitive to the assumption that 80% of the impact on radiative forcing is offset by a corresponding reduction in stratospheric ozone. The tax will rise and fall approximately pro rata with the assumed ozone offset.

Sulfate Aerosols confer benefits in this model amounting to \$404 per tonne of sulphur in the decade centred around 1995 rising to a surprising \$14,567 by the end of the next century when the stock of GHGs in the atmosphere is much higher than today. These values simply reflect the ability of sulfate aerosols to fend off global warming. They do not reflect the damage done by these emissions as precursors of acid rain. Were the acid rain damage component of these emissions to be included in the analysis then the marginal benefits of sulphur emissions would fall and might become negative. The shadow prices for sulphur have been included merely to emphasise the extent to which dealing with one problem (acid rain) may aggravate another (global warming).

TABLE 4: The Impact Of Controls On The Climate

Year	No Controls Warming (°C)	Optimal Control Warming (°C)
1995	0.38	0.38
2005	0.41	0.41
2015	0.49	0.49
2025	0.63	0.60
2035	0.79	0.76
2045	1.00	0.94
2055	1.22	1.14
2065	1.46	1.36
2075	1.71	1.59
2085	1.96	1.81
2095	2.20	2.04

Source: See Text.

TABLE 5: Current Value Marginal Damage from GHG and Aerosol Emissions \$(/tonne)

Year	Carbon	Methane	Nitrogen	CFC-11	CFC-12	Sulphur
1995	-6.07	-47	-884	-2,115	-4,194	+404
2005	-8.44	-68	-1,267	-3,129	-6,089	+642
2015	-11.47	-98	-1,778	-4,523	-8,654	+1,014
2025	-15.19	-138	-2,439	-6,376	-12,024	+1,563
2035	-19.66	-191	-3,276	-8,772	-16,342	+2,334
2045	-24.92	-260	-4,316	-11,804	-21,757	+3,375
2055	-31.00	-346	-5,590	-15,570	-28,434	+4,735
2065	-37.98	-456	-7,136	-20,183	-36,545	+6,467
2075	-45.90	-592	-8,987	-25,763	-46,266	+8,633
2085	-54.80	-760	-11,178	-32,431	-57,750	+11,305
2095	-64.69	-967	-13,732	-40,287	-71,028	+14,567

Source: See Text

In *current value* terms all of these damage figures rise quickly through time. But if one wished to evaluate a project like afforestation which would remove carbon at points of time in the future it would be necessary to discount these values. The need to do this substantially reduces the attractiveness of long term carbon removal schemes. However; in scenarios where a much greater cutback in emissions is called for (perhaps because

damages are deemed to be high or the climate more sensitive to radiative forcing) then afforestation might yet have a role to play.

The relative damage potential of the various gases differs from what might be expected on a Global Warming Potential basis. This occurs for a number of reasons but mainly because the GWPs are a measure of the summed radiative forcing of a unit of gas relative to that of CO₂, but radiative forcing is not proportional to economic damage. For example; although the GWP of methane is considerably higher than that of CO₂ the latter has a much longer lifetime. A tonne of CO₂ emitted today will be around for longer than a tonne of methane. And since concentrations of GHGs are rising over time the CO₂ will impact at a time when the damage done by emissions is greater. On the other hand because this occurs further in the future we care less about it.

Turning now to the optimal control scenario, the optimal cutback in carbon emissions appears to be 6.9% in the decade centred around 1995 rising to 14.5% by the end of the next century (see table 6). These controls on carbon emissions are rather modest. They are of course dependent on among other things the strong assumption that non carbon GHG emissions do not change as carbon emissions are cut. If for instance carbon reductions also reduced methane emissions from coal mines being closed then the "price" of abatement would fall and the optimal amount of abatement would rise. On the other hand sulphur emissions would probably fall too if power producers started to switch away from coal. The optimal reduction in carbon emissions is sensitive to large scale attempts to cut sulphur emissions. Cutting sulphur emissions *ceteris paribus* increases the optimal cutback in carbon emissions in this model. This seems to suggest that ambitions to reduce sulphur emissions need to be tempered somewhat whilst carbon emissions reductions require to be stepped up.

TABLE 6: Optimal Reduction in Fossil Fuel Emissions of Carbon

Year	Percentage Reduction
1995	6.9
2005	7.7
2015	8.6
2025	9.5
2035	10.3
2045	11.1
2055	11.9
2065	12.6
2075	13.3
2085	13.9
2095	14.5

Source: See Text.

The emissions tax rates necessary to drive the economy along the optimal trajectory are described in table 7. Naturally these tax rates are lower than the figures for marginal damage in the no controls BAU scenario due to the decrease in emissions. In the decade centred around 1995 the optimal carbon tax is \$5.87 which is 20 cents less than the marginal damage figure without abatement. Whereas the two sets of figures differ only a little in this scenario the difference for other scenarios might be much greater. The

TABLE 7: Current Value Optimal Tax Rates on GHG and Aerosol Emissions (\$/tonne)

Year	Carbon	Methane	Nitrogen	CFC-11	CFC-12	Sulphur
1995	-5.87	-45	-833	-2,003	-3,945	+397
2005	-8.14	-65	-1,111	-2,941	-5,706	+620
2015	-11.06	-92	-1,658	-4,227	-8,070	+967
2025	-14.67	-129	-2,266	-5,933	-11,171	+1,467
2035	-19.02	-178	-3,034	-8,135	-15,136	+2,188
2045	-24.18	-241	-3,987	-10,916	-20,101	+3,147
2055	-30.19	-320	-5,154	-14,365	-26,212	+4,397
2065	-37.12	-420	-6,565	-18,581	-33,624	+5,986
2075	-45.03	-545	-8,254	-23,673	-42,492	+7,969
2085	-53.97	-698	-10,250	-29,748	-52,954	+10,410
2095	-63.93	-886	-12,572	-36,895	-65,081	+13,384

Source: See Text

optimal taxes for methane over the same period are \$45 and for Nitrogen \$833. The optimal taxes on CFC-11 and CFC-12 are \$2,115 and \$4,194 respectively. The shadow values suggest that the scheme for removing methane outlined earlier is not and will not become cost effective. The plan for reducing N₂O emissions becomes active in the second half of the next century.

With so little abatement being desirable the temperature change associated with the optimal climate policy looks very similar to the BAU temperature change (see table 4). In fact the optimal control and BAU paths for temperature rise look identical for the next thirty years and only begin to diverge by the end of the next century. At that time the temperature rise associated with the optimal policy is 2.04°C - only 0.16°C less than in the BAU scenario.

Comparing the flow of green income in the BAU and the Optimal Control scenario reveals that they are also almost identical. The optimal control GGNP exceeds the BAU GGNP by just 0.2% at the end of the next century. In terms of the impact on the present value of future income up to the year 2200 the percentage difference between the doing nothing and following the best policy available is approximately 0.01%. Even when applying the optimal control very little can be done to retrieve the losses in GGNP caused by the existence the carbon constraint. The remedy, as they say, is almost as bad as the disease.

By introducing further constraints into the model it is possible to examine the present value future income associated with various other protocols which have, from time to time, been proposed (table 8). Naturally all of these are inferior to the optimal control. The first protocol - that of stabilising global emissions at 6GtC annually - reduces the present value of future income by 0.5% relative to the optimal control solution. A policy of stabilising the atmospheric concentration of CO_2 at 400ppm on the other hand is tremendously costly and involves a reduction of 1.6% in the present value of future income relative to the optimal control solution. Limiting the rate of temperature change to 0.1°C per decade is also unnecessarily costly and entails a loss in the present value of income amounting to 0.6%. Somewhat surprisingly all three protocols are worse than doing nothing at all.

The present value cost of the greenhouse problem itself is estimated to be \$3 trillion representing about 0.2% of the present value of future income. This is the amount that we should be prepared to pay for information leading to a cost free solution to the global warming problem.

TABLE 8: The Present Value of Future Income Under Different Protocols (\$tr)

Policy	P.V. of Income	% Diff. to Op. Con.
Optimal Control	1,481	-
Business as Usual	1,481	-0.01
Stabilise Emissions @ 6GtC	1,474	-0.5
Stabilise Concentration @ 400ppm	1,457	-1.6
Limit Change to 0.1°C/Decade	1,472	-0.6
No Greenhouse Effect	1,484	+0.2

Source: See Text

5 CONCLUSIONS

This paper has presented a new applied model of the optimal control of global warming. The model can demonstrate how differing assumptions regarding the costs of abatement and the damage potential from global warming translate into different policy implications. Using this model and input assumptions implicit in the IPCC's IS92a best guess scenario the model is used to estimate the shadow price of the five main GHGs and the optimal cutback in emissions. These shadow prices represent the marginal rate at which gases may be traded whilst holding the present value of climate damage constant. Later it is hoped to produce a paper to illustrate the sensitivity of the optimal

control solution to different parameter and input assumptions. The paper also makes clear the difference between the marginal damages concept and the optimal tax rates. The marginal damage figures relate to the damage done per tonne of emissions when no abatement activity is undertaken. The optimal tax rates on the other hand refer to the taxes necessary to drive the economy along the optimal abatement path. The optimal tax on carbon is currently \$5.87 with the input assumptions used here whilst the marginal damage figure is 20 cents higher.

The paper has also sought to demonstrate the extent to which dealing with the acid rain problem may aggravate the global warming problem. The conclusion here is not necessarily that we should think again about large scale desulphurisation measures but that if large scale desulphurisation measures are seen as a necessity the cloak of protection sulfate aerosols provide disappears and a much greater degree of control would have to be exercised over carbon emissions.

The paper examines present value of future income under the optimal control and the business as usual scenarios. The message seems to be that it matters little whether carbon emissions are cut or not but that protocols to stabilise emissions or concentrations must be resisted. However; it is important to emphasise the tentative nature of these findings. They rely upon a particular set of views relating to the abatement cost function, the damage function and the sensitivity of the climate to heightened radiative forcing. If the reduction in carbon emissions yields significant secondary benefits or if the costs of a carbon tax can be offset by reducing other distortionary taxes then a much greater degree of abatement may be desirable. Moreover this analysis proceeds by replacing the uncertain parameters with their expected values. The question the model therefore address is what would be the optimal policy to follow if all the parameters were known with perfect certainty. *But since it is absolutely not the case that all parameters are known with perfect certainty the results of these exercises are not policy relevant and may yield poor policy advice.* Attempts to compute the optimal control under uncertainty indicate that, at least in the context of somewhat arbitrary assumptions regarding the form the uncertainty, the use of expected values can

alter the policy prescriptions obtained from these models significantly. But because of the arbitrary nature of assumptions regarding the probability distributions used in such analyses it would be wrong to take the findings of uncertainty analyses as being anything more than purely illustrative.

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APPENDIX 1

Model Variables

A_t	Proportionate loss in GNP due to abatement activity
$B_{t,b=1...5}$	Contents of the MRH carbon cycle boxes (GtC)
C_t	Proportionate cutback in carbon emissions
D_t	Proportionate loss in GNP due to global warming
$E_{t,i=1}$	Annual carbon emissions (GtC)
$E_{t,i=2}$	Annual methane emissions (TgCH ₄)
$E_{t,i=3}$	Annual nitrogen emissions (TgN)
$E_{t,i=4}$	Annual CFC-11 emissions (kt)
$E_{t,i=5}$	Annual CFC-12 emissions (kt)
$E_{t,i=6}$	Annual sulfate aerosol emissions (kt)
$M_{t,i=1}$	Atmospheric concentration of CO ₂ (ppm)
$M_{t,i=2}$	Atmospheric concentration of CH ₄ (ppb)
$M_{t,i=3}$	Atmospheric concentration of N ₂ O (ppb)
$M_{t,i=4}$	Atmospheric concentration of CFC-11 (ppt)
$M_{t,i=5}$	Atmospheric concentration of CFC-12 (ppt)
P_t	Population (billions)
Q_t	Conventional GNP (trillions of 1990 US dollars)
$R_{t,i=1...5}$	Radiative Forcing (w ⁻¹ m ²)
U_t	Equilibrium warming (°C)
W_t	Warming above preindustrial times (°C)
Y_t	Green GNP (trillions of 1990 US dollars)

MODEL SETS

$t=1,...,250$	The number of time periods (years)
$i=1,...,6$	The set of GHGs (1 refers to CO ₂ , 2 to CH ₄ , 3 to N ₂ O, 4 to CFC-11, 5 to CFC-12 and 6 to sulfate emissions)
$b=1,...,5$	The number of MRH boxes

MODEL PARAMETERS

Utility Discount Rate:

$$\rho = 0.03$$

Population Growth Parameters:

$$\pi_1 = 11.31$$

$$\pi_2 = 1.154$$

$$\pi_3 = 67.66$$

1990 Per Capita Labour Productivity:

$$\alpha = 4.247$$

The Rate of Growth in Labour Productivity:

$$g = 0.016$$

The Rate of Growth in GHG Intensities:

$$h_{i=1} = -0.0138 \text{ or } -0.0122$$

$$h_{i=2} = -0.0176$$

$$h_{i=3} = -0.0204$$

$$h_{i=4} = -0.0685$$

$$h_{i=5} = -0.0766$$

1990 GHG Intensities:

$$\omega_{i=1} = 0.3318 \text{ or } 0.2691$$

$$\omega_{i=2} = 22.69$$

$$\omega_{i=3} = 0.578$$

$$\omega_{i=4} = 13.36$$

$$\omega_{i=5} = 16.28$$

Damage Function Parameters:

$$\beta_1 = 0.004$$

$$\beta_2 = 2$$

Abatement Cost Function Parameters:

$$\delta_1 = 0.67058$$

$$\delta_2 = -0.2839\text{E-}3$$

Increase in Atmospheric Concentrations per Unit Emissions:

$$\mu_{i=1} = 0.471$$

$$\mu_{i=2} = 0.351$$

$$\mu_{i=3} = 0.207$$

Increase in Atmospheric Concentrations per Unit Emissions (contd):

$$\mu_{i=4} = 5.47\text{E-}5$$

$$\mu_{i=5} = 6.48\text{E-}5$$

MRH Class Fractions:

$$\gamma_{b=1} = 0.13$$

$$\gamma_{b=2} = 0.20$$

$$\gamma_{b=3} = 0.32$$

$$\gamma_{b=4} = 0.25$$

$$\gamma_{b=5} = 0.10$$

MRH Atmospheric Lifetimes (Years):

$$\eta_{b=1} = \infty$$

$$\eta_{b=2} = 363$$

$$\eta_{b=3} = 74$$

$$\eta_{b=4} = 17$$

$$\eta_{b=5} = 2$$

Non Carbon GHG Atmospheric Lifetimes (Years):

$$\tau_{i=2} = 11$$

$$\tau_{i=3} = 130$$

$$\tau_{i=4} = 55$$

$$\tau_{i=5} = 116$$

Climate Parameters:

$$\psi_1 = 6.3$$

$$\psi_2 = 0.047$$

$$\psi_3 = 0.14$$

$$\psi_4 = 0.47$$

$$\psi_5 = 2.01\text{E-}5$$

$$\psi_6 = 0.75$$

$$\psi_7 = 5.31\text{E-}15$$

$$\psi_8 = 1.52$$

$$\psi_9 = 0.22$$

$$\psi_{10} = 0.28$$

Climate Feedback Parameter (Kw^{-1}m^2):

$$\lambda = 0.572$$

Time Delay Parameter:

$$\xi = 0.0513$$

THE MODEL LISTING

Maximise:

The Intertemporal Utility Function:

$$\int_{t=0}^{t=250} P_t \log\left(\frac{Y_t}{P_t}\right) e^{-\rho t} dt \quad (1)$$

subject to:

The Population Growth Equation:

$$P_t = \frac{\pi_1}{1 + \pi_2 e^{\pi_3 t}} \quad (2)$$

GNP Growth:

$$Q_t = \alpha P_t e^{g t} \quad (3)$$

The Emission of Carbon:

$$E_{i=1,t} = \omega_{i=1} (1 - C_p) Q_t e^{r_{i=1} t} \quad (4)$$

The Emission of Other GHGs:

$$E_{i,t} = \omega_i Q_t e^{r_i t} \quad \forall i = 2, \dots, 5 \quad (5)$$

The Damage Function:

$$D_t = \beta_1 W_t^{\beta_2} \quad (6)$$

The Abatement Cost Function:

$$A_t = (\delta_1 + \delta_2 t) C_t^3 \quad (7)$$

Green GNP Identity:

$$Y_t = (1 - D_t - A_t) Q_t \quad (8)$$

The Evolution of the Contents of the MRH Boxes:

$$\dot{B}_{b,t} = \gamma_b E_{i=1,t} - \frac{B_{b,t}}{\eta_b} \quad (9)$$

The Evolution of the Atmospheric Concentration of GHGs:

$$\dot{M}_{i,t} = \mu_i E_{i,t} - \frac{M_{i,t}}{\tau_i} \quad \forall i = 2, \dots, 5 \quad (10)$$

1990 Contents of the MRH Boxes:

$$B_{b=1,t=0} = 404.71 \quad (11)$$

$$B_{b=2,t=0} = 134.90 \quad (12)$$

$$B_{b=3,t=0} = 142.40 \quad (13)$$

$$B_{b=4,t=0} = 52.46 \quad (14)$$

$$B_{b=5,t=0} = 14.99 \quad (15)$$

Atmospheric Concentration of CO₂:

$$M_{i=1,t} = \sum_{b=1}^{b=5} \mu_{i=1} B_{b,t} \quad (16)$$

1990 Atmospheric Concentrations of GHGs:

$$M_{i=2,t=0} = 1720 \quad (17)$$

$$M_{i=3,t=0} = 310 \quad (18)$$

$$M_{i=4,t=0} = 0.280 \quad (19)$$

$$M_{i=5,t=0} = 0.484 \quad (20)$$

The Radiative Forcing Equations:

$$R_{i=1,t} = \psi_1[\log(M_{i=1,t}) - \log(280)] \quad (21)$$

$$R_{i=2,t} = \psi_2(\sqrt{M_{i=2,t}} - \sqrt{800}) - f(M_{i=2,t}) \quad (22)$$

$$R_{i=3,t} = \psi_3(\sqrt{M_{i=3,t}} - \sqrt{285}) - f(M_{i=3,t}) \quad (23)$$

$$R_{i=4,t} = \psi_9 M_{i=4,t} \quad (24)$$

$$R_{i=5,t} = \psi_{10} M_{i=5,t} \quad (25)$$

The CH₄ - N₂O Overlap Term:

$$\begin{aligned} f(M_{i,t}) = & \psi_4 \log[1 + \psi_5 (M_{i,t} M_{j,t=1800})^{\psi_6} + \psi_7 M_{i,t} (M_{i,t} M_{j,t=1800})^{\psi_8}] \\ & - \psi_4 \log[1 + \psi_5 (M_{i,t=1800} M_{j,t=1800})^{\psi_6} + \psi_7 M_{i,t=1800} (M_{i,t=1800} M_{j,t=1800})^{\psi_8}] \end{aligned} \quad (26)$$

Equilibrium Warming Equation:

$$U_t = \lambda \sum_{i=1}^{i=5} R_{i,t} \quad (27)$$

The Evolution of Realised Warming:

$$\dot{W}_t = \zeta(U_t - W_t) \quad (28)$$

1990 Realised Warming:

$$W_{t=0} = 0.45 \quad (29)$$

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