Economic Damage Control for Greenhouse Gas Emissions

Hans W. Gottinger

Abstract

Future emissions of trace gases are intrinsically linked to economic growth and abatement policies, which in turn, are governed by expectations of greenhouse damages. Trace gas indices that depend upon future emissions can be calculated either on the basis of emissions scenarios, such as those devised by the IPCC, or using optimal control techniques where the trade off between damages and abatement costs is made explicit. The scientific and economic issues of multiple gas abatement policies and trace gas indices are comprehensively addressed.

Keywords: Energy, Greenhouse Gases, Economic Damage, Environmental Policy

1 . Introduction

A key element of possible policy responses to global climate change is the abatement of emissions of greenhouse gases (GHG). There has been considerable interest in viewing the emissions abatement problem as one involving a composite of multiple gases and not CO_2 alone. Comprehensive abatement strategies were proposed by the IPCC (1990) based on the

rationale that all greenhouse gases contribute to climate change. Under a comprehensive plan greenhouse gas abatement should be carried out cost effectively. In such an approach a cost effective solution would require the control of multiple gases.

It has been argued that a comprehensive abatement strategy requires the formulation of a greenhouse gas damage function that would allow for an evaluation of tradeoffs between greenhouse gases in a number of possible abatement contexts, including:

(1) The evaluation of tradeoffs between gases in a comprehensive abatement strategy.

(2) Comparison of investments in abatement projects made toward mitigating climate change.

(3) Comparing the current and future emissions responsibility of nations.

A most widely discussed metric relating to potential damage is the Global Warming Potential (GWP) (Lashof and Ahuja, 1990; IPCC, 1990, Fuglestvedt, Isaksen and Wang, 1994). In addition to various problems having been identified with the formulation and use of GWPs, it is also said that "GWPs do not account for the time variation in the economic opportunity costs of an increment of radiative forcing," (Eckaus, 1992). Consequently, they do not provide much insight for abatement policy formulation. Damages linked to climate change and abatement costs associated with emissions reductions are both time varying quantities, and consequently, need to be explicitly included in the calculation of a metric that determines gas-by-gas greenhouse responsibility.

Optimal control and dynamic optimization models have been extensively used in natural resource economics (see for e.g., Kamien and Schwartz, 1981, Conrad and Clark, 1987). Optimal control models have also been used to study greenhouse gas abatement policies (Nordhaus, 1994; Peck and Teisberg, 1993; Falk and Mendelsohn, 1993). Reilly and Richards (1993) have used an economy−climate optimal control model to estimate greenhouse damages based on the relative economic impact of current and past greenhouse gas emissions. Schmalensee (1993) arrives at similar results based on comparing damages from unit emissons of trace gases.

In practice the specification of a dynamic damage function and abatement costs is a complex task. We formulate a cost-effectiveness framework, where climate change and damage information is included through constraints on model variables. First, cost−effective trace gas composites based on IPCC emissions scenarios are determined, while recognizing that these scenarios have been developed under different assumptions regarding future expectations of technological diffusion and damages from climate change. Second, the optimal abatement problem for a multiple gas abatement strategy involving methane and carbon dioxide is approached numerically, assuming costs of abatement and climate damages presented in the literature. Next to CO_2, Methane is the second most important greenhouse gas; the instantaneous radiative forcing due to a unit mass of methane is 58 times that of a unit mass of CO_2. This, coupled with the possibility of low costs of abatement, makes methane an attractive short−term abatement option.

The cost benefit (C−B) analysis formulation is set up in section 2. Trace gas indices, defined as the cost of abating the next unit of a non CO_2 trace gas

(relative to CO_2), are analytically determined using a general form of damage function. In section 3, a similar analysis is carried out using the cost-effectiveness (C–E) framing, and scenario-based trace gas indices are determined using IPCC scenarios. Section 4 deals with the numerical estimation of the optimal index for a two gas strategy. This is followed by a discussion of the results and the policy implications of this work.

2. Trace Gas Indices Using Cost-Benefit Framing

In this section we briefly describe an optimal control framework. We restrict the analysis to two gases $-CO_2$ (referred to as gas 1) and a non-CO_2 gas (referred to as gas 2) $-$ without loss of generality. In a cost benefit context the cost abatement and damages due to climate change are minimized. The optimal control problem can be stated as:

$$\min \int_0^t \{A_1(a_1(t)) + A_2(a_2(t)) + D(c_1(t), c_2(t))\} e^{-rt} dt \qquad (2.1)$$

$$\frac{dc_1}{dt} = -\gamma_1 \, c_1(t) + \beta(s_1(t) - a_1(t)) \qquad (2.2)$$

$$\frac{dc_2}{dt} = -\gamma_2 \, c_2(t) + (s_2(t) - a_2(t)) \qquad (2.3)$$

Equation 2.1 is the cost objective function, while 2.2 and 2.3 are dynamic GHG equations.

$A_{1,2}$, $a_{1,2}$, $c_{1,2}$, $s_{1,2}$, $\gamma_{1,2}$, are the costs of abatement, levels of abatement, atmospheric concentration and Business-As-Usual emissions, and atmospheric lifetimes of gases 1 and 2, respectively. β is the atmospheric airborne fraction of CO_2 and $D(c_1, c_2)$ is the damage function due to climate change. The Hamiltonian H is given by

$$H = \{A_1(a_1(t)) + A_2(a_2(t)) + ... + D(c_1, c_2)\}e^{-rt} +$$
$$\lambda_1(t)[-\gamma_1 \ c_1(t) + \beta(s_1(t) - a_1(t))] + \lambda_2(t)[-\gamma_2 \ c_2(t)$$
$$+ (s_2(t) - a_2(t))] \qquad (2.4)$$

The first order necessary conditions are given:

$$\frac{\partial H}{\partial a_1} = 0 \qquad (2.5)$$

$$\frac{\partial H}{\partial c_i} = -\lambda_i \qquad (2.6)$$

This leads to

$$\lambda_1 = \frac{1}{\beta} * \frac{\partial A_1}{\partial a_1} e^{-rt} \text{ and } \lambda_2 \frac{\partial A_2}{\partial a_2} e^{-rt} \qquad (2.7)$$

$$\dot{\lambda}_1 = \gamma_1 \lambda_1 - \left[\frac{\partial D(c_1, c_2)}{\partial c_1}\right]e^{-rt} \text{ and } \dot{\lambda}_2 = \gamma_2 \lambda_2 - \left[\frac{\partial D(c_1, c_2)}{\partial c_2}\right]e^{-rt} \qquad (2.8)$$

Equation 2.7 is the static optimality condition that relates the shadow price of the emissions constraint to the cost of abatement. Equations 2.7 and 2. 8 in conjunction with equations 2.2 and 2.3 and initial conditions on c_i (e.g. the current value of atmospheric concentrations), and final conditions on λ_i represent a two point boundary value problem that can be solved numerically. The quantities $\frac{\partial A_1}{\partial a_1}$ and $\frac{\partial A_2}{\partial a_2}$ are the marginal costs of abatement for gases 1 and 2 and are subsequently denoted M_1, M_2. Assuming (restrictively) that the air-borne fraction β for CO_2 is a constant we can eliminate λ_1 and λ_2 and $\dot{\lambda}_1$ and $\dot{\lambda}_2$ from 2.7 and 2.8 and obtain

$$\dot{M}_1 = (\gamma_1 + r)M_1\left[\frac{\partial D(c_1, c_2)}{\partial c_1}\right] \text{ and } \dot{M}_2 = (\gamma_2 + r)M_2\left[\frac{\partial D(c_1, c_2)}{\partial c_2}\right] \qquad (2.9)$$

Equation 2.9 is a key equation that expresses the economic optimality condition-that the marginal costs of abatement of each gas is equal to the

marginal damages from climate change, if that unit of gas is left unabated. It contains the greenhouse gas attributes we need to capture-the gas lifetimes $(1/\gamma_1, 1/\gamma_2)$, marginal costs of abatement (M_1, M_2), marginal climate damages $(\frac{\partial D}{\partial c_1}, \frac{\partial D}{\partial c_2})$ and discount rate, r. We now need to consider the specification of physically realistic damage functions. Typically damages due to climate change will be a function of particular climate variables. In the simplest case, the damage function is assumed to be a function of the mean global temperature[1], $T(t)$. Thus we can write:

$$\frac{\partial D(c_1, c_2)}{\partial c_{i(i=1.2)}} = \frac{\partial D}{\partial c_i} = \frac{\partial D}{\partial T} * \frac{\partial T}{\partial c_i} \qquad (2.10)$$

The terms $\frac{\partial T}{\partial c_1}$ and $\frac{\partial T}{\partial c_2}$ depend on the temperature trajectory $T(t)$, which is the response of the climate system to radiative forcing, $R(c_1(t), c_2(t))$. A simple model to evaluate $T(t)$, which treats the climate system as linear, is the convolution integral:

$$T(t) = \int_0^t R(C_{i=1.2}(t)) H(t-\tau) d\tau. \qquad (2.11)$$

where $H(t)$ is the impulse response of the climate system. Models with linear systems approximations of the climate system have been formulated by Dickinson (1981) and Schneider and Thompson (1981), and also used for policy analysis (IPCC), 1990; Nordhaus, 1992). We further assume that radiative forcing $R(c_1(t), c_2(t))$ is linearly separable, i.e. $R(c_1(t), c_2(t)) =$

---

1) We limit ourselves to damage functions that are dependent on the instantaneous value of temperature. In reality, damages will depend not only on the instantaneous value, but also on the time trajectory of temperature and other climatic variables, as well as on human adaptation activities.

$R_1(c_1(t)) + R_2(c_2(t)^{2})$.

From 2.8, 2.10, and 2.11 the marginal cost of abatement for gas i is given by

$$M_i(t) = \int_t^T \frac{\partial D(T(t))}{\partial T(t)} * \left\{ \int_0^t \frac{\partial R(C_i(t))}{\partial C_i(t)} * H(t-\tau) * F_i(\tau) d\tau \right\} e^{-rt} \ dt. \quad (2.12)$$

where $F_i(\tau)$ is the impulse response of the atmospheric concentration of gas i to its emission. The ratio of the marginal costs of abatement of a non CO_2 gas with that of CO_2 is defined as the trace gas index I. At the economic optimum I is equal to the ratio of damages caused per unit emissions of each gas. This index is evaluated at time $t=0$, which is set nominally at some benchmark date, say, 1990.

$$I = \left[\int_0^T \frac{\partial D(T(t))}{\partial T(t)} * \left\{ \int_0^t \frac{\partial R(C_i(t))}{\partial (C_i(t))} * H(t-\tau) * F_i(\tau) d\tau \right\} e^{-rt} \ dt \right]_{i=2} \Big/$$

$$\left[\int_0^T \frac{\partial D(T(t))}{\partial T(t)} * \left\{ \int_0^t \frac{\partial R(C_i(t))}{\partial (C_i(t))} * H(t-\tau) d\tau \right\} e^{-rt} \right]_{i=1} \quad\quad (2.13)$$

In the above equation, $F_i(\tau)$ is the additional increase in future concentration per unit of the source relased at time $(\tau=0)$. If the trace gas cycle is approximated by a linear system this term is equal to the impulse response of atmospheric concentration to source emissions.[3] $H(t-\tau)$ in (2.12) is equal to the change in global mean temperature at future time t for small change

---

2) While this assumption does not hold for gases with significant overlap, such as CH_1 & N_2O, it is reasonable in most cases.

3) Although the trace gase cycles of CO2 and CH_4 have non-linearities, it is routine to use linear approximations for the purposes of prediction. Impulse responses have been derived for most trace gases.

in the radiative forcing at time τ, $0 < \tau < t$. This captures the inherent lag in the climate response to an increase in radiative forcing. $\dfrac{\partial R(C_i(t))}{\partial (C_i(t))}$ is the instantaneous radiative forcing of gas i, i.e., it is the increase in radiative forcing due to a unit increase in the atmospheric concentration of the gas[4]. $\dfrac{\partial D(T(t))}{\partial T(t)}$ describes how climate damages may change with temperature. There is much evidence and concern that climate damages measured in physical units (for example, sea level rise due to temperature change or soil moisture) or in corresponding economic units (damages from coastal erosion and storms or loss in agricultural yield) are likely to be non-linear and convex. i.e., the rate of increase in damages may increase with increasing temperature (Fankhauser and Pearce, 1993)

We can obtain the GWP from equation (2.13) by making the following simplifying assumptions:

  1. Assume that damages are a linear function of temperature, i.e., the term $\dfrac{\partial D(T(t))}{\partial T(t)}$ from equation (2.12) can be replaced by a constant.

  2. Assume that the climate lag time (i.e., the time constant for the oceanic response) is zero, i.e., the function $H(t-\tau)$ is set equal to $\delta(t)$, the Dirac delta function.

This effectively replaces the integral inside the curly brackets with the term $\dfrac{\partial R(C_i(t))}{\partial C_i(t)} * F_i(\tau)$. In addition to assumptions 1 and 2, if the discount rate is set equal to zero, then equation (2.13) reduces to

---

4) Relative to CO_2, most other trace gases have high values of instantaneous radiative forcing.

$$I = \frac{\left[\int_0^T \frac{\partial R(C_i(t))}{\partial C_i(t)} * F_i(\tau) d\tau\right]_{i=2}}{\left[\int_0^T \frac{\partial R(C_i(t))}{\partial C_i(t)} * F_i(\tau) d\tau\right]_{i=1}}$$

which is exactly the definition of the Global Warming Potential (GWP).
Thus the GWP is an optimal trace gas index under unrealistic scientific and
economic assumptions although for different reasons than those put forth by
Reilly and Richards (1993). This analysis does not require that the shadow
price of emissions be a constant in order for an index exclusive of economic
damages to be optimal. Additionally, the index devised by Reilly and
Richards can be derived from equation (2.13) by setting the oceanic
response time to zero. In general, optimal trace gas indices defined in equ-
ation (2.13) have to be numerically evaluated by solving the two point
boundary value problem described by equation (2.9); this would involve
specifying costs of abatement and greenhouse damages. However, the rela-
tive costs of greenhouse abatement and damages from climate change are a
subject of much controversy. Costs of abatement vary from the relatively
high "top down" estimates from energy-economic modeling, to the low
"bottom up" estimates from engineering feasibility studies. Similarly,
damage estimates vary greatly, as do expert judgments regarding them
(Nordhaus, 1992). In order to capture these different expectations, an al-
ternative approach to the calculation of trace gas indices would be to specify
scenarios for future temperature trajectories and directly evaluate equation
(2.13), assuming different functional forms for the damage functions. This
approach is termed here as a cost-effectiveness approach. Note that for the
cost-effectiveness approach it is sufficient to specify only the functional de-

pendence of greenhouse damages on global mean temperature; the index-does not depend on a scale factor for conversion into economic units. In the next section, the cost-effectiveness analysis is described and trace gase indices are calculated for a variety of emissions/abatement scenarios.

3 . Cost-Effectiveness Analysis

A cost-effectiveness analysis is often regarded as a plausible alternative to cost benefit analysis when benefits are uncertain or unknown or when value of the benefit stream from a set of actions cannot be explicitly quantified (Tietenberg, 1991). A desirable and obtainable objective is selected-with the implicit assumption that the investments/decisions are worthwhile-but a formal cost-benefit criterion is not applied (Morgan and Henrion, 1990). A cost-effectiveness analysis has several potential advantages. First, from the perspective of negotiating a climate treaty, several contentious issues dealing with determining costs and damages are replaced by politically negotiated choices on climatic variables and trajectories.[5]
Second, constraining physical variables can allow us to implicitly value the preservation of natural systems-something most estimates of greenhouse damages[6] fail to do.

The cost-effectiveness analysis is formulated by minimizing the total costs subject to a constraint on the global mean temperature trajectory of the form

5) Indeed, the guidelines for greenhouse abatement in the Framework Convention on Climate Change (UNCED, 1992) seek to 'achieve stabilization of atmospheric carbon at a level and in a time frame sufficient to: 1) allow ecosystems to adapt naturally to climate change, 2) to en-sure that food production is not threatened, and 3) to enable economic development to proceed in an sustainable manner.'

6) For a critical assessment of greenhouse damages, see Ayres and Walters (1991).

$T(t) = T^*(t)$ where $T^*(t)$ is an exogenously specified temperature trajectory. It can easily shown that the trace gas index is the same as that in equation (2.13), where the term $\frac{\partial D(T(t))}{\partial T(t)}$ is evaluated at $T(t) = T^*(t)$. The resultant trace gas index has been evaluated for two different scenarios; the IPCC scenarios A and D reflecting business as usual, and high abatement situations.

Index evaluations could be carried out for methane, nitrous oxide, and HCFCs for the time horizon T of 100 years. CFCs are omitted because their role in net radiative forcing is considered to be small due to offsetting effects of ozone depletion. With the exception of CO_2 greenhouse gas impulse responses $F_i(\tau)$ are constructed using a single exponential lifetime (See table 1). For CO_2 a single lifetime model is inadequate to accurately represent the oceanic uptake (Enting and Newsam, 1990) hence, the multiple exponential model devised by Meier-Reimer and Hasselmann (1987) is used. Additionally, biospheric sources and sinks of CO_2 are assumed to be equal. Concentration dependent radiative forcing was determined by using the Wigley-Raper relationships provided in the IPCC scientific assessment (Wigley and Raper, 1992). A simple climate model with climate sensitivity (ΔT of CO_2 doubling) of 3℃ and an ocean response time of 30 years was used. Calculations were carried out for discount rates of 0%. 3%. and 6 %. The corresponding values for global warming potentials, which are independent of the emissions scenarios, are also presented. All index calculations are based on direct radiative forcing: indirect effects of methane resulting from tropospheric interactions have not been included.

In table 1 we provide for reference the assumed lifetime, current values for

instantaneous radiative forcing (relative to CO_2) and the global warming

potentials for methane, nitrous oxides, and HCFC-22- a representative

halocarbon. Table 2 provides trace gas indices derived from this analysis for

each of the emissions and damage scenarios at an assumed discount rate of

2%. In table 3 we capture the effect of discount rates on the scenario-based

trace gas index for methane. For gases that are short-lived relative to CO_2,

i.e. Methane and HCFC-22, the trace gas index decreases with increasing

non-linearity of the damage function and climate-derived temperature

change which accumulates with time, thus de-emphasizing gases with life-

times shorter than CO_2. Conversely, nitrous oxide has a higher effective

lifetime relative to CO_2 and, hence, the value of index increases with in-

creasing non-linearity of the damage function.

The effect of emissions scenarios A and D, on trace gas indices is slightly

more complicated. The temperature trajectories resulting from the IPCC

emission scenarios A and D deviate significantly from one another on time

scales greater than the lifetimes of short-lived gases. Since the marginal

damages due to the realized temperature change increase monotonically

with temperature, the difference in indices for the two scenarios results

primarily from differences in temperature trajectories on longer time scales.

Thus a gas with a short lifetime has a smaller index for scenario A (high

future temperature trajectory) than for Scenario D (low future temperature

trajectory) and vice versa.

From table 2 it is seen that trace gas indices are more sensitive to the level

of non-linearity in the damage function than they are to that in the emissions

scenario. Scenarios A and D capture very different, opposing views-ranging

from a coal intensive energy supply for scenario A to a renewable and nuclear intensive enery supply for scenario D-of the expected future energy mix. This suggests that index calculations are reasonably robust over a wide range of possible outcomes of energy supply futures. From table 3 it is apparent that trace gas indices depend critically upon the choice of the discount rate. A higher discount rate reduces the impact of future damages from trace gases with longer lifetimes and leads to an increase in the value of the index

Trace Gas	Instantaneous forcing $CO_2=1$	Life time (years)	GWP*
Carbon Dioxide	1	See Text	1
Methane	58	10.5	11
Nitrous Oxide	206	150	· 290
HCFC–22	5440	15	1500

Table 1: Key Scientific Attributes of Trace Gases.
*GWP Integration time is 100 years

Trace Gas	Cubic Damages		Quadratic Damages		Linear Damages
	IPCC–A	IPCC–D	IPCC–A	IPCC–D	
Methane	8.5	10	12	12.9	19
Nitrous Oxide	289	286	282	280	269
HCF–22	1284	1466	1706	1811	2445

Table 2: Scenario based trace gas indices for trace gases (Integration time of 100 year years) for a discount rate of 2%. Note that for damages that depend linearly on temperature, the index is independent of damage function and emissions scenario.

Discount rate	Cubic Damages		Quadratic Damages		Linear Damages
	IPCC–A	IPCC–D	IPCC–A	IPCC–D	
r=0%	6.4	7.6	8.5	9.3	13.3
r=2%	8.5	10	12	12.9	19
r=6%	15	16	20.6	21	27.7

Table 3: The effect of discount rate on trace gas index for methane

for species that are short-lived relative to CO_2. Conversely, for a species that is long lived relative to CO_2 higher discount rates lead to an decrease in its trace gas index.

These results may differ from the corresponding ones given by Reilly and Richards (1993) for several reasons. This analysis includes a representation of the lagged oceanic response to radiative forcing not included in their work. The ocean lag tends to increase the amount of time between emissions of the trace gas and the resulting damages. Therefore, the inclusion of more realistic science in the form of oceanic lag tends to increase the value of the trace gas index for shorter lived gases and vice versa. Second, this analysis includes realistic representations of the relationship between radiative forcing and trace gas concentrations. Finally, we use a more representative oceanic carbon cycle model: a single exponential model, such as that used by Reilly and Richards (1993) tends to underestimate predicted concentrations of CO_2.

4. Estimation of Optimal Index for Methane

In the previous section numerical values for trace gas indices were determined under scenarios for future greenhouse warming. Since the emissions trajectories were exogenously specified, the calculation did not require an explicit characterization of the costs of abating greenhouse emissions. In section 2 it was noted that an optimal trace gas index could be determined if costs of abatement for greenhouse gases and damages from climate change were specified. Here the calculation of such an optimal index is presented on the basis of estimates of greenhouse abatement costs and damages available in the literature. A note of caution needs to be added before one presents a

cost-benefit analysis for climate change policy, indeed as one should when attempting any such analysis over century long time scales. Despite recent efforts, greenhouse damage estimates remain sketchy at best. The estimates by Nordhaus (1992) suggest a rather benign impact of climate change on the human economic system. Ayres and Walters (1991) and Cline (1992), among others, tend to disagree with this assessment and suggest much larger values for benefits of greenhouse abatement. Lave and Vickland (1989) argue that developing countries may be more vulnerable to climate change and could face large damages. Estimates of Funkhauser amd Pearce (1993) to CO_2 emissions alone range from 20\$/tC in this decade to 28\$/tC between 2020 to 2030. Additionally, non-market/ecosystem damages of global temperature rise remain largely unknown. On the cost side, engineering estimates of carbon abatement costs (per ton of carbon emitted) differ greatly from those derived from macro-economic energy modeling. For example, one study cites that estimates for a 20% percent reduction in current emissions the marginal costs vary from 120\$/tC to 50\$/tC across models (Wilson and Swisher, 1993).

Bearing in mind the above uncertainties, the analysis that follows should be treated as purely illustrative. Greenhouse damages are specified as a fraction (1.3%) of an exogenous global GDP, based on Nordhaus (1992), with the global GDP following the Nordhaus n-controls scenario. The lack of an explicit economy growth model means that economic feedbacks are not modeled. If climate damages are large this could lead to an underestimate of total damages compared to a model where economic feedbacks are explicitly modeled.

Costs of abatement of CO_2 were taken from Falk and Mendelsohn (1993), whose estimates for the cost curve are based on work by Nordhaus. The costs used in the analysis, therefore, reflect the energy economic "top down" view of CO_2 abatement. The costs of abatement for methane are extremely sketchy, and estimates vary over a wide range. Adams et al. (1992) estimate costs of abatement for agricultural activities in the US ranging from \$500 to \$4000 per ton. The NAS report on policy implications of greenhouse warming (NAS, 1992) suggests far lower US costs of 50–100\$/tC. Additionally the NAS report estimates landfill emissions control costs as low as 20–30 \$/tC. To reflect this variation two scenarios were chosen for the costs of abatement for methane relative to CO_2. One scenario, where the cost of abatement for the two gases is equal for the same level of abatement, i.e. $A_1(e_1) = A_2(e_2)$ when $e_1 = e_2$ —(Scenario 1)— and a second scenario, where costs of abating methane are an order to magnitude higher, i.e. $A_1(e_1) = 0.1*A_2(e_2)$ when $e_1 = e_2$ —(Scenario 2).

The trace gas index for methane was determined by solving the optimal control problem for the costs and damages described above. Trace gas and climate models were the same as those described in section 3. The formulation requires the specification of a Business As Usual (BAU) scenario which was taken from the IPCC Scientific Assessment. The problem was solved as a dynamic, non-linear optimization problem. The control profile was approximated as a time dependent polynomial, whose coefficients were estimated by optimization. In order to obtain physically realistic solutions, the abatement activity of methane was limited to its anthropogenic emissions.

The analysis was carried out for linear, quadratic, and cubic damage functions and for discount rates of 0%, 2% and 6%. The scenario-based optimal indices for methane are presented in Table 4. The optimal temperature trajectories resulting from the solution of the optimal control problem, are shown in Figure 1.

Discount rate	Cubic Damages		Quadratic Damages		Linear
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Damages
r=0%	9	9.65	12.2	12.9	19.6
r=2%	11.9	12.8	17.0	18	28
r=6%	20.8	22.6	30	31	42.6

Table 4: Optimal values of trace gas index for Methane (including indirect effects)

As observed from figure 1, the optimal temperature trajectories for the two scenarios of methane abatement costs do not differ significantly. When the costs of methane abatement are low (Scenario 1), the high per unit instantaneous radiative forcing of methane results in significant early methane abatement. This causes the temperature trajectory to deviate from the BAU case at t=1990. For high costs of abatement (Scenario 2) this deviation takes place later in time. Additionally, the two trajectories do not differ sufficiently enough to cause significantly different marginal damages. Hence, the indices for the two scenarios do not differ significantly, suggesting that accurate costs of abatement for methane may not be critical in trace gas index calculation. As in the previous section, the degree of non-linearity in the damage function continues to be a more critical determinant of the trace gas index than the temperature trajectory. The discount rate also continues to be the most important parameter in the calculation of the optimal trace gas index.

Much of the early discussion on trace gas indices, particularly GWPs, revolves around the choice of an appropriate time horizon for integration. This is particularly problematic because there is no clear way to choose an integration time. When the problem is cast into an economic framing the choice of time horizon is converted into a choice of an approriate discount rate. The choice of a discount rate is then linked to expectations of future economic growth, and, in turn to the degree of optimism that a decision-maker has regarding future outcomes(Gottinger and Barnes, 1997). More optimistic outcomes would imply higher discount rates. The analysis by Lave and Dowlatabadi (1993) suggest that future expectations and decision criteria of decision-makers may be the most important determinants of climate change policy decisions. Hence, the fact that the choice of a discount rate may be key to climate change policy decisions is also reflected in the value of trace gas indices.

Scientific uncertainty plays an important role in determining trace gas indices, particularly for methane. Uncertainties in tropospheric interactions and resulting indirect effects and uncertainties in the lifetime of methane continue to plague trace gas index calculations (IPCC, 1992) Sensitivity analysis performed on model parameters shows that methane lifetime is a key parameter; varying the lifetime of methane from 8 to 12 years (best estimate 10.5 years) could change the index by up to 50%; the index for methane was less sensitive to uncertainties in the carbon cycle. Uncertainties in climate models were the least important.

From the analyses in sections 2 and 3 we can draw some conclusions regarding the relative importance of the various economic and scientific

uncertainties in trace gas index calculation for methane. We list them below in order of importance:

- Social Discount Rate
- Uncertainty in Methane lifetime
- Non linearity in Damage Functions
- Costs of abatement for Carbon

5. Conclusions

Comprehensive abatement strategies are based on the rationale that a minimum cost abatement strategy would require the control of multiple gases. This calls for the use of trace gas indices that allow for trading off between gases in a variety of possible abatement policies. This paper provides an evaluation of trace gas indices based on an optimal control framing. The analysis suggests that robust greenhouse gas indices require a better knowledge of non-linear greenhouse damage functions and greenhouse gas lifetimes. Uncertainties in costs of carbon abatement are less important. Additionally, the choice of an appropriate discount rate has an important bearing on the outcome of index calculations.

The key issue of side benefits/costs of CO_2 abatement has been left out of the analyses on trace gas indices. To be sure, carbon abatement strategies will be accompanied in many cases by reductions in Sulfate, NOx and TSP emissions. The subsequent side benefits may have a net present value exceeding the benefits from damages avoided by carbon abatement. However, carbon abatement will also lead to a reduction in aerosol emissions and a

subsequent increase in atmospheric radiative forcing.

Although an economics based approach, such as that presented in this paper, has several advantages compared to a purely scientific index, much of the debate on trace gas indices continues to be dominated by GWP, in spite of its scientific and conceptual flaws. If damages from climate change are highly non-linear then the use of GWPs may result in an overestimate of the benefits of greenhouse abatement projects involving non CO_2 trace gases. It is therefore important for approaches incorporating economics in calculations of greenhouse indices to gain more currency in the policy debate.

Acknowledgement
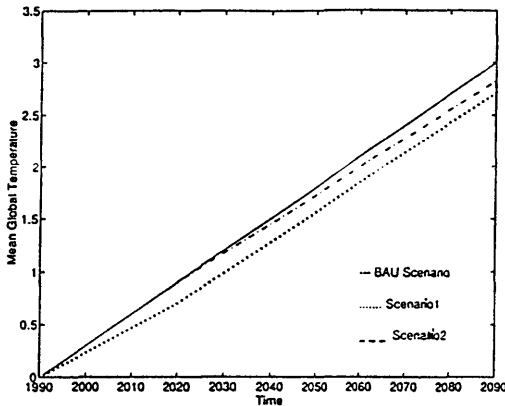
Figure; 1 Optimal global temperature paths with comprehensive abatement

References

Adams, R.M., Chang, C.C., McCarl, B.A., Callaway, J.M., 1992, 'The role of agriculture in climate change: A preliminary evaluation of emissions control strategies', in Economic issues in Global Climate Change, pp. 273, 287., Westview Press.

Ayres, R.U., Walters, J., 1991, 'Greenhouse effects: Damages, Costs and Abatement.' Environmental and Resource Economics, 1:237:270.

Conrad, J.M. and C.W. Clark, 1987, Natural Resource Economics, Cambridge Univ. Press: Cambridge.

Eckaus, R., 1992, 'Comparing the effects of greenhouse gas emissions on global warming.' The Energy Journal, 13, 1, 25–25.

Enting, I., G. Newsam, 1990. 'Atmospheric Constituent Inversion Problems: Implications for Baseline Monitoring,' J. Atmos. Chem., 11, 69–87.

Falk I., R. Mendelsohn 1993, 'The Economics of Controlling Stock Pollutants: An Efficient Strategy for Greenhouse Gases,' Journal of Environmental Economics and Management, 25. pp.76–88.

Fuglestvedt, J.S., Isaksen, I.S.A. and W.-C. Wang, 1994 'Direct and Indirect Global Warming Potentials of Source Gases', CICERO, Univ. of Oslo, Report.

Fankhauser, S. and D.W. Pearce, 1993, 'Cost Effectiveness and Cost-Benefit in the Control of Greenhouse Gas Emissions,' Working Group III, IPCC, Montreal.

Gottinger, H.W. and P. Barnes, 1997, 'Energy, Economy and The CO_2 Problem' in L. Hens (ed.), Handbook of Environmental Management, Routledge, London.

Gottinger, H.W., 1998, Global Environmental Economics, Kluwer, Boston.

IPCC (International Panel of Climate Change), 1990, 'Greenhouse gases and aerosols' in Climate Change. The IPCC Scientific Assessment. Cambridge University Press, 7–40.

IPCC, 1992, The Supplementary Report to The IPCC Scientific Assessment, Cambridge University Press, 1992, 51–67.

Kamien, M.I., N.L. Schwartz 1981, Dynamic Optimization: The Calculus of Variations and Optimal Control, North Holland, Amsterdam.

Lashof, D.A., and D.R.. Ahuja 1990, 'Relative Contributions of Greenhouse Gas Emissions to Global Warming.' Nature, 344, 529–531.

Lave, L.B., Dowlabati, H., 1993, 'Climate change policy: The effects of personal beliefs and scientific uncertainty.' Envrion. Sci. Technol. 27–10, 1962–1972.

Maier-Reimer, E. and Hasselmann, K., 1987. 'Transport and Storage of CO_2: An Inorganic Ocean Circulation Carbon Cycle Model,' Climate Dynamics, 112, 63–90.

Morgan, M.G., Henrion, M., 1990, Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis, Cambridge University Press, Cambridge.

National Academy of Science (NAS), 1992. Policy Implications of Greenhouse Warming. National Academy Press, Washington D.C.

Nordhaus, W.D., 1994, Managing the Global Commons, The Economics of Climate Change, MIT Press: Cambridge, Mass.

Nordhaus W.D. 1992, 'An optimal transition path for global climate policies.' Science 258. 1315–1319.

Reilly. J., Richards, K.R., 1993. 'Climate Change and Trace Gas index issue.' Environmental and Resource Economics, 3:41–61.

S.C. Peck and T. Teisberg, 1993, 'Global Warming Uncertainties and the Value of Information: An Analysis using CETA', Resource and Energy Economics 15 (1), 71–97.

Schmalensee, R., 1993, 'Comparing Greenhouse Gases for Policy Purposes,' Energy Journal 141, 245–255.

Tietenberg, T., 1991. Environmental and Natural Resource Economics, Harper Collins.

Wigley, T.M.L. and S.C. Raper, 1992, 'Implications for Climate and Sea Level of revised IPCC Emissions Scenarios', Nature 357, 293–300.

Wilson, D., Swisher, J., 1993. 'Exploring the Gap: Top down versus bottom up analyses of the costs of mitigating global warming,' Energy Policy 21–3, 249–262.