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529

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Berlin, November 2005

IMPRESSUM

DIW Berlin
German Institute for Economic Research
Königin-Luise-Str. 5
14195 Berlin
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Fax +49 (30) 897 89-200
www.diw.de
ISSN print edition 1433-0210
ISSN electronic edition 1619-4535

25-Nov-05

A FLEXIBLE GLOBAL WARMING INDEX FOR USE IN AN INTEGRATED APPROACH TO CLIMATE CHANGE ASSESSMENT

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Abstract. Global Warming Potential (*GWP*) is an index used to measure the relative accumulated radiative effect of a tonne of greenhouse gas (GHG) compared to that of a 'reference' gas (CO_2). Due to the different lifetimes of the GHGs, the *GWP*s are often measured over a fixed and long period of time (usually 20, 100, or 500 years). The disadvantage of this time-approach is that the index may give a good indication of the relative *average* effect of each GHG or total radiative forcing over the chosen time horizon, but it may not describe accurately the *marginal* contribution of each GHG to the overall climate change at a *particular point in time*, and *conditional on a particular climate change policy scenario* which is being considered. In this paper, we propose an alternative approach which measures the relative contribution of each GHG to total radiative forcing more accurately and in accordance with the current policy context being considered. We suggest the use of a *marginal* global warming potential (*MGWP*) rather than the existing (total or cumulative) *GWP* index. The *MGWP* can be calculated accurately and endogenously within a climate model. This is then linked to the *marginal abatement cost* (*MAC*) of the gas, estimated within an economic model linked to the climate model. In this way the balancing of the benefits and costs associated with the reduction of a unit of emission of the GHG can be achieved more accurately. We illustrate the use of the new approach in an illustrative experiment, using a multi-sector multi-gas and multi-regional computable general equilibrium economic model (GTAP-E) coupled with a reduced form climate change model (ICLIPS Climate Model, or ICM). The results show that the new approach can significantly improve on the existing method of measuring the trade-offs between different GHGs in their contribution to a climate change objective.

1. Introduction

Climate change is a long-term issue because of the long lifespan of some greenhouse gases (GHGs) and the delayed response of the climate system. To reach a particular climate change target in the future, there can be several different paths. To determine if one particular path is cost effective, it is essential to compare and balance the economic costs of reducing a unit of a greenhouse gas emission with the benefit of such reduction measured in terms of the reduction in damages that such emission might have caused to the economy and environment. The chain of causation is often described as: emission changes → concentration changes → radiative forcing → climate impacts → economic and environmental impacts → economic damages[i]. Given the difficulty of measuring the potential economic damages, estimates of the benefit of a climate policy is often described in terms of the reduction in radiative forcing or mean global temperature as a result of the reduction in GHGs emissions. In studies where there is only one GHG to consider, there is no difficulty in relating the benefit to the cost of emission reductions required by that policy. In a multi-gas situation, however, there is the issue of how to compare the benefits and costs across different GHGs. The Intergovernmental Panel on Climate Change (IPCC) recommends the use of a (fixed) set of Global Warming Potentials (*GWP*s) to compare the climate impacts across different greenhouse gases (IPCC 1990; IPCC 2001). There have been some criticisms of the use of these *GWP*s[ii]. Essentially, the main criticism from an economic viewpoint is the fact that these *GWP*s are exogenously determined and cannot necessarily relate to the particular context of the policy experiment being considered. For example, given that time horizon chosen for the measuring the *GWP*s being quite arbitrary, even though critical (Manne and Richels, 2001), the value of the *GWP*s may not reflect accurately, not only the instantaneous (or marginal) contribution of each GHG to total global warming impact, but also the average or cumulated effects. This is because each particular policy experiment has a different time frame to consider, and also is being assessed against a background of changing environmental, social, and economic context, hence, it cannot be regarded as being similar to the one which was used to estimate the *GWP*s in the first place. The difference may be substantial, and in this paper, we set up an illustrative policy experiment to measure and assess this difference.

We also propose an alternative approach to the measurement of the relative contributions of different GHGs to the total radiative forcing (which produces the climate change) more accurately and in accordance with the current policy context being considered. This approach looks at the *marginal* global warming potential (*MGWP*) contribution, rather than the total or cumulative contribution, although the latter can easily be derived from the former. The *MGWP* can be estimated accurately and endogenously within a climate model. This is then linked to the *marginal abatement cost* (*MAC*) of the gas, estimated within an economic model linked to the climate model. In this way the balancing of the benefits and costs associated with the reduction of a unit of emission of the GHG can be achieved more accurately. We illustrate the use of this new approach in an illustrative experiment, using a multi-sector multi-gas and multi-regional computable general equilibrium economic model (GTAP-E) coupled with a reduced form climate change model (ICLIPS Climate Model, or ICM). The results show that the new approach can significantly improve on the existing method of measuring the trade-offs between different GHGs in their contribution to a climate change objective.

The plan of the paper is as follows: Section 2 develops the theoretical framework for calculating the *MGWP*s. Section 3 shows how this theory can be applied to a policy experiment. Section 4 conducts an illustrative experiment and compares the results of the experiment using the new approach and the ‘traditional’ approach where a fixed set of *GWP*s are used to estimate the relative contribution of each GHG. Section 5 concludes the paper.

2. Marginal Global Warming Potential as the relative price of trade-off between greenhouse gases

The Intergovernmental Panel on Climate Change (IPCC, 1990) defines the *GWP*s of different GHGs as follows:

$$GWP_i = \frac{\int_0^T x_i(t).[\delta_i(t)]dt}{\int_0^T x_j(t).[\delta_j(t)]dt} \tag{1}$$

Here T is the time horizon over which the *GWP* is estimated, x_i is the (marginal) radiative forcing caused by a unit increase in GHG i in the atmosphere (i.e., Wm^{-2} kg^{-1}), δ_t is the rate of decay of the GHG i, and j denotes the 'reference' gas. The Global Warming Potential (*GWP*) index thus measures the ratio of average, or total, i.e. time-integrated, radiative forcing level – both direct and indirect – from one unit mass of a greenhouse gas relative to that of a reference gas (CO_2) over a given time horizon. The relative effect of the gas is measured cumulatively over a long period of time to overcome the problem of different life spans (different decaying rates) of different GHGs. From a climate perspective, this may be desirable. But from an economic viewpoint, this approach would not allow for an accurate reflection of the relative (marginal) benefits of a climate change policy *at a particular point in time* with its relative (marginal) economic costs. This reflection is essential if optimal decentralised decision making process (for each individual GHG emitter) is to be achieved. To achieve this objective, we propose that global warming potential be measured, not only on average or cumulatively over an extended period of time, but also at the margin and at a particular point in time, to reflect the current policy context and environment being considered. We propose the use of a *marginal global warming potential* (*MGWP*) index which will supplement the use of the (total) *GWP*s, both of these can be estimated within an integrated assessment model rather than being given exogenously. The use of these indices is to facilitate the assessment of the (minimum) economic costs of a particular climate change policy.

Let $x_t = \{x_{1t},\ldots,x_{nt}\}$ be the (vector of)[iii] levels of radiative forcing contributed by various green house gases (GHGs) *i*'s to the total level of radiative forcing at time period t[iv]. The radiative forcing level for each GHG is in turn a function of the concentration levels $c_t = \{c_{1t},\ldots,c_{nt}\}$. Concentration levels are related to the decay rate (lifetime) of each GHG and also to the emission rate $e_t = \{e_{1t},\ldots,e_{nt}\}$. The overall relationship between radiative forcing level and emission rates can then be summarised by the following equations[v]:

$$\dot{x}_{it} = f^{i}(\dot{c}_t), \quad i = 1,\ldots,n. \tag{2}$$

$$\dot{c}_{it} = g^{i}(c_{i,t-1}, e_{it}), \quad i = 1,\ldots,n. \tag{3}$$

where a dot (.) on top of a variable denotes the (time) rate of change. Equation (2) says that changes in radiative forcing level is determined by changes in GHGs concentration levels. Equation (3) then says that changes in concentration level is determined partly by 'history' (i.e. accumulated emissions and decaying in the past) but also – and more importantly – by the *current* emission rate e_t[vi]. To summarise the above relationships further, we can re-write (2) and (3) as:

$$\dot{x}_{it} = h^{i}(c_{t-1}, e_t), \quad i = 1,\ldots,n. \tag{4}$$

Equation (4) can now be referred to as a 'reduced form' representation of a climate sub-model. In this sub-model, the *marginal* impact of a change in emission rate e_t on the radiative forcing level - *given* (or *conditional* on) any pre-existing concentration level c_{t-1} – can be estimated:

$$MGWP_{it} = \left.\frac{\partial \dot{x}_{it}}{\partial e_{it}}\right|_{c_{t-1}} \tag{5}$$

The term ($MGWP_{it}$) is used to denote the (absolute) *marginal* global warming potential of greenhouse gas i over period t.

Next, assume that we can denote the economic costs (and benefits)[vii] associated with GHG emissions (reductions) as follows:

$$C_t = C(x_t, e_t) \tag{6}$$

Here, ($\partial C/\partial x_{it}$)>0 represents the marginal damage cost (MDC_{it}) of climate change caused by a change in the radiative forcing level contributed by green house gas i in period t, and ($-\partial C/\partial e_{it}$) >0[viii] represents the marginal abatement cost (MAC_{it}) of green house gas i in period t. The *MDC* is also used to denote the 'benefit' of (avoided) climate change. The *MAC* is used to represent current marginal economic costs of emissions abatement to achieve such (avoided) climate change.

Assume that the objective of a particular climate change policy is to minimise an inter-temporal economic cost function:

$$J = \int_0^T e^{-\rho t} C(x_t, e_t) dt \tag{7}$$

subject to the constraint (4), where ρ is the discount rate and T is the target year of a particular climate policy. Forming the present-value Hamiltonian for this optimisation problem as:

$$H = e^{-\rho t} C(x_t, e_t) - \sum_i \lambda_i \dot{x}_{it} \tag{8}$$

where $\lambda = \{\lambda_1, \ldots, \lambda_n\}$ is the (vector of) co-state variables[ix], we can then state the first-order conditions for optimisation as:

$$\frac{\partial H}{\partial x_{it}} - \frac{d}{dt}\left(\frac{\partial H}{\partial \dot{x}_{it}}\right) = 0 \tag{9a}$$

$$\frac{\partial H}{\partial e_{it}} - \frac{d}{dt}\left(\frac{\partial H}{\partial \dot{e}_{it}}\right) = 0 \tag{9b}$$

Equations (9a) and (9b) hold for each of the greenhouse gas[x] i in period t. From (9a)-(9b), we derive:

$$e^{-\rho t}\frac{\partial C}{\partial x_{it}} - \frac{d\lambda_i}{dt} = 0 \tag{10a}$$

$$e^{-\rho t}\frac{\partial C}{\partial e_{it}} - \lambda_i \left.\frac{\partial \dot{x}_{it}}{\partial e_{it}}\right|_{c_{t-1}} = 0 \tag{10b}$$

Or simply:

$$e^{-\rho t}(MDC_{it}) = \dot{\lambda}_i \tag{11a}$$

$$e^{-\rho t}(MAC_{it}) = -\lambda_i(MGWP_{it}) \tag{11b}$$

If we assume that a damage caused by a climate change coming from a change in the radiative forcing level is the same (irrespective of where the change in radiative forcing level is coming from), then we can write: $MDC_{it} = MDC_{jt} = MDC_t$ for all i,j's[xi]. This implies, from equation (11a): $\lambda_i = \lambda_j = \lambda$ for all i,j's. Equation (11b) can then be re-written in a relative form:

$$(MAC_{it})/(MAC_{jt}) = (MGWP_{it})/(MGWP_{jt}) \quad \text{for } \forall i, j. \tag{12}$$

Equation (12) provides us with a formula for linking the benefits of emission reductions, the ratio $(MGWP_{it})/(MGWP_{jt})$, with the associated marginal abatement costs, the ratio (MAC_{it}/MAC_{jt}), the former being estimated from a climate sub-model, the latter from an economic sub-model. We note that although the ratio ($MGWP_{it}$)/($MGWP_{jt}$) measures only the potential climate change over a 'short' time period (interval t only), this measurement is 'conditional' on – i.e. taking into account – the previous history of all emissions and decays as reflected in the concentration level of the GHGs at the beginning of the time period, i.e. c_{t-1} (see equation (5)). Hence, different life spans (and different decay rates) of all different GHGs *are* being taken into account, even though indirectly, via the concentration levels. The ratio ($MGWP_{it}$)/($MGWP_{jt}$) is also time- and *path*-dependent, meaning that it is 'conditional' on a particular policy scenario and context being considered. This should be the strength, rather than the weakness, of the new approach. Compare this to the conventional approach where a fixed GWP is used: the time horizon T chosen for its measurement (see equation (1)) would have been arbitrary, but more importantly, the particular policy environmental and objective being considered would have been different from the existing one. Equation (12), on the other hand, takes these current situations into account.

In the next section, we illustrate how the new approach can be applied to a policy experiment, to measure the economic costs of a particular climate change policy. We show that the use of the new index will result in a more accurate estimate of the relative economic costs of different GHGs in their contributions to total climate change. The approach can also be used to measure the *cumulative* effects of the different GHGs over a particular time horizon, and this can then be compared against the (fixed) *GWP*s as recommended by the IPCC. We show that depending on a particular set of assumptions about the elasticiticies of GHGs abatement (i.e. the ease with which each GHG emissions can be 'substituted' for more economic resources devoted to its abatement) the difference between the use of the new approach and the conventional (i.e. fixed relative *GWP*s) approach can be substantial.

3. Application

For the purpose of illustrating the usefulness of the new approach, we use the theory developed in the last section and apply this to a particular policy experiment. We use an integrated approach to the assessment of the policy. The approach consists of the use of an economic sub-model, called GTAP-E, which is a multi-gas, multi-sector, and multi-regional economic-trade-environment model[xii], soft-linked with a climate sub-model, called ICM (or ICLIPS[xiii] Climate Model). We first run the GTAP-E sub-model to produce a set of emission paths for the various GHGs and use these as inputs into the ICM sub-model. The ICM sub-model then estimate the *MGWP*s for the various GHGs. The ratios of the *MGWPs* are then used to define the 'shadow prices' of the GHGs, which are used as inputs into the GTAP-E sub-model to constrain the ratios of the *MAC*s as required by equation (12). An iterative process is used until convergence of the two ratios is achieved.

3.1 THE EXPERIMENT

First, we define a 'Business-as-Usual' (BaU) scenario which reflects the current set of assumptions about future levels of resource utilisations and economic activities for all regions. The BaU scenario produces a set of emissions paths for the GHGs which we can use as the reference point. For the purpose of an illustrative experiment, we then define a scenario which we refer to as 'Policy scenario'. In this scenario, we seek to reduce the total radiative forcing level of all GHGs by the year 2100[xiv] to a level of around 4.5 W/m^2 (see Figure 1). This will require substantial reductions in the emissions of all GHGs as compared to the BaU level. To determine the relative paths of different GHGs, we first assume a *fixed* set of relative 'shadow'[xv] prices for all the GHGs and set these relative prices at the level equal to the *GWP*s as defined by the IPCC[xvi]. We refer to this as the 'fixed relative prices' scenario. Next, using the approach developed in this paper, we allow these relative prices to vary, and using equation (12) to constrain these relative price ratios (i.e. the ratios of the *MAC*s) to be equal to the ratios of the *MGWP*s. We refer to this as the 'flexible relative prices' scenario. Clearly, the rate of trade-off between different GHGs will be different in these two situations, and hence their emissions paths will also be different (see Figure 2). The overall result in terms of the policy target, however, is to remain the same (see Figure 1).

3.2 THE RESULTS

Figure 3 shows the *MAC*s estimated under the two sets of assumptions, i.e. 'fixed relative prices' and 'flexible relative prices' for the GHGs as defined in the previous section. Under the 'fixed relative prices' scenario, all GHGs are converted to a 'carbon equivalent' (Ceq) unit and priced at the same level, hence their *MAC*s are also the same as can be seen from Figure 3[xvii]. Under the 'flexible relative prices' scenario, however, each GHG will be priced at a different level - according to their 'flexible' (i.e. time-varying) *MGWPs* as seen from equation (12). This will result in the prices of all GHGs being different as can be seen from Figure 3. The prices of N_2O and CO_2, for example, are now higher than the case when 'fixed relative prices' are assumed, and the reverse is true for CH_4[xviii].

Figures 4A and 4B and Table 1 show the time paths of the *MGWP*s for CH_4 and N_2O (relative to CO_2)[xix] when 'fixed relative prices' are used. Quite clearly, this will be different if 'flexible relatives prices' are used (Figures 5A and 5B and Table 2). We also estimate the *cumulative* or total *GWP*s and these are shown at the bottom of Tables 1 and 2. From these, it can be seen that the *MGWP*s as well as the cumulative *GWP*s are sensitive to the particular scenario being considered and the assumptions ('fixed relative prices' or 'flexible relative prices' for the GHGs) underlying the estimation of these global warming potentials.

From Table 1, it can be seen that the *MGWP*s, and therefore the cumulative *GWP*, for CH_4 are consistently below the IPCC figure of 21 for CH_4[xx]. The reverse is mostly true for N_2O, even though if we consider a longer time horizon (2000-2200), there are periods when the *MGWP*s for N_2O fall significantly below the IPCC level of 310, hence the cumulative *GWP* for N_2O also falls below this figure. What is more important, however, is the fact that if the *MGWP*s represent the marginal benefit of GHG emission reduction, and the *MAC* is its marginal cost, then deviation of *MGWP*s from *MAC*s implies a divergence of benefits from costs, and this implies the resulting time paths of GHG emissions are not optimal. To achieve this optimality, we need to constraint the *MAC*s to the *MGWP*s, and this is done under the 'flexible relative prices' scenario. The results are shown in Figures 5A, B and Table 2.

To calculate the 'economic efficiency gains' from using the 'flexible relative prices' approach as compared to the 'fixed relative prices' approach, we first estimate the changes in relative prices between these two situations (ΔP) and then measure the resulting changes in quantities of emissions (ΔQ) caused by that price difference. The product: $[-0.5*\Delta Q*\Delta P]$ then gives an approximate measure of the value of 'efficiency gains' when using the (optimal) 'flexible relative prices' approach as compared to the non-optimal 'fixed relative prices' approach[xxi]. The efficiency gains are shown in Table 3. From this table it can be seen that for the initial years, the size of these efficiency gains can be small, but this gets larger as time goes by. By 2100, the gains can reach a level of around 0.26 percent of the world GDP, which is not an insignificant figure.

3.3 SENSITIVITY TESTS

We conduct some sensitivity analysis to see how the values of the *MGWP*s may vary as we change some of the assumed parameters in the economic model[xxii]. Under the heading of 'sensitivity' scenario, we lower the assumed elasticity of substitution in CH_4 abatement activity (i.e. σ_{CH4}) in the important sectors of 'Rice' and 'Crops' in all regions (see Table A3) by a factor of one-tenth[xxiii] while increasing the elasticity for N_2O (i.e. σ_{N2O}) by a factor of 10. The results are shown in Figure 6A and 6B. It can be seen from these Figures that the path of the *MGWP*s, and hence the values of the cumulative *GWP*s, are sensitive to the assumed values of the elasticity of substitution. In general, a higher elasticity of substitution in abatement activities will encourage substitution away from a particular GHG emission towards other GHGs emissions, if the relative emission price of that particular GHG emission increases. Thus, a higher (lower) substitution elasticity will tend to result in a lower (higher) emission rate for that particular GHG, and hence also a lower (higher) *MGWP*. This is clearly seen in Figures 6A and 6B.

4. Conclusion

In this paper, we have shown how an integrated assessment (IA) model of economic-climate change can be used to estimate the marginal global warming potential (*MGWP*) of a greenhouse gas (GHG) emission measured in terms of its potential impact on the total radiative forcing level. The *MGWP* is a useful concept, not only because it reflects more accurately the potential marginal contribution of a unit of GHG emission on the overall level of climate change (radiative forcing) – as compared to the cumulative or average *GWP* index recommended by the IPCC, it can also be meaningfully and endogenously linked to the marginal emission reduction or abatement cost which is also estimated within these IA models. This provides a strong theoretical support for the use of an IA model as compared to a non-integrated approach. Empirically, it also helps to estimate the relative prices of trade-offs between the GHGs more accurately, which will truly reflect their potential relative contributions to climate change. Failure to do this may result in an underestimation of the impacts for some GHGs, while it is an overestimation for others. This will cause not only inequities among different GHGs emitters, but also inefficiencies, and result in a higher overall economic cost to achieve the same climate change target. Our illustrative experiment shows that the magnitude of this inefficiency is not insignificant, but future research can throw more light on this empirical issue, by looking at different assumptions regarding the nature of the emission trading market, the climate change target, the values of the elasticities assumed, as well as the different closures reflecting different assumptions about the economic and trade conditions in the world economy.

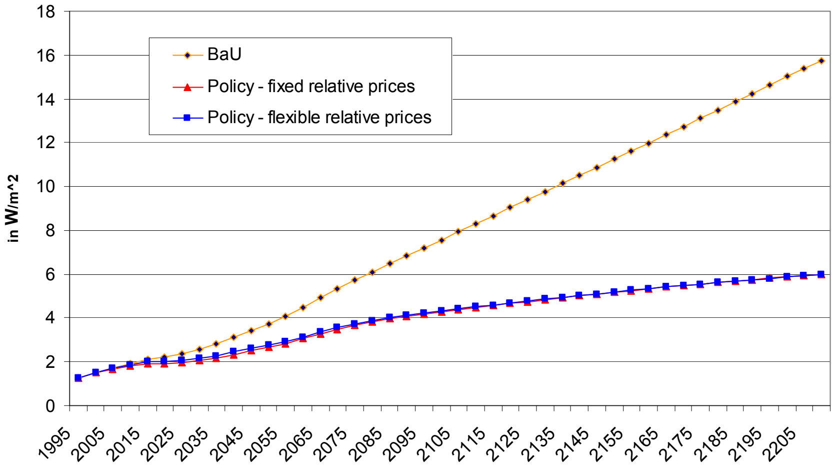

Figure 1: Radiative forcing levels for different alternative scenarios

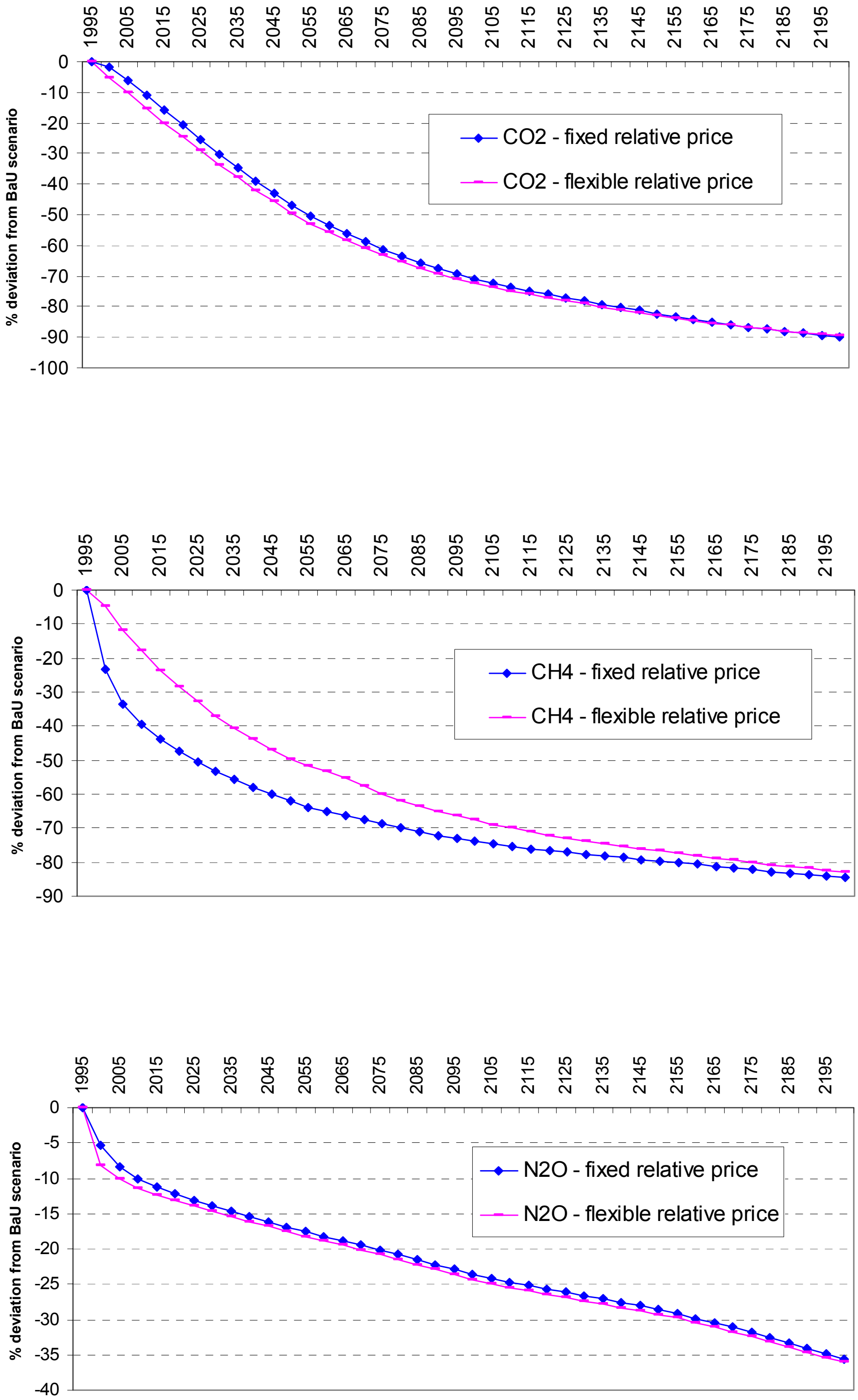

Figure 2: Percent reduction of emissions from 'BaU' scenario to achieve 'Policy' target.

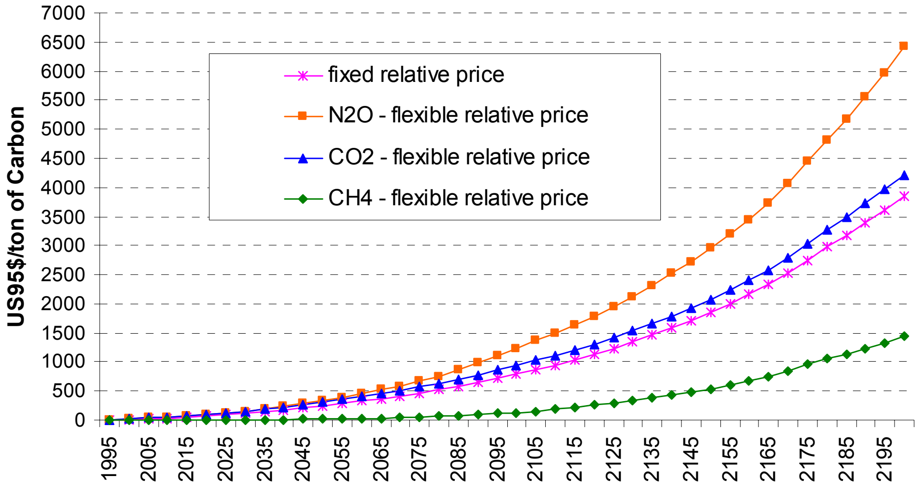

Figure 3: Marginal Abatement Costs (*MAC*s) under different approaches.

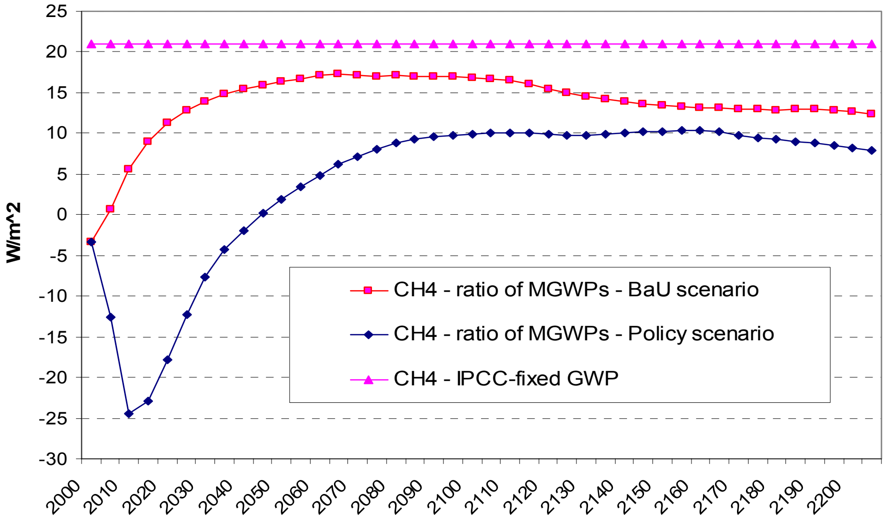

Figure 4A: Ratios of the *MGWP* for CH_4 (relative to CO_2) under different experimental scenarios - assuming 'fixed relative prices' for the GHGs.

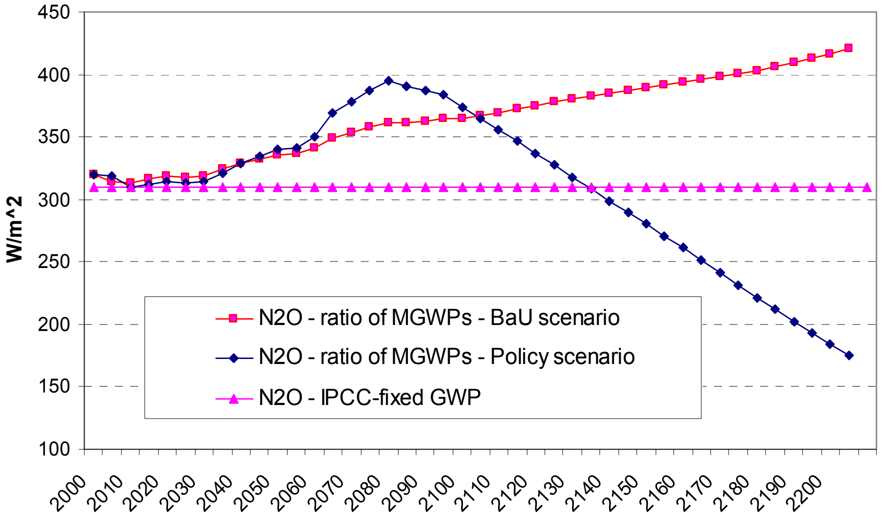

Figure 4B: Ratios of the *MGWP* for N_2O (relative to CO_2) under different experimental scenarios – using 'fixed relative prices' for the GHGs

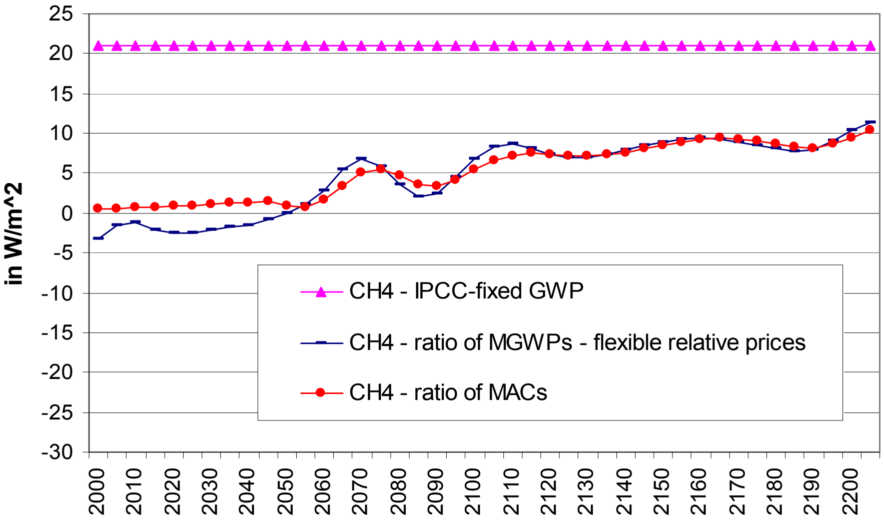

Figure 5A: Ratios of the *MGWP* for CH_4 (relative to CO_2) under different experimental scenarios - assuming ‘flexible relative prices’ for the GHGs

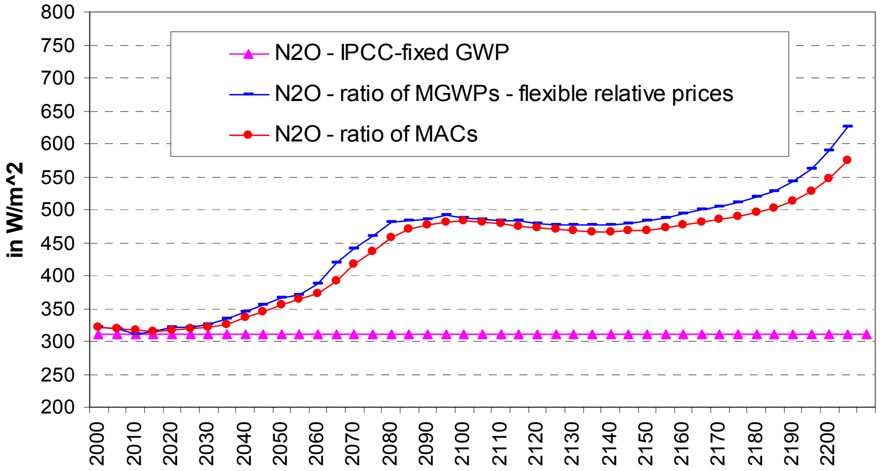

Figure 5B: Ratios of the *MGWP* for N_2O (relative to CO_2) under different experimental scenarios – using ‘flexible relative prices’ for the GHGs

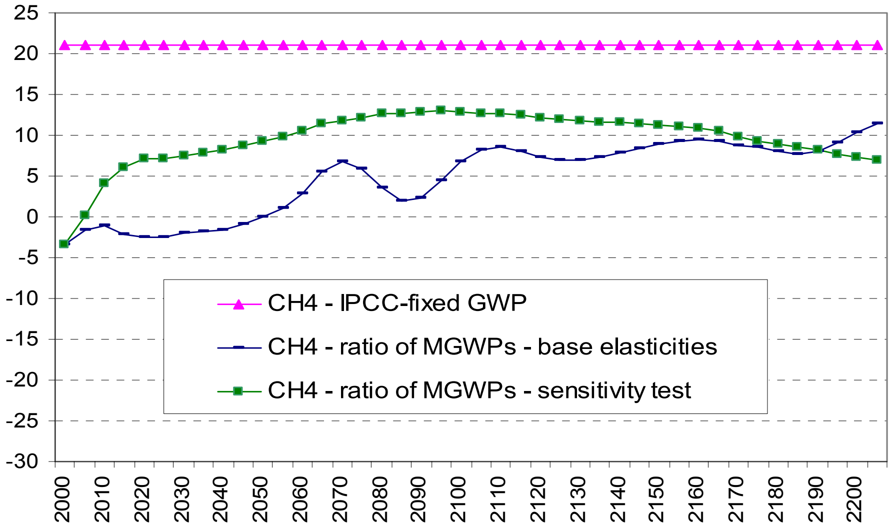

Figure 6A: Ratios of the *MGWP* for CH_4 (relative to CO_2) under different assumptions about abatement elasticities (σ_{CH4}).

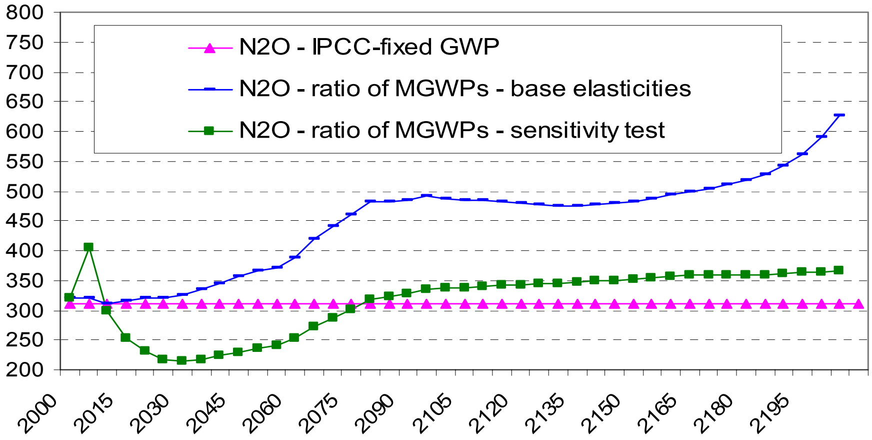

Figure 6B: Ratios of the *MGWP* for N_2O (relative to CO_2) under different assumptions about abatement elasticities (σ_{N2O}).

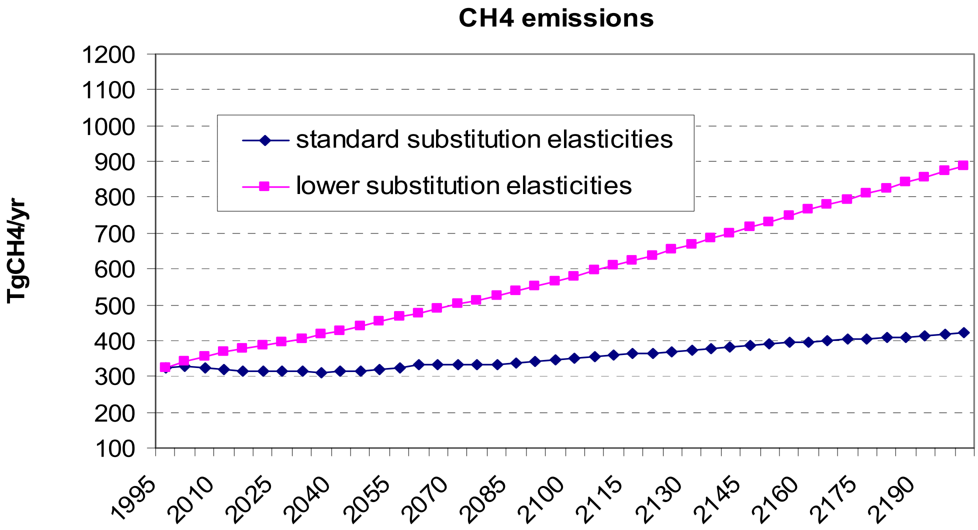

Figure 7A: Emissions of CH_4 under alternative assumptions about abatement substitution elasticities (σ_{CH4}).

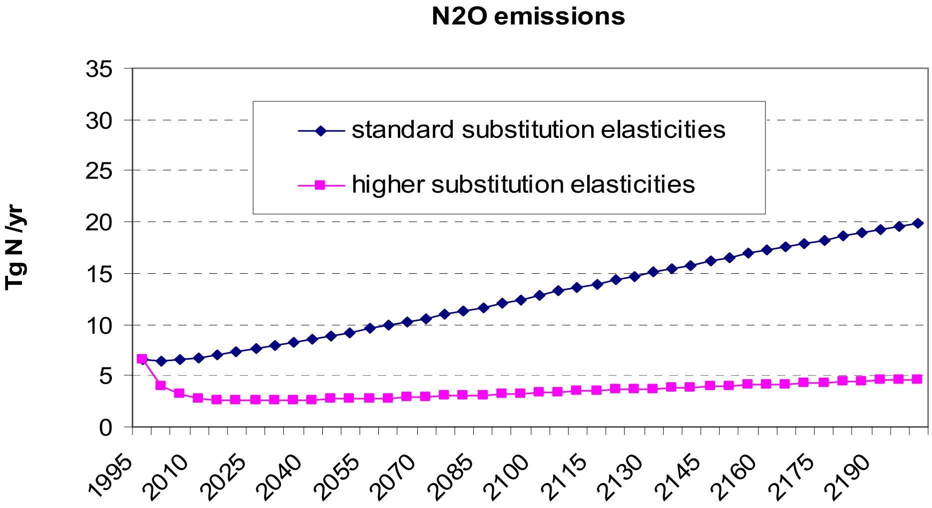

Figure 7B: Emissions of N_2O under alternative assumptions about abatement substitution elasticities (σ_{N2O}).

Table 1: Marginal Global Warming Potentials (*MGWPs*) – When Relative Prices of the GHGs are FIXED at the IPCC's *GWPs*.

Time period beginning	Absolute (W/m^2 ton)			Relative (to the value for CO_2)		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
2000	6.59	-22.0	2111.3	1	-3.3	320.3
2005	6.49	-81.9	2072.5	1	-12.6	319.3
2010	6.29	-153.5	1952.7	1	-24.4	310.2
2015	5.96	-136.2	1858.8	1	-22.8	311.8
2020	5.67	-100.8	1782.1	1	-17.8	314.3
2025	5.48	-67.4	1715.5	1	-12.3	312.9
2030	5.27	-40.3	1655.9	1	-7.7	314.2
2035	4.99	-21.6	1602.7	1	-4.3	321.0
2040	4.72	-9.2	1551.6	1	-1.9	328.4
2045	4.50	0.7	1505.0	1	0.2	334.8
2050	4.30	8.4	1461.9	1	2.0	340.4
2055	4.17	14.4	1422.2	1	3.5	341.0
2060	3.96	19.0	1385.4	1	4.8	350.3
2065	3.66	22.5	1352.4	1	6.1	369.7
2070	3.48	25.0	1317.0	1	7.2	378.2
2075	3.32	26.8	1284.1	1	8.1	386.7
2080	3.17	28.1	1253.3	1	8.9	395.4
2085	3.13	28.9	1224.3	1	9.2	390.8
2090	3.09	29.5	1197.1	1	9.5	386.9
2095	3.05	29.9	1171.4	1	9.8	383.4
2100	3.07	30.3	1147.0	1	9.9	373.6
2105	3.08	30.8	1123.6	1	10.0	364.4
2110	3.09	31.3	1101.0	1	10.1	355.8
2115	3.11	31.3	1079.5	1	10.1	347.0
2120	3.13	30.8	1055.8	1	9.8	337.0
2125	3.16	30.9	1032.9	1	9.8	327.2
2130	3.18	31.3	1010.8	1	9.8	317.6
2135	3.21	31.8	989.3	1	9.9	308.1
2140	3.24	32.5	968.5	1	10.0	298.7
2145	3.28	33.3	948.3	1	10.1	289.4
2150	3.32	34.0	928.8	1	10.2	280.1
2155	3.36	34.7	909.9	1	10.3	270.8
2160	3.41	35.3	891.8	1	10.4	261.7
2165	3.47	35.2	874.4	1	10.1	251.9
2170	3.55	34.5	855.3	1	9.7	241.2
2175	3.63	34.2	837.3	1	9.4	230.9
2180	3.71	34.2	820.4	1	9.2	221.0
2185	3.80	34.3	804.8	1	9.0	211.7
2190	3.90	34.3	789.8	1	8.8	202.3
2195	4.02	34.2	775.5	1	8.5	193.1
2200	4.14	34.0	762.2	1	8.2	184.1
2000-2100	4.52	-16.1	1467.1	1	-3.6	324.8
2000-2200	4.07	12.6	1090.0	1	3.1	268.1
IPCC					21	310

Table 2: Marginal Global Warming Potentials (*MGWPs*) – When relative prices (*MACs*) are jointly determined with (*MGWPs*).

Time period beginning	Absolute (W/m^2 ton)			Relative (to the value for CO_2)		
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O
2000	6.59	-21.96	2111.3	1	-3.3	320.3
2005	6.57	-9.98	2099.8	1	-1.5	319.8
2010	6.23	-7.18	1930.3	1	-1.2	309.8
2015	5.84	-12.40	1844.5	1	-2.1	315.9
2020	5.52	-14.15	1771.6	1	-2.6	321.0
2025	5.31	-13.18	1706.5	1	-2.5	321.2
2030	5.08	-10.40	1647.6	1	-2.0	324.5
2035	4.77	-8.40	1594.8	1	-1.8	334.5
2040	4.47	-6.80	1543.8	1	-1.5	345.5
2045	4.20	-3.66	1496.7	1	-0.9	356.0
2050	3.97	0.20	1453.1	1	0.1	366.2
2055	3.81	4.26	1412.6	1	1.1	370.8
2060	3.55	10.24	1374.9	1	2.9	387.4
2065	3.19	17.47	1340.6	1	5.5	420.1
2070	2.96	20.25	1303.7	1	6.8	439.9
2075	2.76	16.15	1269.3	1	5.9	460.4
2080	2.57	9.16	1237.2	1	3.6	481.5
2085	2.50	4.93	1206.9	1	2.0	482.1
2090	2.43	5.81	1178.1	1	2.4	485.4
2095	2.34	10.36	1150.5	1	4.4	491.6
2100	2.30	15.48	1124.1	1	6.7	487.8
2105	2.26	18.61	1098.8	1	8.2	485.5
2110	2.22	19.13	1074.5	1	8.6	483.9
2115	2.18	17.64	1051.3	1	8.1	482.3
2120	2.14	15.61	1026.1	1	7.3	479.0
2125	2.10	14.48	1002.0	1	6.9	476.8
2130	2.06	14.28	978.8	1	6.9	475.7
2135	2.01	14.72	956.3	1	7.3	475.9
2140	1.96	15.42	934.7	1	7.9	477.2
2145	1.91	16.03	913.9	1	8.4	479.6
2150	1.85	16.40	893.8	1	8.9	483.1
2155	1.79	16.50	874.3	1	9.2	487.7
2160	1.73	16.40	855.6	1	9.5	493.7
2165	1.67	15.59	837.1	1	9.3	500.0
2170	1.62	14.31	816.6	1	8.8	504.2
2175	1.56	13.29	797.0	1	8.5	510.3
2180	1.50	12.19	778.0	1	8.1	518.1
2185	1.44	11.12	759.5	1	7.7	527.8
2190	1.37	10.99	741.7	1	8.0	541.6
2195	1.29	11.75	725.0	1	9.1	562.3
2200	1.20	12.44	709.0	1	10.4	590.3
2000-2100	4.18	0.56	1454.5	1	0.13	348.1
2000-2200	3.15	8.27	1059.5	1	2.62	335.9
IPCC					21	310

Table 3: Efficiency gains from using the ‘flexible relative prices’ approach

Year	Changes in Emission levels(*) (ΔQ)			Changes in Emission Price(*) (ΔP)			Efficiency Gains from the change (–0.5*ΔQ. ΔP)			
	CO2	CH4	N2O	CO2	CH4	N2O	CO2	CH4	N2O	Total
	Gt C	Tg CH4	Tg N	US$95/ ton C	US$95/ Tg CH4	US$95/ Tg N	US$95 billions	US$95 billions	US$95 billions	as % of world GDP
2000	-0.238	64.2	-0.200	14.3	-21.0	15.5	9.7	0.7	9.7	0.03
2005	-0.317	80.6	-0.128	17.7	-33.3	19.2	16.7	1.7	16.7	0.05
2010	-0.339	83.9	-0.100	21.4	-47.5	23.2	22.0	2.8	22.0	0.07
2015	-0.346	84.0	-0.086	25.7	-64.0	27.9	27.2	4.0	27.2	0.08
2020	-0.348	83.1	-0.077	30.8	-84.2	33.9	32.7	5.3	32.7	0.09
2025	-0.348	82.1	-0.073	36.6	-107.4	40.8	39.3	6.9	39.3	0.11
2030	-0.346	80.6	-0.070	43.1	-133.5	49.2	46.4	8.6	46.4	0.12
2035	-0.345	79.4	-0.068	50.4	-162.8	59.6	54.6	10.6	54.6	0.13
2040	-0.346	78.7	-0.068	58.5	-195.3	72.7	63.9	12.8	63.9	0.15
2045	-0.348	78.3	-0.069	69.1	-232.3	90.5	74.5	15.3	74.5	0.17
2050	-0.350	78.2	-0.071	80.3	-267.7	110.1	88.7	18.2	88.7	0.19
2055	-0.363	80.8	-0.076	90.2	-304.0	130.1	107.0	21.6	107.0	0.21
2060	-0.379	84.1	-0.082	96.8	-339.5	150.0	125.3	25.6	125.3	0.24
2065	-0.381	84.0	-0.086	101.2	-374.0	171.9	135.3	28.5	135.3	0.25
2070	-0.367	79.7	-0.088	106.1	-409.9	199.6	136.0	29.8	136.0	0.24
2075	-0.345	74.0	-0.091	113.8	-450.6	236.8	134.4	30.3	134.4	0.23
2080	-0.330	69.6	-0.095	124.6	-497.8	283.9	137.5	31.4	137.5	0.22
2085	-0.323	67.8	-0.102	136.5	-550.0	336.7	147.7	33.7	147.7	0.23
2090	-0.325	67.9	-0.110	146.7	-603.9	390.9	162.6	37.3	162.6	0.24
2095	-0.328	68.4	-0.119	153.6	-657.8	443.7	176.3	41.3	176.3	0.26
2100	-0.327	67.9	-0.126	157.7	-710.1	493.2	184.0	44.7	184.0	0.26

(*) under the Policy scenario, when the assumption changes from using ‘fixed relative prices’of the GHGs as set by the IPCC *GWP*s, to using ‘flexible relative prices’ as determined by the ratios of the *MGWP*s (see equation (12) in the text).

Appendix A

The GTAP-E Model

Table A1: Definitions of Countries and Regions in the GTAP-E Model

	Regions
USA	United States of America
EU	European Union
RoA1	Rest of Annex 1 countries
CHIND	China and India
RoW	Rest of the World

Table A2: Definitions of Sectors in the GTAP-E Model

	Sectors
1 Rice	Paddy rice
2 Crops	Primary Agriculture and Fishing
3 Livestock	Livestock products
4 Forestry	Forestry
5 Coal	Coal Mining
6 Oil	Crude Oil
7 Gas	Natural Gas and Gas distribution
8 Oil_Pcts	Oil and Coal products
9 Electricity	Electricity
10 CRP	Chemical Rubber and Plastics
11 Oth_ind_ser	Other industries and services

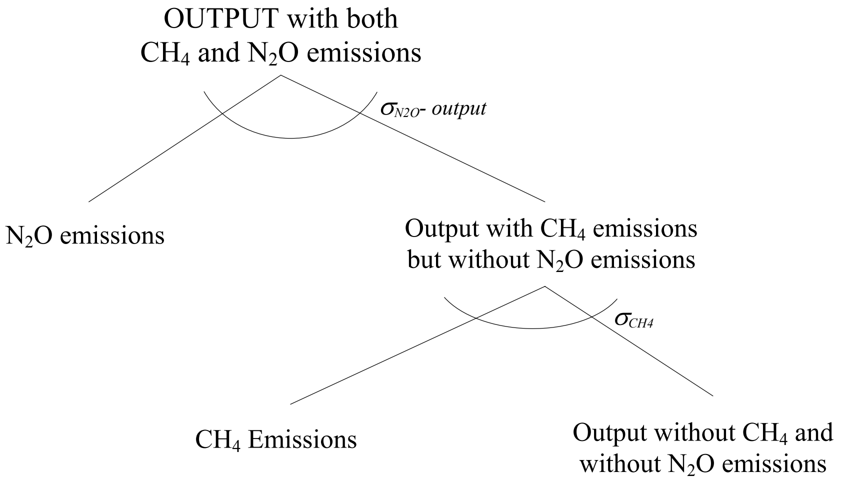

Figure A1: Production structure in a modified GTAP–E model to allow for both CH_4 and N_2O emissions at the output level

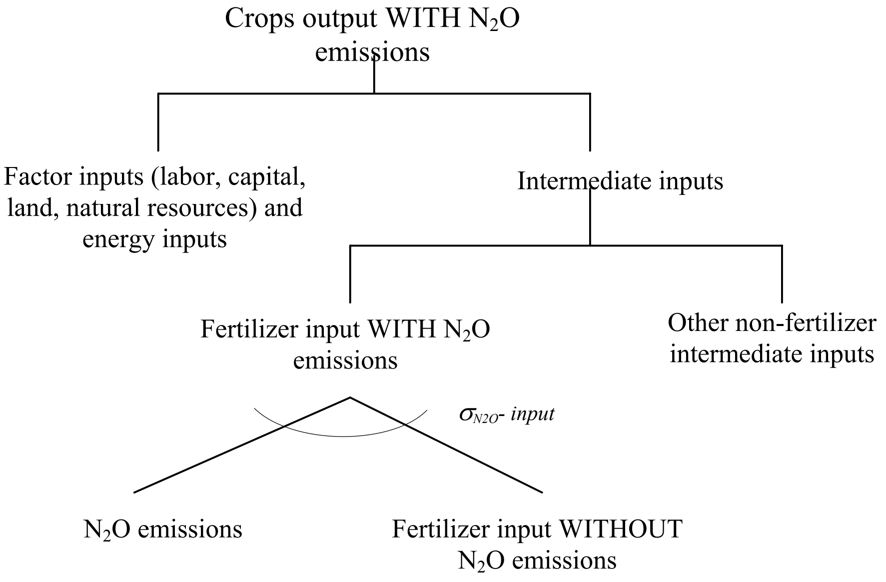

Figure A2: Production structure to allow for N_2O emissions associated with the use of a production input

Table A3: CH_4 abatement elasticities

σ_{CH4}	USA	EU	RoA1	CHIND	RoW
1 Rice	0.5	0.8	0.4	0.1	0.06
2 Crops	0	0	0	0	0
3 Livestock	0.5	0.8	0.4	0.1	0.06
4 Forestry	0	0	0	0	0
5 Coal	0.03	0.03	0.03	0.03	0.03
6 Oil	0	0	0	0	0
7 Gas	0.12	0.12	0.12	0.12	0.12
8 Oil_Pcts	0	0	0	0	0
9 Electricity	0	0	0	0	0
10 CRP	0	0	0	0	0
11 Oth_ind_ser	0.11	0.11	0.11	0.11	0.11

Table A4: N_2O abatement elasticities

σ_{N2O}	USA	EU	RoA1	CHIND	RoW
1 Rice	.04	.04	.04	.02	.02
2 Crops(*)	.04	.04	.04	.02	.02
3 Livestock	.04	.04	.04	.02	.02
4 Forestry	0	0	0	0	0
5 Coal	0	0	0	0	0
6 Oil	0	0	0	0	0
7 Gas	0	0	0	0	0
8 Oil_Pcts	0	0	0	0	0
9 Electricity	0	0	0	0	0
10 CRP	.04	.04	.04	.02	.02
11 Oth_ind_ser	.04	.04	.04	.02	.02

(*) This applies to 'CRP' (Chemical Rubber and Plastic, as a proxy for 'fertilizer') input into 'Crops' as well as to Crops output (see Figure 2).

Appendix B

The ICLIPS Climate Model (ICM)

The ICLIPS Climate Model (ICM) was developed at the Potsdam Institute for Climate Impact Research (PIK) in collaboration with the Max-Planck Institute for Meteorology (MPI), Hamburg (Bruckner et al., 2003; Hooss et al, 2001) as part of the ICLIPS (Integrated Assessment of Climate Protection Strategies) project (see Toth *et al.*, 2003, and references therein). ICM is a computationally efficient reduced-form multi-forcing climate model. It consists of several modules designed to simulate (a) the atmospheric retention and metabolism of carbon dioxide and other important greenhouse gases (CH_4, N_2O, halocarbons, SF_6, and the aerosol precursor SO_2), (b) the time-dependent contributions of these gases to radiative forcing, and (c) the resulting transient patterns of the anthropogenic climate change signal in terms of selected impact-relevant variables, including: air temperature, cloud cover, precipitation, and sea-level rise. The modules used to form ICM are adaptations of peer-reviewed models that have previously been used individually in a variety of other integrated assessment studies (Harvey et al., 1997; Meyer et al., 1999; Joos et al., 2001; Hooss et al., 2001).

ICM is driven by time-series of the anthropogenic emissions of CO_2, CH_4, N_2O, halocarbons, SF_6 and SO_2. The emission paths for CO_2, CH_4, and N_2O are generated from the GTAP-E model, while the emission paths for halocarbons, SF_6 and SO_2 are assumed to be given exogenously of the GTAP-E model. Total anthropogenic emissions are then determined by:

$$TOTEM_{r,t} = E_{r,t} + NonE_{r,t} - S_{r,t} \tag{B1}$$

with $TOTEM_{r,t}$ indicating the total anthropogenic *net* emissions per region r and time period t. $E_{r,t}$ and $NonE_{r,t}$ refer, respectively, to energy-related and non-energy-related regional emissions. The enhanced sinks ($S_{r,t}$) reduce total emissions (this means that the emissions reductions targets are also reduced).

The atmospheric concentration of greenhouse gases may change due to direct emissions, exchange with reservoirs (e.g., ocean, biosphere, pedosphere) and/or chemical reactions (destruction or formation). The biogeochemical sub-modules of ICM take into account these different processes in a gas-specific manner. The core of ICM contains a modified version of NICCS (Nonlinear Impulse Response Representation of the Coupled Carbon Cycle – Climate System) model (Hooss, 2001; Hooss et al., 2001), developed at MPI, Hamburg. The carbon cycle module of NICCS consists of (a) a differential impulse-response representation of the comprehensive three-dimensional Hamburg Model of the Ocean Carbon Cycle (HAMOCC) combined with an explicit treatment of nonlinear sea water carbon chemistry, and (b) a nonlinear differential impulse-response model of terrestrial biosphere CO_2 fertilization effects. Applying an inverse calibration technique, the quantitatively unknown CO_2-fertilization factor has been adjusted so as to give a balanced 1980s mean carbon budget, as advised by the IPCC model inter-comparison exercise.

Various components of the MAGICC model (Wigley, 1988; Wigley and Raper, 1992; Wigley, 1994; Osborn and Wigley, 1994; Wigley *et al.*, 1996; Harvey *et al.*, 1997) were adopted in order to simulate the atmospheric chemistry of the major non-CO_2 greenhouse gases. Changes in the concentration of non-CO_2 greenhouse gases (CH_4, N_2O, halocarbons, and SF_6) are calculated by a simple one-box model approach, according to:

$$\frac{dC(t)}{dt} = \frac{1}{b}\sum_r TOTEM_r - \frac{1}{\tau}(C - C_{pre-industrasl}) \qquad \text{(B2)}$$

where b is a concentration-to-mass conversion factor and τ is the lifetime of the greenhouse gas under consideration. For N_2O, halocarbons, and SF_6, the lifetime is assumed to be constant (IPCC, 1996; Harvey *et al.*, 1997). CH_4 is removed from the atmosphere by soil uptake and chemical reactions with OH. The lifetime calculation for CH_4 takes into account both processes. As the OH concentration itself is influenced by CH_4, the lifetime attributed to chemical processes is modeled dependent on the CH_4 concentration, in accordance with Osborn and Wigley (1994) (see Table B1).

Changes in the atmospheric concentration of different greenhouse gases have the following impact on radiative forcing (IPCC, 1990):

$$\Delta F_{CO2} = 6.3\ln\left(\frac{CO_2}{CO_2|_0}\right) \tag{B3}$$

$$\Delta F_{CH4} = 0.036\left(CH_4^{0.5} - CH_4^{0.5}|_0\right) - f(CH_4, N_2O|_0) + f(CH_4|_0, N_2O|_0) \tag{B4}$$

$$\Delta F_{N2O} = 0.14\left(N_2O^{0.5} - N_2O^{0.5}|_0\right) - f(CH_4|_0, N_2O) + f(CH_4|_0, N_2O|_0) \tag{B5}$$

with ΔF measured in Wm^{-2}, concentrations for CH_4 and N_2O given in ppbv and the subscript 0 used to indicate pre-industrial concentration values. The CH_4-N_2O interaction term, expressed in Wm^{-2}, is determined by:

$$f(CH_4, N_2O) = 0.47\ln\left[1 + 2.01\cdot 10^{-5}\cdot (CH_4\cdot N_2O)^{0.75} + 5.31\cdot 10^{-15}\cdot CH_4\cdot (CH_4\cdot N_2O)^{1.52}\right] \tag{B6}$$

where, in accordance with Eq. 4 and 5, CH_4 and N_2O have to be replaced either by actual CH_4 and N_2O concentration values or alternatively by the respective pre-industrial levels.

In addition to Eq. B3 - B6, the radiative forcing description in ICM takes into account the contributions from SF_6, tropospheric ozone and stratospheric water vapour (both dependent on CH_4 concentrations), aerosols, and halocarbons, including indirect effects originating from stratospheric ozone depletion.

The time evolution of global mean temperature change and sea-level rise is calculated on the basis of impulse response functions that are calibrated to reproduce the results of a long-term forcing experiment carried out with a sophisticated spatially-resolved Atmosphere-Ocean General Circulation Model at MPI, Hamburg (Voss et al., 1998; Voss and Mikolajewicz, 2001). A detailed description of this approach can be found in Hooss (2001), Hooss *et al.* (2001), Bruckner *et al.* (2003), Joos *et al.* (2001), and Meyer *et al.* (1999).

In order to include the radiative forcing contributions of non CO_2-greenhouse gases, the carbon dioxide concentration value used in the response function approach of NICCS is replaced by the *equivalent* carbon dioxide concentration C_{Equiv} (measured in ppm) as defined in IPCC (1996a, p.320):

$$C_{Equiv} = 278\,ppm \cdot \exp\left(\frac{\Delta F}{6.3\frac{W}{m^2}}\right) \qquad \text{(B7)}$$

where ΔF denotes the sum of the individual radiative forcing contributions.

Table B1: Summary Key Assumptions greenhouse gases[1]

Trace Gas	CO2	CH4	N20
Atmospheric Concentration			
Pre- Industrial (ppmv)	278	.789	0,275
1992 (ppmv)	353	1.72	0,310
Energy related Emissions			
1992 (billion tons)	6.0	.08	.0001
growth rate, post 1992			
Non-energy related Emissions			
1992 (billion tons)	.2	.454	.0139
growth rate, post 1992	0	.8	.2

[1] Source: IPCC (90) and IPCC (92)

Acknowledgement: Useful comments by Alan Manne on an earlier version of this paper are gratefully acknowledged. So are the comments by participants at the Session on Climate Change at the Seventh Annual Conference on Global Economic Analysis held in Washington DC, on June 2004. All remaining errors are the authors' responsibility. Financial assistance from the Hanse-Wissenschaftkollege in the form of a Fellowship for the first author to complete this study is gratefully acknowledged.

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Notes

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[i] See Fuglestvedt *et al.* (2003), O'Neill (2000), Smith and Wigley (2000).

[ii] See Schmalensee (1993); Kandlikar (1995); Hammitt *et al.* (1996); Wigley (1998); Fuglestvedt *et al.* (2000); O`Neill (2000); Smith and Wigley (2000a, 2000b); Manne and Richels (2000, 2001).

[iii] Wherever there are more than one green house gases involved in the model, the word 'vector of' will be implied, unless the gas subscript "*i*" also appears explicitly. Also, to simplify notation, we denote 'time' as a subscript rather than as a variable.

[iv] Although the chemistry of climate change is complex, we assume here for simplicity that the total radiative forcing level is a linear additive function of various components each attributable to a particular GHG.

[v] Note that the argument inside the function $f^i(.)$ is the general *vector* c_t rather than a single component c_{it} of the vector. This is because there maybe some interactions between concentration levels of various components in determination of the radiative forcing level (such as in the case of CH_4 and N_2O, see Appendix 1). In the case of CO_2, however, radiative forcing from CO_2 is dependent only on the concentration level of CO_2 (see Appendix 1).

[vi] In this sense, current emission rate is the *control* variable and concentration level is a *state* level (in the language of optimal control). While both are important for the outcome of the climate environment, the state variable represents past history, while the control variable is the 'current' decision. In terms of practical policy environment, it is important to have an index which can relate more to the 'current' (marginal) economic decision rather than just past (and average) history, to allow it to be used in an optimal and decentralised decision making process.

[vii] Benefits are sometimes the reverse side of costs, depending on the direction of change. Hence a function can be used to represent *both*.

[viii] Economic cost level C is increasing with a *reduced* level of emissions as compared to a 'business-as-usual (BaU) situation, i.e. $(-\partial C/\partial e_{it})=\{[(C(e_{it})\ -\ C(e_{itBaU})]/[e_{itBaU} - e_{it}]\}>0$, where the subscript 'BaU' is used to indicate the business-as-usual or 'reference' level.

[ix] In the language of optimal control, x_t is the state variable, e_t is the control variable, and λ_t is the Lagrange multiplier.

[x] In this study, we consider only three GHGs: CO_2, CH_4, and N_2O.

[xi] There are important non-linearities in the relationship between emissions, concentration levels and radiative forcing levels, and also some interactions between the GHGs, but we assume that the contribution to *total* radiative forcing level from individual may simply be considered as the sum of the radiative forcing levels from all GHGs added together.

[xii] See Burniuax and Truong (2000), and Burniaux (2002. For the purpose of this study, we also expand the production structure in Burniaux (2002) to allow the model to take on a more general case when *both* CH_4 and N_2O emissions occurring in any given industry. For details about the sectoral and regional definitions in the model as well as details about the production structure extensions, see Appendix A.

[xiii] After the name of a project called ICLIPS (**I**ntegrated Assessment of **Cli**mate **P**rotection **S**trategies), see Toth *et al.*, (2003). The ICLIPS model is a reduced from version of the Non-linear Impulse-response representation of the coupled Carbon cycle-Climate System, or NICCS model (see Bruckner *et al.* (2003), Hooss *et al.* (2001), Hooss (2001), Joos *et al.* (2001), Meyer *et al.* (1999)). ICM is driven by time-dependent paths of the anthropogenic emissions of CO_2, CH_4, N_2O, halocarbons, SF_6 and SO_2. In this paper, however, we will be concerned only with CO_2, CH_4, and N_2O, as these are the GHGs covered in the GTAP-E model.

[xiv] For the purpose of our experiment, we do not consider the question of what climate objective is beyond the target year 2100. However, to test the sensitivity of our model calculations with respect to length of the time horizon, we let the simulation runs until 2200, assuming that whatever growth rates of emissions achieved in 2100 will continue on until 2200.

[xv] Since these gases are not actually traded in the market, their values are referred to as 'shadow prices', and reflecting the relative benefits (in terms of climate change impact) of reducing a unit of these GHGs.

[xvi] IPCC (2001). These *GWP*s are 1 for of CO_2 (reference gas), 21 for CH_4, and 310 for N_2O. This implies one ton of CO_2, CH_4, and N_2O are equivalent to (12/44), 21*(12/44) and 310*(12/44) tons of carbon respectively and therefore, all the relative prices of the GHGs are set according to these carbon equivalent (Ceq) measurements.

[xvii] In estimating the *MAC*s, we assume there is world trading in emissions so that at equilibrium, there is only a single shadow price for all regions and which also represents the theoretically minimum price of emission for the world as a whole. The assumption simplifies the analysis and the presentation of the results. The alternative is to assume there is no trading so that each region will end up with a different shadow price for emissions. This will complicate the analysis without adding much to the conclusion, hence is not followed in this paper, although this assumption could be taken up in future studies.

[xviii] To compare the relative prices under the sets of assumptions, 'fixed relative prices' versus 'flexible relative prices', we continue to convert all units of GHGs into 'carbon equivalent units' using the weights of 1, 21, 310 for CO_2, CH_4, N_2O respectively, even though these weights are no longer necessary or meaningful for the case of 'flexible relative prices'. This, however, is merely is to facilitate a comparison which is to be shown in a single graph. The alternative is to make the scale of the vertical axis in Figure 3 different for all GHGs. This will make comparison difficult and also not as meaningful. As it is, Figure 3 shows the *relative* changes in the prices of all GHGs from the case of 'fixed relative prices' to the case of 'flexible relative prices' rather than being concerned about the absolute units of measurements for either the prices or quantities.

[xix] That is, they show the paths of the *ratios* of ($MGWP_i/MGWP_j$) where j refers to CO_2.

[xx] There are periods when the *MGWP*s (and hence also the cumulative *GWP*) for CH_4 falls below zero. This implies the average rates of emissions of CH_4 over this period or time horizon is below the rates of decay of CH_4 in the atmosphere (ignoring the small interaction between CH_4 and N_2O).

[xxi] We notice that ΔQ will be opposite in sign to ΔP (except for the rare cases where the utput effect may overwhelm the price or substitution effect), hence the negative sign appearing in the formula for the value of the distortion triangle.

[xxii] Since we are mainly concerned with the impact of different assumptions on *GWP*s on the estimates of economic costs of climate policy, it makes sense to vary the parameters of the economic model rather than the parameters of the climate model, and not varying *both*, since comparison would then be made difficult, if not invalid.

[xxiii] This is because under the standard 'Policy' scenario assumption, the values of σ_{CH4} are already relatively high as compared to the values of σ_{N2O}, (see Table A3 and A4) - these are taken from empirical studies by Hyman *et al.*(2002). As a result, for a sensitivity analysis, it makes sense to reverse this situation, and make the values of σ_{CH4} lower while increasing the values of σ_{N2O}. It does not make sense to increase the values of σ_{CH4} still further and make the values of σ_{N2O}.even lower.