Global Warming Potentials:
A Cost-Effectiveness Approach

David F. Bradford and Klaus Keller

Paper to be presented at the NBER Summer Institute
Environmental Economics Workshop
August 7-8, 2000

Version 01.1 July 14, 2000

David F. Bradford
Woodrow Wilson School
Princeton University
Princeton, NJ 08544-1013
609-258-1856
bradford@princeton.edu

Klaus Keller
Princeton Environmental Institute
Princeton University
Princeton, NJ 08544
609-258-2612
klkeller@princeton.edu

Global Warming Potentials:
A Cost-Effectiveness Approach

David F. Bradford and Klaus Keller

Abstract

The Kyoto Protocol prescribes obligatory limits on the emission of greenhouse gases by the industrialized countries during the period 2008-2012. Six specific gases are covered. The Kyoto limits apply to an aggregate of emissions of the covered gases expressed in carbon dioxide (CO_2) equivalents, obtained by application of a "global warming potentials" (GWPs). In regard to *concentrations*, or *stocks* in the atmosphere, such equivalents are relatively unproblematic. But it is not obvious how to define CO_2-equivalent *emissions* of different greenhouse gases, since such emissions affect not only the stock today but the stocks through time in the future, each with a different characteristic residence time path. In constructing the GWP of a gas, the increments to radiative forcing at different times resulting from emission of an incremental emitted ton are simply summed out to some arbitrarily chosen time horizon.

As has been recognized in the literature, the GWP measure has some serious defects. In the first place, it depends on the horizon one chooses to use in calculating it. Equally problematic is the fact that the GWP takes no account of the fact that increases in radiative forcing in the future are generally worse than increases in the present for two related reasons: They impose larger costs in the form of climate damage and they impose larger costs in the form of offsetting abatement then required to meet any given climate objective. A further shortcoming related to timing is that the GWP takes no account of the opportunity cost of capital. Even if the impacts over time, added together, were the same in dollar terms, the fact that they occur at different times is highly relevant.

Previous attempts to address these problems have focussed on the estimates of the incremental damage, due to climate change, caused by incremental emissions. In this paper we suggest a better approach is to work from an assumed required path of radiative forcing; hence the "cost-effectiveness" in the title. Such a constraint is arguably a better model of the behavior of the regulatory system. It also simplifies the quantitative estimation of what we call Economic Global Warming Potentials (EGWPs). We present numerical results based on simplified mathematical forms for the various elements of the model.

Global Warming Potentials: A Cost-Effectiveness Approach

David F. Bradford and Klaus Keller

Table of Contents

Preliminary (Version 01.1); comments invited July 14, 2000
Please do not quote without permission

Global Warming Potentials: A Cost-Effectiveness Approach

David F. Bradford and Klaus Keller*

Problem Background

The international community has been struggling to find agreement on limits on greenhouse gas emissions. In the negotiations, the United States, in particular, has stressed the need for a comprehensive approach, taking into account all gases and sinks as well as sources. So far, the countries have (in the Kyoto Protocol) agreed on obligatory limits on the emission of six greenhouse gases by the industrialized countries during the period 2008-2012.

Carrying out the program requires a way to aggregate the different gases. Recognizing the central role of CO_2 (because it is quantitatively the most important gas under significant human influence), it is customary to speak of "CO_2 equivalent" emissions and concentrations. In regard to *concentrations*, or *stocks* in the atmosphere, there is a natural definition of CO_2 equivalence. This is because greenhouse gases (GHG) have in common an impact on the radiative forcing of the atmosphere, usually expressed as watts per square meter. It is at least conceptually possible to calculate the radiative forcing at a point in time of given stocks of the six greenhouse gases. And one can calculate the amount of CO_2 in the atmosphere that, taken

* Bradford is Professor of Economics and Public Affairs, Princeton University; Adjunct Professor of Law, NYU Law School; Research Associate, National Bureau of Economic Research; Research Fellow, CESifo (Munich). Keller is Research Associate, Princeton Environmental Institute, Princeton University.

alone, and without the other gases, would result in the same radiative forcing. This would then be the "CO_2 equivalent" stock.

So to speak of a target trajectory through time for the CO_2 equivalent stock of greenhouse gases in the atmosphere is the same as to speak of a target trajectory of radiative forcing. If there were just CO_2, it would be straightforward to calculate the allowable emissions of CO_2 each year that would meet any given agreed target trajectory for radiative forcing. If agreement were reached on the radiative forcing trajectory, the usual tools of environmental control, including emission taxes or tradable emission allowances, could be used to implement it.

A problem arises in trying to do the same sort of thing for CO_2-equivalent *emissions* of several (six, in the case of the Kyoto protocol) greenhouse gases. Now one would like to be able to quantify the emission of, say, an extra ton of methane emitted, as equivalent to a certain number of extra tons of CO_2 emitted. Such emissions affect not only the stock today but the stocks through time in the future, each with a different characteristic residence time path. (It is even a little worse than that, since the path of residence of an extra ton of a gas may depend on the amount of the various gases that are also present. Also, the residence time path of a gas in the atmosphere may depend on the rate at which it is added to the atmosphere. We neglect these niceties here.) There are many ways to package emissions paths that translate into a given trajectory of radiative forcing, or, the same thing, a given CO_2 equivalent stock in the atmosphere. The question is, how should the temporally distributed effects of the various gases be accounted for?

The answer adopted in the Kyoto Protocol is expressed by the "global warming potential" (GWP) of a greenhouse gases (the idea and the label apparently originated with Lashof and

Ahuja, 1990, building on a similar concept developed in the context of the stratospheric ozone problem). In the following sections we briefly outline the GWP concept and its major shortcomings. The starting point is the perturbation in the path of GHG stock that results from adding an extra ton of CO_2 to the atmosphere. A schematic representation of such a perturbation is shown in Figure 1. The picture incorporates the assumption we have mentioned that the persistence in the atmosphere of a unit emitted at a point in time does not depend on either the level of the stock at that time or the level of the stocks of other greenhouse gases in the atmosphere.

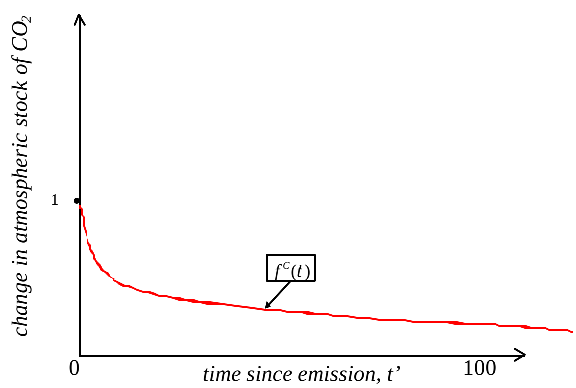

Figure 1. Perturbation in Stock from a Unit Emission

The perturbation path shown in Figure 1 is to be interpreted as the fraction, $f^C(t')$, of an extra ton emitted that is still resident in the atmosphere t' years after the time of emission. It starts at some number possibly less than 1 (since some may be immediately absorbed into the ocean, etc.) and declines toward zero (or possibly some positive limit) over time.

A similar path of the residence time of an incremental emitted ton of each of the other greenhouse gases can also be obtained. Figure 2 adds to Figure 1 the perturbation in the path of the stock of some other gas, G, in the atmosphere, $f^G(t')$, due to the injection of an extra ton of

g at some time point. To simplify, in addition to the simplifying assumptions mentioned already, we ignore the impact of such an injection of G on the stock of CO_2 (since G may break down in part into CO_2). The particular perturbation path shown in the figure implies the extra ton stays in the atmosphere undiminished for exactly 10 years and then vanishes.

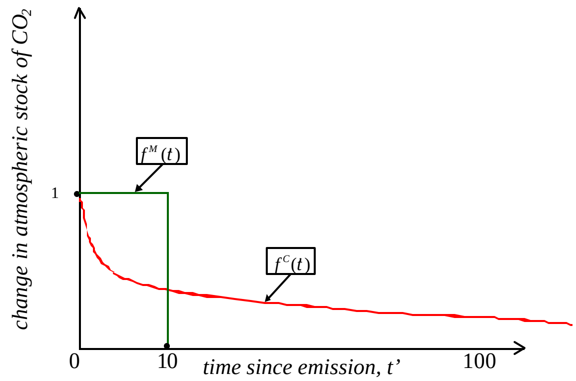

Figure 2. Perturbations for Two Gases

The next step is to associate with each unit increment of a gas resident in the atmosphere the incremental impact on radiative forcing, ΔF^g, where the superscript indexes the gas (CO_2, methane, etc.). This is the extra forcing due to an extra ton of the gas resident in the atmosphere.

In constructing the GWP of a gas, the increments to radiative forcing at different times resulting from emission of an incremental emitted ton are simply summed. So, for CO_2, the amount of such accumulated effect out to a horizon of T years would be (expressed in forcing-years)

$$\int_0^T \Delta F^C(x) f^C(x) dx .$$

The global warming potential of a gas is the ratio of the impact of an incremental ton of that gas emitted, thus expressed, to that of CO_2:

$$GWP_T^g = \frac{\int_0^T \Delta F^g \cdot f^g(x)dx}{\int_0^T \Delta F^C \cdot f^C(x)dx}.$$

As has been pointed out the GWP measure has some serious defects. In the first place, it depends on the horizon one chooses to use in calculating it (see, for example, the discussion in Harvey (1993), Lashof (2000), O'Neill (2000), Smith and Wigley (2000a, 2000b), Wuebbles et. al. (1995), and Wigley (1998)). Not surprisingly, the choice of horizon matters a lot, since the different gases have very different residence time paths. (In our simple example the GWP for G, GWP_T^G, would first increase with T out to 10 and then decline more and more with increases in T.) Table 1 illustrates the problem expressed in the actual calculations for three gases. The IPCC decided a good compromise value for T was 100 years and this time horizon is used in the Kyoto Protocol to determine equivalence among the different gases for purposes of meeting the agreed CO_2 equivalent targets.

Species		GWP by Horizon		
		20 years	100 years	500 years
carbon dioxide	CO_2	1	1	1
methane	CH_4	56	21	6.5
nitrous oxide	N_2O	280	310	170
sulphur hexafluoride	SF_6	16300	23900	34900

Source: IPCC, 1995, Table 2.9, p. 121

Table 1. Illustrative GWP Values for Different Horizons

Equally problematic is the fact that the GWP takes no account of the fact that increases in radiative forcing in the future are generally worse than increases in the present for two related reasons: They impose larger costs in the form of climate damage and they impose larger costs in the form of offsetting abatement then required to meet any given climate objective.

A further shortcoming related to timing is that the GWP takes no account of the opportunity cost of capital [see, for example, Eckaus (1992) or Kandlikar (1996)]. Even if the impacts over time, added together, were the same in dollar terms, the fact that they occur at different times is highly relevant. Other things equal, it is better if a given dollar-valued negative impact occurs farther in the future.

Improving the Measure

Various analysts of CO_2 equivalence have attacked these problems. One class of studies compares the negative effects of various greenhouse gases on human welfare (e.g., Reilly and Richards; 1993; Kandlikar, 1996, Hammitt *et al,* 1996). In general, these studies estimate the ratio of the discounted value of the damage done by an incremental unit emission of a gas to that done by an incremental unit of CO_2. Such a calculation is based on the residence times of the two gases and the damage done at each moment through time. This ratio was given the name the "economic damage index (EDI)" of a gas by Hammitt *et al* (1996), in an elegant implementation using a sophisticated carbon cycle simulation focussing on (discounted) incremental damage due to climate change. Such calculations require a model of the assumed path of emissions and the resultant radiative forcing, the implied temperature change, the damage-temperature relationship, and the discount rate. In principle, the EDI of a gas changes through time, as the system evolves. Hammitt *et al* (1996) present EDIs for the six Kyoto GHGs as of the present, with sensitivity analysis indicating that the various modeling assumptions do matter. Since the standard GWPs are sensitive to the chosen horizon, it goes without saying that the vector of EDIs generally differs as well from any given GWP vector.

One important problem of the EDI concept is its sensitivity to what must inevitably be somewhat speculative modeling of damages, not to mention the speculative aspects of the model of the physical system. But, from an economist's perspective, there is no doubt this concept is on the right track. Putting to one side the GWPs' dependence upon an arbitrary horizon, there is no virtue in whatever basis they may have in undisputed physical science. The tradeoff between emissions of one gas for those of another implied by their respective impacts on climate-related damages is logically inseparable from an evaluation of those damages. It makes no sense to speak of a "correct" or "approximately correct" set of tradeoffs apart from some such evaluation.

In this paper we explore the implications of a slightly different cut at the same general approach, one that substitutes for explicit assumptions about the value of climate impacts an acceptance of the valuations implicit in whatever policies are adopted. To develop the point, suppose there were just one GHG, say CO_2. Expressed in economic analytical terms, an optimal emission control policy would be one that maximized some function of the welfare of the people subject to that policy through time. Nordhaus (1994, 1998) provides a well-known example. A slightly less general expression of much the same objective is the minimization of the discounted value (or perhaps expected discounted value, recognizing the stochastic character of the problem) of the sum of damage due to climate change and the cost of abating emissions. We would describe this as a benefit-cost criterion. (If benefits and costs are appropriately defined, a welfare-maximizing policy will dominate all alternative policies in a benefit-cost sense; i.e., passing a benefit-cost test relative to the alternatives is a necessary condition of optimality.) Hammitt *et al* (1996) use the benefit-cost framework as the basis for their EDI.

Along a path that is optimal in this sense, the marginal discounted value of the damage done by an incremental unit of emissions will just equal the marginal cost of abatement. That common value will be the tax on emissions that would result in the optimal path being chosen in competitive markets. But we can use that common value, the shadow price of emissions, as a way to characterize the optimal policy, however it may be implemented. If command-and-control methods are used, the shadow price will not be directly observed; if marketable allowances are used, the shadow price will be revealed as the equilibrium market price of allowances.

If we extend the analysis to include several greenhouse gases, by a similar line of reasoning, associated with an optimal policy of controlling emissions of all of them will be a vector of shadow prices through time, one for each gas. Those shadow prices will have the same economic interpretation as has just been given to the single shadow price in the one-gas case. The *ratio* of the shadow price of any gas to the shadow price of CO_2 will tell us exactly the quantity of CO_2 emissions that is just equal in its impact on the objective of the policy to a unit emission of the gas in question. In other words, that ratio is the economic equivalent of the GWP for that gas *at that moment*. The EDIs of Hammitt *et al* (1996) are such shadow price ratios.

Associated with a policy that is optimal in the sense used here will be a path of climate change, expressed, for example, by the global average surface temperature, driven by a particular path of radiative forcing. Suppose we now consider a slightly different problem, namely, to choose from among all possible paths of GHG emissions that give rise to this path of radiative forcing the one that minimizes the discounted abatement cost. Since we have constrained the policy to produce the path of radiative forcing associated with an overall optimum, the GHG

emissions paths prescribed in the solution will also be the same, as will the shadow prices that characterize those paths. These shadow prices, however, have only one of the two interpretations mentioned above. That is, they express the discounted marginal abatement costs at all points along the cost-minimizing paths. We know about the marginal discounted damage done by those emissions only by virtue of the way we derived the path of radiative forcing that is treated as a constraint.

Since, however, the estimate of damage done by climate change is one of the least well established pieces of the policy puzzle, the characteristics of the subproblem may be of particular interest. It may be possible to develop an agreed policy target in terms of a path of GHG concentrations (that is, a path of radiative forcing) even without articulating or agreeing on the valuation of the climate-associated damages. To be sure, an assertion that a given path of radiative forcing is the best target contains an implicit statement about the damages associated with that and other paths. But articulation of that valuation is no more necessary in the climate context than is the articulation of the value of, say, incremental defense spending in the setting of national security policy. Whether or not the path of radiative forcing that emerges as the objective of policy is optimal, policy makers should be interested in achieving that path at minimum cost.

The main objective of this study is to explore the quantitative implications of this viewpoint for the tradeoff among emissions of GWPs. For lack of a better term at this point, we refer to these ratios as "Economic GWPs" or "EGWPs."

Derivation of the Economic Global Warming Potential (EGWP)

To derive the EGWP for a given gas, it is helpful to imagine that a manager has been assigned to control the emissions of each GHG. The overall objective is to hit the prescribed path of radiative forcing. The CO_2 manager has been given the key task of adjusting to the paths chosen by the other gas managers, so as to meet the constraint. (This is similar to the approach described in Wigley, 1998.) An incremental unit emission pulse of, say, a ton of methane imposes on the carbon manager the requirement to make an offsetting downward pulse adjustment in CO_2 emissions, followed by a further flow adjustment as a consequence of the different residence times of these two gas pulses. An incremental pulse by the methane manager therefore translates into a perturbation in the CO_2 emission path, which is to say a perturbation in the path of carbon abatement control.

This adjustment in CO_2 emissions has a discounted cost that we can calculate. The *ratio* of that discounted cost to the *current* marginal cost of abating CO_2 tells us the EGWP for methane. If the joint program of GHG emission controls is cost minimizing for the path of radiative forcing that is taken as a constraint, this ratio is the same as the ratio of shadow prices on the emission controls that we have discussed above. (Strictly speaking, the approach relies on the sufficiency of using these implicit shadow prices for cost minimization.)

To calculate the EGWP of a gas involves four steps. First, we have to determine the change in carbon emissions over time that would be required to offset a unit emission pulse of the GHG in question. The offset is defined by the constraint of a zero net change in environmental impact due to the perturbations, which translates in this context to "no change in the path of radiative forcing." Second, we determine the implied increment to CO_2 abatement

cost at each point in time. Third, we discount the costs to the present (or, more generally, to the time of the emission of the subject gas). Fourth, and finally, we divide the net present value of the costs by the present marginal cost of CO_2 abatement.

To illustrate, Figure 3 displays a hypothetical perturbation in the CO_2 emission path required to just offset the impact on radiative forcing of emission of an extra ton of methane at some time, t. (Because we have assumed the residence times and radiative forcing impacts are independent of the stocks of the gases, the shape of this perturbation will be the same at all times.) The thick line at $t'=0$ indicates that to offset the one-ton positive pulse in emissions of methane a negative pulse in emissions of CO_2 is required, in an amount that depends on the two radiative forcing coefficients, $\Delta F^M, \Delta F^C$, and the extent to which such emissions of the two gases are immediately reabsorbed into the earth, $f^M(0), f^C(0)$. The rest of the path, designated $\Delta e^C_{M,t}(t')$ to indicate the dependence on the various elements of the story, is required to fix up the concentrations as the methane and carbon dissipate according to their respective characteristic residence time relationships.

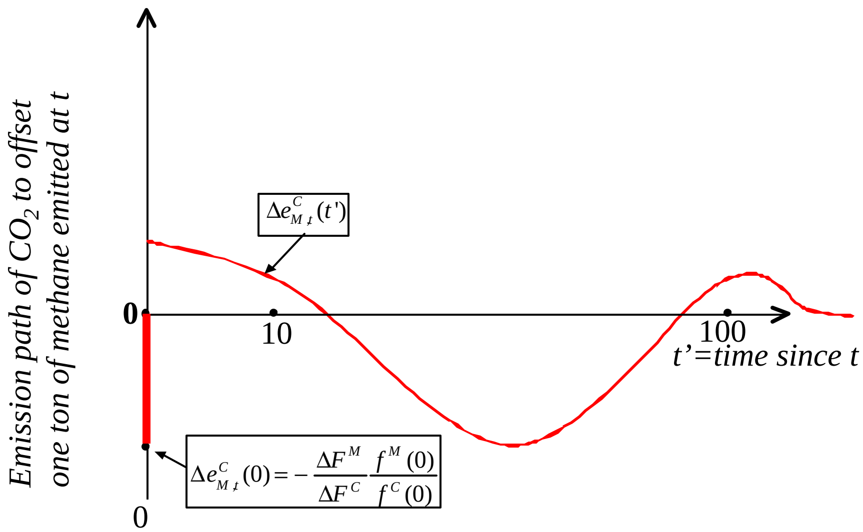

Figure 3. Hypothetical Perturbation in CO_2 Emissions to Offset 1 Ton Methane Pulse at Time *t*. Note that this picture is an illustration only.

The changed emission path translates into extra cost imposed on the carbon dioxide manager due to the required adjustment in abatement. Let the costs of abatement (from the business as usual (BAU) paths) of CO_2 be given by $A^C(x^C(t))$, where $x^C(t)$ stands for the number of tons by which the rate of emission in a given year falls below the BAU path in that year. The marginal abatement cost in a given year is simply the derivative of the *A* function with respect to the amount of abatement, $\frac{dA^C}{dx^C}(x^C(t))$. Then, if t is the moment of emission of the extra ton of methane, $\Delta e^C_{M,t}(t')\frac{dA^C}{dx^C}(x^C(t+t'))$ is the rate of extra abatement cost per unit time at *t+t'*, at successive points of time extending into the future.

The capitalized value of these costs over time is obtained by discounting each bit to the time of emission of the subject GHG and adding them up:

$$\int_t^{\infty} e^{-r(x-t)} \Delta e^C_{M,t}(x-t) \frac{dA^C}{dx^C}(x^C(x))dx ,$$

where r is the applicable discount rate.

Finally, the Economic GWP for methane at time t is given by:

$$EGWP_{M,t} = \frac{\int_t^{\infty} e^{-r(x-t)} \Delta e^C_{M,t}(x-t) \frac{dA^C}{dx^C}(x^C(x))dx}{\frac{dA^C}{dx^C}(x^C(t)}$$

Quantifying Economic Global Warming Potentials

As outlined above, the first step in evaluating EGWPs is to determine the carbon perturbation, $\Delta e^C_{g,t}(t')$, for each subject gas, g. This step requires a model of the biogeochemical cycles of CO_2 and the GHG in question. For most GHGs, a single exponential pulse-response function describes the system reasonably well. For CO_2, the single exponential decay function is a very rough approximation (IPCC, 1996, Kaufmann, 1997), and we adopt the slightly improved carbon cycle model reported by Nordhaus (1994). In the model of Nordhaus (1994), a fraction of the emitted CO_2 is instantaneously absorbed by the carbon sinks, the remainder decays with a constant rate. Although numerical methods permit solving more complex (and accurate) carbon cycle models (e.g., Joos *et al*., 1996), this arguably crude approximation allows us the advantage of analytical solutions for developing an intuitive feel for the impact of alternative assumptions.

The general requirement defining the necessary CO_2 emissions offset to an arbitrary perturbation, $\Delta e^M(t')$, in emission of a greenhouse gas, say methane, is given by

$$\int_{-\infty}^{t'} \Delta F^C \Delta e^C(x) f^C(t'-x)dx + \int_{-\infty}^{t'} \Delta F^M \Delta e^M(x) f^M(t'-x)dx = 0 .$$

The particular methane perturbation of interest is given by

$$\mathbf{d}_t \equiv \text{Dirac delta function at } t,$$

so the functional equation becomes

$$\int_{-\infty}^{t'} \Delta F^C \Delta e^C_{M,t}(x) f^C(t'-x)\, dx + \Delta F^M f^M(t'-t) = 0.$$

For the exponential pulse response case, the offsetting emissions path is

$$\Delta e^C_{g,0}(t') = \frac{r_g}{a}(-d_0(t') + (g_g - g_C)e^{-g_g t'}), \text{ where}$$
$$d_0 \equiv \text{Dirac delta function at } 0,$$
$$a \equiv \text{Initial concentration after unit } CO_2 \text{ pulse.}$$

See Table 2 for details.

The second step involves estimating the marginal CO_2 abatement costs over time. To obtain estimates of the marginal abatement costs, we can take advantage of the fact that studies of the GHG emission paths needed to meet various radiative forcing objectives (or paths of CO_2 concentration) often report the tax on CO_2 emissions, typically implicit, that would induce the intended path in a competitive system. Alternatively, they may report the prices of allowances predicted to hold along a controlled path implemented through a tradeable allowance system. Either the tax rate or the allowance price is exactly the marginal abatement cost estimate that we need. An example of such a simulation result is given in Figure 4.

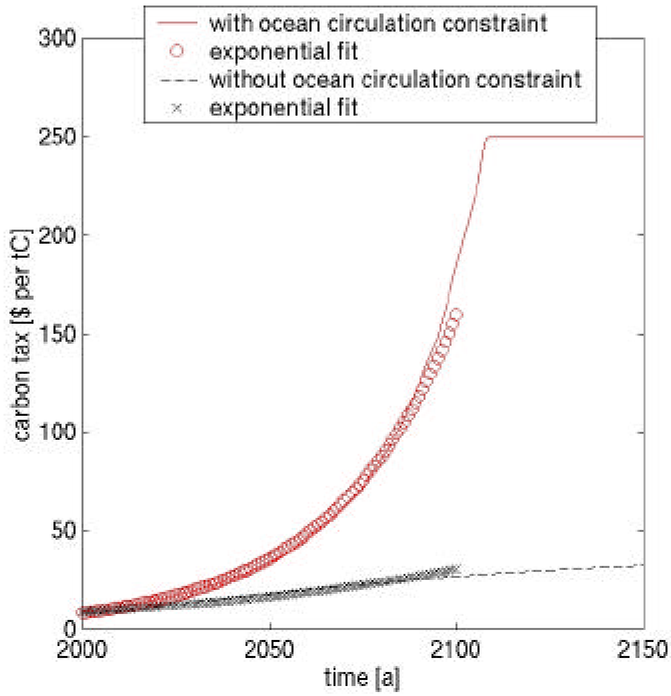

Figure 4. Illustrative Carbon Tax Paths in the DICE Model (Nordhaus, 1994), Modified to Account for a Possible Ocean Circulation Collapse (Keller *et al*, 2000a, 2000b). The circles and crosses denote the fit of an exponential growth curve to the carbon taxes between the years 2000 and 2100. The approximate growth rates with and without the ocean circulation constraint are 3 and 1.2 percent per year, respectively. The shown carbon tax paths assume a backstop technology at 250 U.S. $ per ton of carbon.

These model results suggest that optimal carbon taxes to achieve an exogenously determined climate constraint might be well approximated in the near-term by an exponential growth rate (b).

So, for example, if a study provides an estimate of the allowance price path, $p^C_{Allowance}(x)$, associated with some specification of the policy needed to meet the radiative forcing target, the EGWP for a GHG g is given by

$$EGWP_{g,t} = \frac{\int_t^{\infty} e^{-r(x-2000)} \Delta e^C_{g,t}(x-t) p^C_{Allowance}(x) dx}{p^C_{Allowance}(t)}.$$

An attractive feature of this formulation the EGWP is that it shows how we can, in principle, shift the focus from meeting a hypothetical path of radiative forcing to developing the implications of a particular path of allowance prices/carbon tax rates. Thus, for example, if we had good reason to expect that a backstop technology would become available in the future that put an effective ceiling on allowance prices, we could calculate the EGWPs that would apply, regardless of the particular path of radiative forcing that were chosen (since all such paths would, at some point, involve a shadow price set at some given level implied by the backstop technology.)

For the above mentioned simplifying assumptions (plus an assumption that the carbon tax rate grows at rate $\boldsymbol{b}$, Figure 4), the EGWP becomes:

$$EGWP_g = \frac{\boldsymbol{r}_g}{\boldsymbol{a}} \frac{(\boldsymbol{b} - r - \boldsymbol{g}_C)}{(\boldsymbol{b} - r - \boldsymbol{g}_g)}, \text{ provided } \boldsymbol{b} - r - \boldsymbol{g}_g < 0.$$

In this equation, $\boldsymbol{r}_g$ is the relative radiative forcing coefficient, defined as:

$$\boldsymbol{r}_g \equiv \frac{\Delta F_g}{\Delta F_c} = \frac{m_c \Delta F_g^{conc}}{m_g \Delta F_c^{conc}},$$

where m_c and m_g are the molecular weights of CO_2 and the GHG in question and ΔF_g^{conc} is the incremental forcing effect of a unit increment in the concentration by volume of a gas in the atmosphere (the units in which radiative forcing effects are typically reported). For comparison, the GWP for this case is given by:

$$GWP_{g,T} = \boldsymbol{r}_g \frac{\boldsymbol{g}_c}{\boldsymbol{a}\boldsymbol{g}_g} \left[\frac{1 - e^{-g_g T}}{1 - e^{-g_c T}} \right]$$

For an infinite time horizon, this simplifies to:

$$GWP_{g,\infty} = r_g \frac{g_c}{a g_g}$$

Note that for the case of b = r (in other words, the carbon tax grows at the same rate that the discount factor shrinks) the EGWP is equal the GWP for an infinite time horizon.

Results

We use the analytical solutions to calculate the EGWP for various parameter values. The first question is: How reasonable is the exponential decay approximation? We address this question by comparing the GWP values based on the simple exponential model with GWPs calculated with a more complex carbon cycle model, given by the IPCC (1996) (Table 2). Table 2 indicates that our approximation might capture the salient features of the GWP values calculated using more complex models (IPCC,1996).

Species		Residence Time		Exponential Decay Approximation*		GWP from IPCC
		Half Life in Years	Decay Rate in Percent per Year	Relative Forcing Coefficient (r_g)	Approximation to 100-Year GWP	100 Year Horizon
carbon dioxide	CO_2	120	0.58	1.0	1	1
methane	CH_4	12	5.78	70.7	29	21
nitrous oxide	N_2O	120	0.58	205.6	367	310
sulphur hexafluoride	SF_6	3200	0.02	10715.4	24967	23900

* Assumes all species, other than CO_2, decay at constant rate per year. A fraction .44 of a CO_2 pulse is immediately absorbed by terrestial sinks; the remainder decays at the indicated constant rate.

Table 2. Comparison of the GWP from the Exponential Approximation and the IPCC (1996) Values

Having established that the analytical solution might be a useful approximation to the problem, we present in Table 3 EGWP values for various scenarios. Based on the carbon tax paths shown in Figure 4, we estimate EGWP values for rates of carbon tax increase (b) of 3 and 1.2 % per year. In this simplified model, the rate of increase in carbon tax and the discount rate are completely symmetric in their effects: Only the difference, b-r, enters the calculation. The case of methane illustrates dramatically the sensitivity of the carbon equivalence to this "net" discount factor, which ranges from 0% (3%-3%) to 4.8% (5%-1.2%). At the highest of these illustrative rates the EGWP for methane is nearly three times the GWP level prescribed by the Kyoto terms. At the lowest, the EGWP is only a little over one half the Kyoto level.

Species		EGWP for Exponential Case*				GWP from IPCC		
		EGWP for r=5%, beta=3%	EGWP for r=5%, beta=1.2%	EGWP for r=3%, beta=3%	EGWP for r=3%, beta=0%	20 years	100 years	500 years
carbon dioxide	CO_2	1	1	1	1	1	1	1
methane	CH_4	42	58	13	51	56	21	6.5
nitrous oxide	N_2O	367	367	367	367	280	310	170
sulphur hexafluoride	SF_6	24417	21928	552630	22668	16300	23900	34900

* Assumes all species, except CO_2, decay at constant rate per year; .44 of a pulse of CO_2 is instantaneously reabsorbed, remainder decays exponentially; carbon tax grows at constant rate beta.

Table 3. EGWPs Based on the Exponential Decay Assumptions
Compared to IPCC (1996) Values

Note that the present calculations neglect so far the possibility of carbon backstop technologies. In the long term (and in certain cases), this approximation might be questionable (see Figure 4), and the analytical solution must be amended to account for this effect. The potential bias by the neglected backstop technologies becomes obvious for long lived gases in the case where the discount rate is less or equal to the growth rate of the carbon tax (i.e., column 3 in Table 3 for sulfur hexafluoride).

Conclusions

We develop a novel economic measure – the Economic Global Warming Potential (EGWP) - to analyze the tradeoffs between emissions of different greenhouse gases. The EGWP is an economic extension of the global warming potential (GWP). In contrast to previous economic extensions of the GWP that analyze changes in environmental damages, the EGWP requires only information about the marginal carbon abatement cost along a projected path of environmental regulation — arguably more accessible information. We derive analytical approximations for simplified cases and evaluate the EGWP for the greenhouse gases regulated in the Kyoto protocol. Not surprisingly, the EGWP values are sensitive to the adopted discount rate, the atmospheric residence time of the gas and the future carbon tax rates. For typically adopted discount rates and potential future carbon tax paths, the EGWP for methane are larger than the GWP adopted in the Kyoto protocol. The discrepancy between the GWP and the EGWP confirms previous conclusions that a regulation policy based on GWP alone (as in the Kyoto protocol) is likely to be economically inefficient.

References

Eckaus, Richard S. "Comparing the effects of greenhouse gas emissions on global warming," The Energy Journal (XIII), 1992, pp. 25-35.

Hammitt, James K., Atul K. Jain, John L. Adams, and Donald J. Wuebbies, "A Welfare-Based Index for Assessing Environmental Effects of Greenhouse-Gas Emissions," Nature, (CCCLXXXI) May 23, 1996, pp. 301-303.

Harvey, L.D. Danny, "A Guide to Global Warming Potentials (GWPs)," Energy Policy, (XXI-1) January 1993, pp. 24-34.

Intergovernmental Panel on Climate Change (IPCC), Climate Change 1995: The Science of Climate Change (Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change), J. T. Houghton, L. G. Mera Filho, B. A. Callander, N. Harris, A. Kattenberg and K. Maskel, eds., Cambridge University Press, 1996.

Joos, F., *et al*: "An Efficient and Accurate Representation of Complex Oceanic and Biosphere Models of Anthropogenic Carbon Uptake." Tellus, (XLVIII B) 1996, pp. 397-417.

Kaufmann, R. K. "Assessing the DICE model: Uncertainty Associated with the Emissions and Retention of Greenhouse Gases" Climatic Change, (XXXV) 1997, pp. 435—448.

Kandlikar, M. "Indexes for comparing greenhouse gas emissions: Integrating science and economics," Energy Economics, (XVIII) 1996, pp. 265-281.Keller, Klaus, Benjamin Bolker, and David F. Bradford, "Uncertain Climate Thresholds and

Economic Optimal Growth", Paper to be presented at the Yale/NBER/IIASA Workshop on Potential Catastrophic Impacts of Climate Change, Snowmass, Colorado, July 24-25, 2000.

Keller, Klaus, Kelvin Tan, François M. M. Morel, and David F. Bradford, " Preserving the Ocean Circulation: Implications for Climate Policy," issued as CESifo Working Paper 199, Center for Economic Studies, University of Munich, October 1999 and NBER Working Paper No. 7476, Cambridge, MA: National Bureau of Economic Research January 2000; accepted for publication in Climatic Change, as of November 1999.

Lashof, Daniel A., and Dilip R. Ahuja, "Relative Contributions of Greenhouse Gas Emissions to Global Warming, Nature, (CCCLXIV) April 5, 1990, pp. 529-531.

Lashof, Daniel A., "The Use of Global Warming Potentials in the Kyoto Protocol: An Editorial Comment," Climatic Change, (XLIV) 2000, pp. 423-425.

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

Nordhaus, William D., "Roll the DICE Again: The Economics of Global Warming," MS, Yale University, New Haven, CN, December 18, 1998.

O'Neill, Brian C., "The Jury is Still Out on Global Warming Potentials: An Editorial Comment," Climatic Change, (XLIV) 2000, pp. 427-443.

Reilly, John, R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, C. Wang, "Multi-Gas Assessment of the Kyoto Protocol," Nature, (CCCCI) October 7, 1999, pp. 549-555.

Reilly, J. M., and K. H. Richards, “Climate Change Damage and the Trace Gas Index Issue”, Environmental and Resource Economics (III) 1993, pp. 41-61.

Smith, Steven J., and T. M. L. Wigley, "Global Warming Potentials: 1. Climatic Implications of Emissions Reductions," Climatic Change, (XLIV) 2000, pp. 445-457.

Smith, Steven J., and T. M. L. Wigley, "Global Warming Potentials: 2. Accuracy," Climatic Change, (XLIV) 2000, pp. 459-469.

Wuebbles, D. J., A. K. Jain, K. O. Patten, and K. E. Grant, "Sensitivity of Direct Global Warming Potentials to Key Uncertainties," Climatic Change, (XXIX) 1995, pp. 265-297.

Wigley, T. M. L., "The Kyoto Protocol: CO_2, CH_4 and Climate Implications," Geophysical Research Letters (XXV-13) July 1, 1998, pp. 2285-2288.