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Comparing Greenhouse Gases

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Abstract

Controlling multiple substances that jointly contribute to climate warming requires some method to compare the effects of the different gases because the physical properties (radiative effects, and persistence in the atmosphere) of the GHGs are very different. We cast such indices as the solution to a dynamic, general equilibrium cost-benefit problem where the correct indices are the relative shadow values of control on the various substances. We find that use of declining discount rate, as recommended by recent research, suggests that the current physical-based indices adopted in international negotiations overestimate the value of control of short-lived gases and underestimates the value of control of very long-lived species. Moreover, we show that such indices will likely need to be revised over time and this will require attention to the process by which decisions are made to revise them and how revisions are announced.

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1. INTRODUCTION

Controlling multiple substances that jointly contribute to climate warming requires some method to compare the effects of the different gases because the physical properties (radiative effects, and persistence in the atmosphere) of the greenhouse gases (GHGs) are very different. As reported by the Intergovernmental Panel on Climate Change (IPCC, 1996), the radiative effect of a part per billion volume (ppbv) increase in the atmosphere concentration differs by 5 orders of magnitude across the different GHGs identified for control (UN FCCC, 1997). At current concentrations a 1 ppbv increase in CO_2 causes an estimated 1.8 x 10^{-5} watt per meter^2 (Wm^{-2}) increase in forcing whereas for HFCs, PFCs, and SF_6 the radiative forcing effect of a 1 ppbv increase is on the order of 0.2 to 0.65 Wm^{-2}. Just on the basis of differences in radiative forcing one would be willing to pay on the order of 10,000 times as much per unit volume to reduce HFCs, PFCs, or SF_6 than to reduce CO_2. Differences in the persistence of these gases in

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the atmosphere are equally large. SF_6 and PFCs decay very slowly with estimated lifetimes on the order of 10,000 to 50,000 years. At the other end of the spectrum, the lifetimes of CH_4 and HFCs are on the order of 10 years.[1] The relevant lifetime of CO_2 in the atmosphere is on the order of 100 years.

An accurate measure of the relative effect of each of these gases is needed so that governments can set the relative price for each so that reductions in climate change can be achieved most cost-effectively. Much of the attention on emissions trading under the Kyoto Protocol is for trading of CO_2 credits among countries or among firms that have been allocated emissions rights. Advocates of a cap and trade system imagine that it might also apply across the various GHGs. In such a circumstance a country or firm that had reduced CH_4 emissions might wish to sell any credit earned to a country or firm to use against its CO_2 emissions. In such a trade, one would need to know what exchange rate to use. If governments set independent targets for each gas then a trading system would result in a market exchange rate. But, if the individual targets were set arbitrarily (without reference to the differential climatic effects of each gas) there would be no reason to expect that the market determined exchange rate would reflect the differential climate effects of the gases. For example, a tight limit on CO_2 combined with a loose limit on SF_6 might result in a market exchange rate of one-for-one, one-for-ten, or one-for-one hundred when we have clear evidence that a ton of SF_6 causes thousands of times more warming than a ton of CO_2 and lasts much longer in the atmosphere. Thus, effective management of these gases require information on the relative effects of each gas to set either individual caps or differential tax rates on emissions of each GHG or to determine the preset rate of exchange among gases.

The current solution to this index problem are calculations made by the Intergovernmental Panel on Climate Change (IPCC, 1996) known as Global Warming Potentials (GWPs). These are calculated by combining purely physical properties of the gases. The basic idea is to calculate the cumulative radiative forcing over time resulting from one unit of the GHG emitted at t = 0. By convention, the GWP index is defined relative to CO_2, the GHG that is the largest direct anthropogenic source of increased radiative forcing. Following Smith and Wigley (2000) the GWP formula can be generally represented as:

$$GWP_x = \frac{\int_0^H q_x(t')dt'}{\int_0^H q_{\mathrm{CO}_2}(t')dt'} \tag{1}$$

where $q_x(t)$ is the unit response function for GHG x. Specifically, $q_x(t) = Q_{impulse}(t) - Q_{base}(t)$ where $Q_{base}(t)$ is the radiative forcing that results from the baseline emissions and $Q_{impulse}(t)$ is the forcing that results when a unit emissions is added at t = 0. Radiative forcing, q_x is a function

[1] We do not consider other climatically important substances such as sulfate aerosols, organic and black carbon (*i.e.* soot), or tropospheric ozone as control of these is not part of current climate negotiations. Sulfate aerosols having a cooling effect whereas black carbon and tropospheric ozone contribute to warming. These substances last in the atmosphere on the order of days or hours and, as such, are not well-mixed in the atmosphere thereby their climatic effects are local and regional. We also do not consider chlorofluorocarbons (CFCs) already subject to control and phase-out under the Montreal Protocol because of their role in destroying stratospheric ozone (*i.e.* creating an ozone hole over polar regions).

of *t* because: (1) a pulse of gas emitted at t = 0 is destroyed or removed from the atmosphere over time through various processes that differ for each of the gases, and (2) the radiative effect of a unit of gas depends on the concentration of the gas (and other gases) in the atmosphere (*i.e.* there is some saturation effect as concentrations become higher). The removal of these gases in the atmosphere depends on complex physical science processes. In actual calculations, models and formulas of varying complexity are used to make estimates and there are omissions on the atmospheric science side of the problem that lead to inaccuracies in the IPCC estimate as has been shown elsewhere (Reilly *et al.*, 1999; Smith and Wigley, 2000) and broad questions remain (O'Neill, 2000).

Here we would like to focus on economic aspects of the greenhouse gas comparison issue. As has been argued elsewhere (Eckaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993) the trace gas index problem can be readily interpreted as an economic problem. As such, the correct comparison index is the relative shadow values of control for each of the greenhouse gases that one derives from the optimal dynamic control problem that balances the cost of controlling each of the greenhouse gases with the damages associated with climate change. Reilly and Richards (1993), hereafter RR, and more recently Manne and Richels (2001), hereafter MR, have moved the furthest to produce empirical estimates of these indices showing their sensitivity to damage estimates and to the assumed discount rate. In principle, the economic approach solves a problem that perplexes the purely scientific approach; *i.e.* what length of time horizon to use and, relatedly, how to balance the fact that reductions today in emissions of a short-lived gas such as CH_4 have a big effect over the next decade or two but little effect over the longer term whereas the benefits of reductions of a long-lived gas are spread out over centuries or millennia. Of course, the economic approach is to put the benefits of reductions in different years in comparable terms (*i.e.* monetize them and compare across time based on the value of consumption today versus consumption in the future—discounting). One can then make direct trade-offs of the benefits of reductions in emissions whose benefits have very different time profiles.

The principle of monetizing and discounting damages as an input into a dynamic cost-benefit analysis is a straightforward way of thinking for economists and was laid out in RR. Some difficult practical modeling and empirical issues arise, however. In this paper, we explore the empirical implications of some of these issues offering several advances over RR and MR. First, in RR the problem was formulated as a partial equilibrium dynamic problem whereas here we formulate the problem in a general equilibrium, Ramsey growth-type model. Second, RR empirically estimated trace gas indices along the reference emissions path rather than along the optimal path. Because there is a saturation effect (declining radiative effect with increased concentrations) the calculated index value depends on the concentrations that, in turn, depend on the future path of emissions.

Third, considerably more progress has been made in developing current estimates of emissions of GHGs and in forecasting future emissions. We are able to use results from a more detailed study (Babiker *et al.*, 2001) to create a reference projection and then use our simpler economic model to solve the optimal GHG index problem. In fact, even the suite of gases has changed. RR considered CO_2, CH_4, N_2O (nitrous oxide), and CFCs (chlorofluorocarbons). CFCs, the major cause of stratospheric ozone depletion, are also greenhouse gases but are not part of international climate change discussions because they are rapidly being phased out of use under the Montreal Protocol. But, HFCs (CFC replacements), PFCs, and SF_6, substances RR did not consider, have been explicitly identified for control under the Kyoto Protocol. RR also did not include a radiation code that included the saturation effect. We include a radiation code derived from complex climate models and we test sensitivity of our results to other specifications. MR modeled the index problem as the optimal solution in a dynamic integrated assessment model but included only three gases, CO_2, CH_4, and N_2O.

Fourth, two of these new gases (PFCs, and SF_6) are those that persist in the atmosphere for 10 to 50 thousand years. As shown in RR, the choice of discount rate can have an important effect on the calculated index when the lifetimes of gases are different. The persistence of CO_2 and CH_4 (~100 years compared with ~10 years) differ substantially but the difference is not unprecedented for some conventional capital investments where discounting is used. For example, large water projects, seaport development, or major transportation investments have lifetimes that approach 100 years but even in these cases economists have questioned whether conventional discounting is appropriate. The difference between 10 to 100 and 10,000 to 50,000 is of a much different order, far outside the range of conventional investment problems. There has been considerable debate about what discount rate to use for climate policy (*e.g.*, Lind and Schuler, 1998) but Weitzman (1998) has recently made the case that, with uncertainty in the discount rate, "the far distant future should be discounted at the lowest possible rate." We consider the implications of this conclusion for the trace gas index question.

In section 2 we present a Ramsey-growth type economic model, simple relationships that capture the basic accumulation of greenhouse gases and that allow us to calculate an index of warming, and a monetized damage function that allows us to calculate the optimal path or reduction and the shadow prices of control for each GHG. In section 3 we discuss the data and parameterization of the model. In section 4 we present our results and show their dependence on different formulations of the discount rate and other assumptions. In section 5 we discuss the policy implications. In section 6 we offer conclusions.

2. AN ECONOMIC GROWTH MODEL WITH GHG EMISSIONS AND CLIMATE DAMAGES

We assume the household chooses consumption and emission profiles to maximize a life time welfare function:

$$W = \int e^{-rt} C_t^{1-\lambda} dt - \theta \int e^{-\rho_t t} (X_t - X0) dt \tag{2}$$

Where C is consumption, X is the aggregate GHG radiative forcing (an approximation of the climate effect), r is the discount rate for consumption, ρ is the discount rate for climate, λ is the coefficient of relative risk aversion, and θ is a coefficient that represents the marginal damages due to climate change.

The optimization is subject to the following set of constraints:

(1) The productive capacity of the economy given by the output technology:

$$Y_t = A L_t^{1-\beta} \ K_t^{\beta} \tag{3}$$

where A is the productivity coefficient, L is labor, K is capital and β is the capital value share.

(2) The absorptive capacity of the economy given by:

$$C_t + I_t = Y_t \tag{4}$$

where I is investment.

(3) Greenhouse gas (GHG) emissions are a side product of the economic activity:

$$E_{tg} = E0_g \left(\frac{Y_t}{Y0}\right)^{\eta_g} \tag{5}$$

where E and $E0$ are the current and benchmark emissions, $Y0$ initial output, and η is the emissions elasticity with respect to output.

(4) The capital stock evolves over time as:

$$K_{t+1} = (1-\delta)K_t + I_t \tag{6}$$
$$K_1 = K0$$

where δ is the depreciation rate and $K0$ is the initial stock.

(5) The GHG stock evolves over time as:

$$M_{g,t+1} = (1-\gamma) M_{g,t} + E_{g,t} + N_g \tag{7}$$
$$M_{g,1} = M0_g$$

where N is the natural GHG emissions, γ is the dissipation rate and $M0$ is the initial emissions stock.

(6) For radiative forcing we use the following for $M_{g,t}$, g = CO_2:

$$X_t = 4.996 \ln(M_{g,t} + 0.0005 M_{g,t}^2) \tag{8}$$

where CO_2 concentrations are in ppm. For the other gases, concentrations are in ppb.

For CH_4:

$$X_t = 0.0406\sqrt{M_{\mathrm{CH4},t}} - 0.5\ln\left[1 + 2\times 10^{-5}(M_{\mathrm{CH4},t} * M_{\mathrm{N2O},t})^{0.75}\right] \tag{9}$$

For N_2O:

$$X_t = 0.136\sqrt{M_{\mathrm{N2O},t}} - 0.5\ln\left[1 + 2\times 10^{-5}(M_{\mathrm{CH4},t} * M_{\mathrm{N2O},t})^{0.75}\right] \tag{10}$$

The formulas for these gases are from (Hansen *et al.*, 2000).

For SF_6, PFCs, and HFCs:

$$X_t = \sum_g \phi_g M_{g,t} \tag{11}$$

where ϕ is the radiative forcing coefficient from the 1995 Intergovernmental Panel on Climate Change (IPCC, 1995).

3. PARAMETERIZATION OF THE MODEL

The model is benchmarked on 1995 economic data from GTAP-E and the 1995 emissions inventories. GTAP-E is a special release of the GTAP data base (Hertel, 1997) that includes physical flows of energy. The discount rates are $r = 0.05$ and ρ is either 0.05 or 0.02 and covers a range of values supported by evidence based on the "descriptive" approach to the discounting (Lind and Schuler, 1998). It is varied over time in some simulations of the model as we describe later. The depreciation rate is 0.05 and the world economy annual growth rate is assumed to be 3%, values supported by the detailed modeling work of Babiker *et al.* (2001). The initial capital stock $K0$ is calibrated from the GTAP benchmark data assuming a capital-output ratio of 3 and the capital value share, β, is computed from the economic data (0.4). Current GHG concentrations are used for $M0$ and the emissions elasticity, η, is computed from the benchmark energy value share and the emissions inventories. The dissipation rates, γ, are calculated as one over the atmospheric lifetime as given in the IPCC (1995). The HFCs and PFCs are families of gases that we represent as HFC-134a and CF_4, respectively. The coefficient of relative risk aversion, λ, is 0.2 and the marginal damage parameter, θ, is calibrated such that the damage from doubling the gas radiative forcing (compared to the pre-industrial level) is 1% of world GDP. This value is based on several attempts to evaluate the monetized damages of climate change as reported in Nordhaus and Boyer (2000) and as reviewed and discussed in IPCC (1996), Mendelsohn (1998) and Reilly (1998).

The economic estimate of GHG index is provided by the shadow value of the emissions stock Equation 7 in relation to that for CO_2. To examine the sensitivity of an economic-based index to these various factors, we first solve the model described above for four cases. *Case 1* solves the model for a 100-year horizon with a constant discount rate of 5 percent. *Case 2* contrasts this case with a declining discount rate. The discount rate starts at 5 percent but declines by one-half percent per 5-year period (the time step of the model) so that after 2050, the discount rate falls to 0. In *Case 3* we then extend the time-horizon of the model to 2200 for the declining discount rate problem of *Case 2*. *Case 4* uses a 100-year horizon and starts instead at a 2 percent discount rate that declines to 0 by 2050.

4. TRACE GAS INDEX RESULTS

4.1 Principal Results and Discount Rate Dependence

The basic results are depicted in **Figure 1**. The index is defined relative to CO_2 and the index value for CO_2 is, by definition 1 in all cases and over all time. We plot results only through 2075 as the period of interest. *Case 1* generates the highest index value for the shorter-lived gases, CH_4 and HFCs, because the relatively high discount rate means that distant damages are largely irrelevant. In *Case 2,* the initial index value for CH_4 and HFCs is about two-thirds that for *Case 1* and the index for the long-lived gases (SF_6 and PFCs) increase by about 50 percent reflecting the fact that the effects of the long-lived gases beyond 2050 and through to 2100 are not discounted. The value of controlling these gases thus rises.

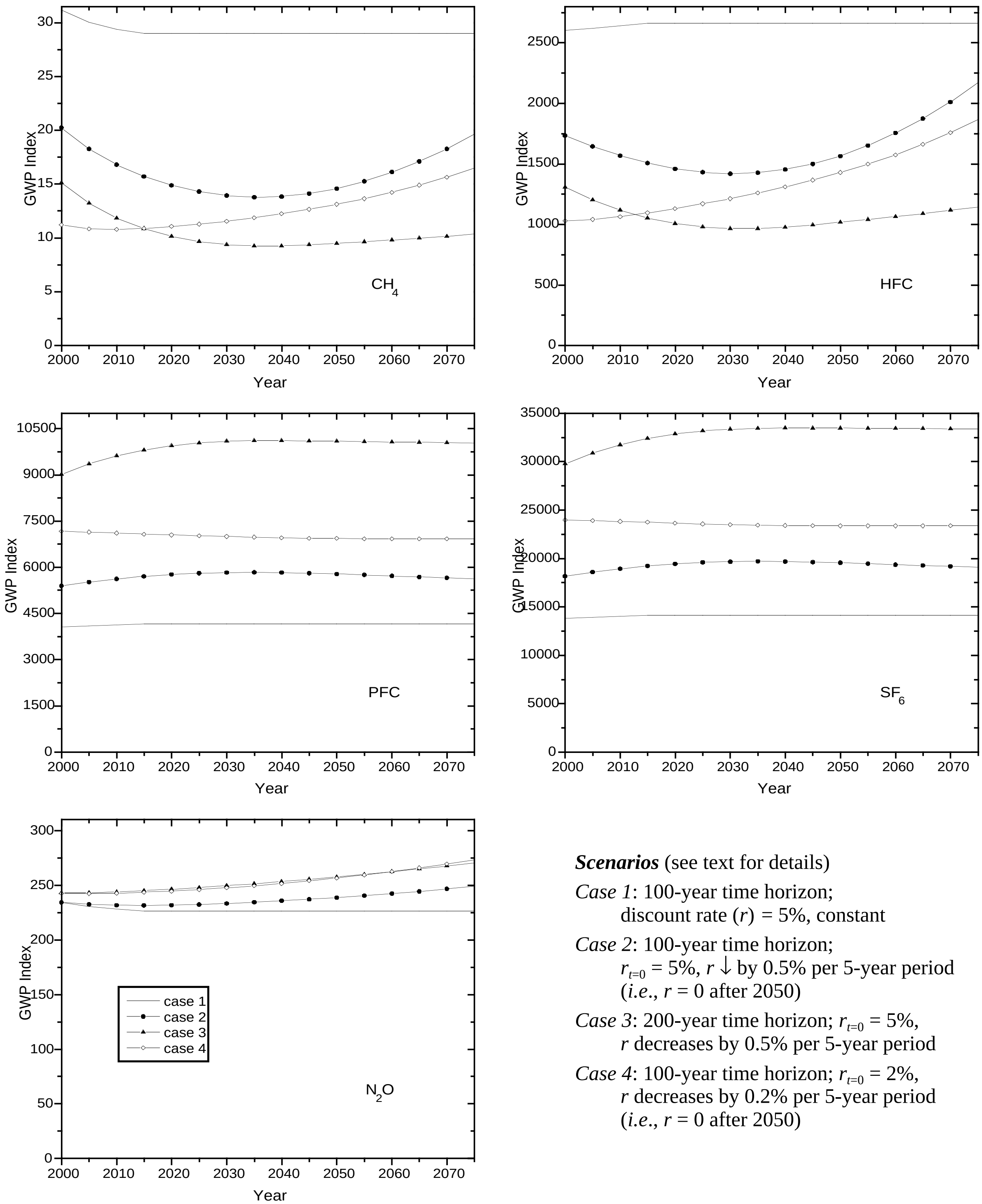

Figure 1. Economic-Based GWP indices: 2000-2075. The HFCs and PFCs are families of gases that we represent as HFC-134a and CF_4, respectively.

Whereas Reilly and Richards (1994) solved analytically for an infinite horizon (though not for an optimal path), solving numerically for an optimal path requires that we choose a finite horizon. For a constant and relatively high 5 percent discount rate this truncation is not important for near-term estimates of the index because damages by 2100 are discounted to essentially zero today. For a declining discount rate, falling to 0 by 2050, this is obviously not the case. Our *Case 3* thus extends the horizon to 2200. This longer horizon largely captures the full effects of CO_2 and N_2O emitted today and on through about 2050. CO_2 and N_2O emitted today will have had, by 2200, 200 years to be removed from the atmosphere. The effect on the index values for CH_4 and HFCs of extending the horizon further than 2200 is limited. We still see effects in the near-term for these gases of the extending the horizon from 2100 to 2200 years as the index for these two gases falls by about one-fourth compared with the 100-year horizon.

The effect of extending the horizon is more substantial for long-lived gases because, with lifetimes of thousands of years they continue to have climatic effects over the 2100 to 2200 period. The index values for these gases more than double. In fact, with a discount rate that falls to zero in the longer-term, the terminal horizon problem underestimates the index for these long-term gases. The very slow dissipation, such that these gases are for practical purposes permanently part of the atmosphere, means that the control value would become very large with a zero discount rate if we could practically extend the model's time horizon to 50,000 years or longer. Thus, with the recent finding that the discount rate for very long horizon problems should decline to near zero, an economic analysis of the index problem gives support for the common-sense notion that we should be truly concerned about these very long-lived gases and do whatever is reasonably practical to keep them out of the atmosphere. This does, however, raise questions about what is the appropriate index value to use in a trading scheme that would allow intergas permit trading that included these long-lived gases.

Our *Case 4* shows the effect of choosing instead a 2 percent discount rate that declines to zero by 2050 with a 100-year horizon. This case is most directly comparable to *Case 2* that also has a 100-year horizon and declining discount rate. The main effect of starting with a 2% rate is to further reduce the index for CH_4 and HFCs because it increases the value of control for all longer-lived gases, including CO_2. The indices for those gases that are even longer-lived than CO_2 increase.

Figure 1 also shows that the time paths of these indices are not constant with a declining discount rate. Here there are two important effects. The indices for the short-lived gases start relatively high, initially decline and then rise whereas the opposite effect occurs with long-lived gases. The early-years time path reflects the sudden introduction of a climate change policy in a forward-looking model. Short-lived gases that have much of their radiative effects compressed in the near-term are a relatively cheaper way to meet the sudden imposition of the control policy. Thus, the optimal control solution is to value these relatively higher in the initial period and the very long-lived gases lower. Once we get to 2030 or so we see a time path that reflects closer to a long-run equilibrium solution.

Perhaps the most instructive part of this part of the exercise is that faced with a sudden imposition of a policy, there is larger value to having the short-lived gases because reductions have larger effects in the short-term. In these model simulations the effect occurs because the 1995 base concentrations are above the optimal trajectory because no policy previously existed to internalize the climate damage effects of GHG emissions. To get back to the optimal trajectory quickly the model uses short-lived gases and this is reflected in their relatively high index value. This is most obvious in *Case 1* where this is the only factor causing significant variation over time in the index values. The non-declining discount rate of 5% decreases the value of the long-term future so substantially that the non-linearity introduced by the saturation effect is not important for the time path. This result of a sudden start-up for the model can be more broadly interpreted as indicative of the value of short-lived gases to deal with a sudden, unanticipated need to slow climate change. The high initial index value for short-lived gases depends in part on our assumption of constant marginal damages with respect to concentration. An implication of this assumption is that there are damages (perhaps largely unrecognized) occurring now from climate change. If, instead, one believes that damages will only occur after a substantial increase in emissions from current levels as some have suggested (*e.g.*, Mendelsohn, 1998), then the urgency of controlling climate change in the near-term would be reduced and we would not expect the initial effects of relatively higher index values for short-lived gases but rather see patterns exhibited after 2030.

4.2 Sensitivities to Other Assumptions

There are a number of assumptions and parameters to which our indices are sensitive. These include the radiation equations, economic growth, the damages of climate change, and the coefficient of relative risk aversion. In this section, we show results based on tests of the sensitivity of the indices to these variables. We test the sensitivity by varying each of the parameters or assumptions, one-by-one, from the values used above. We vary parameters to represent the range observed in the literature. We report a limited set of results, focusing on those that show the greatest sensitivity.

4.2.1 Radiative Effects

Important sensitivities from the science side of the climate issue are the equations that relate the radiative forcing as a function of atmospheric concentrations of greenhouse gases. These equations describe how the radiative effect of the greenhouse gas falls as concentrations increase. This effect occurs because with higher concentrations a saturation effect occurs so that additional increments of the gas are less powerful at trapping heat. The effects of CH_4 and N_2O are interdependent because they absorb heat at similar wavelengths. The reference set of equations (as in Eqs. 8–10) were those from Hansen *et al.* (2000) who fitted reduced form equations to results of the Goddard Institute of Space Studies (GISS) model, labeled “New GISS” in **Table 1**. They thus reflect the complex interactions and specifications of the GISS model. To test the sensitivity of results we compare these with specifications from Hansen *et al.* (1988) that were the basis for the specification reported in the1995 Intergovernmental Panel on Climate Change (Houghton *et al.*, 1995), and based on older GISS results, labeled as “1995 IPCC” in Table 1. We also compare these to an analysis by Myhre *et al.* (1998) that is the basis for revised estimates presented in the Third Assessment Report of the IPCC (2001), labeled “2001 IPCC” in Table 1. The *Case 1* and *Case 3* labels correspond to the earlier cases of a 5% constant discount rate with a 100-year horizon and a 5% declining discount rate with a 200-year horizon.

Table 1. Sensitivity of Results to Radiative Specifications for CO_2, CH_4 and N_2O

Year	2000	2025	2050	2070
CH_4				
New GISS-Case 1	31.2	29.0	29.0	29.0
2001 IPCC-Case 1	29.0	27.2	27.2	27.2
1995 IPCC-Case 1	27.5	25.5	25.5	25.5
New GISS-Case 3	15.1	9.6	9.5	10.1
2001 IPCC-Case 3	14.6	9.5	9.5	10.3
1995 IPCC-Case 3	13.5	8.7	8.6	9.2
N_2O				
New GISS-Case 1	234	226	226	226
2001 IPCC-Case 1	217	211	211	211
1995 IPCC-Case 1	249	242	242	242
New GISS-Case 3	243	248	257	267
2001 IPCC-Case 3	225	229	239	249
1995 IPCC-Case 3	257	261	269	278
PFCs				
New GISS-Case 1	4060	4150	4150	4150
2001 IPCC-Case 1	4380	4440	4440	4440
1995 IPCC-Case 1	3920	3400	4000	4000
New GISS-Case 3	9010	10030	10080	10040
2001 IPCC-Case 3	8700	9640	9690	9660
1995 IPCC-Case 3	7600	8270	8190	8060

Equations 8–10 describe the radiative effects of CO_2, CH_4 and N_2O. Using the GWP convention, CO_2 is the numeraire and its value is 1.0 in all periods. Thus, even though the equations describing the radiative effects of PFCs, HFCs, and SF_6 are unchanged, their index value changes. The change in the index for the PFCs results only from the change in the CO_2 numeraire, and the effect of the changes in CO_2 radiative forcing is similar across gases. One interesting aspect of this sensitivity analysis is to compare the 1995 and 2001 IPCC results. This comparison shows that the PFC index we calculate is higher by 12% (*Case 1*) or 14% (*Case 3*) in the 2001 IPCC formulation, indicating that the radiative effects of CO_2 are that much less. The percentage changes for HFCs and SF_6, though not reported here, are identical to the PFC changes as one would expect because the same numeraire change is causing the index value to change for each gas. An increase is also expected as Myhre *et al.*(1998) indicated that one reason for revising the estimated equations was that several studies found lower radiative forcing for CO_2. The greater increase under the declining discount rate case indicates that, under the reformulated radiation code, the difference is reduction in radiative forcing due to CO_2 is greater in the future when concentrations are higher.

The New GISS formulation used in our reference set of cases results in only a 4% higher value for the PFC index in 2000 compared with the 1995 IPCC for *Case 1*, but 20% higher in the *Case 3* scenario. The reason is that the effects of CO_2 under low concentrations (like those we will experience over the next few decades) differ relatively little from the 1995 IPCC but the difference is more substantial at higher concentrations like those likely to be experienced in the future; *i.e.* the New GISS has a stronger saturation effect. The stronger saturation effect has a bigger impact on the *Case 3* results because declining discount rate weights the distant future heavier than the constant discount rate used in *Case 1*.

The changes in the CH_4 and N_2O indices are the combined effects of changes in the equations describing the radiative effects of each of these gases and that of the change in the numeraire gas, CO_2. We have already seen for the cases of PFCs, HFCs, and SF_6, that the effects of changing CO_2 alone would be to increase the index values by the same 12% (*Case 1*) or 14% (*Case 3*) for each gas as for the 2001 IPCC as compared with the 1995 IPCC. As shown in Table 1, however, the increases for CH_4 for the similar cases is only 5% (*Case 1*) and 8% (*Case 2*). This is less than the 12 and 14% increase due to CO_2. The respecified CH_4 equation is thus also for less radiative effect over the discounted lifetime of the gas compared with the 1995 IPCC estimate but not as much less as for CO_2. The index value for N_2O declines by 9 and 13%. Thus, the reestimated N_2O equation reduces the radiative effects of N_2O even more than CO_2. As shown in Equations 8–10, the saturation effect for CH_4 and N_2O interacts so that increases in concentrations of CH_4 (N_2O) also reduces the radiative effect of N_2O (CH_4).

The New GISS results as compared with the 1995 IPCC show an increase in the index for CH_4 of 13.5% compared with the 1995 IPCC. This is greater than the 3.5% increase for PFCs for the New GISS, indicating that for the near term horizon (heavily weighted in *Case 1* because of the 5% constant discount rate), CH_4 has stronger radiative effect in the New GISS as compared with 1995 IPCC formulation. For *Case 3*, however, the New GISS increase for CH_4 is 12.8% compared with the 1995 IPCC. This is less than the 18.6% increase due to the changed CO_2 formulation. Thus, the New GISS formulation for methane has relatively stronger radiative effects in the short-term but has a strong saturation effect as well. We estimate a reduced index value for N_2O based on the New GISS formulation as compared with the 1995 IPCC but the reduction is not as strong as for the 2001 IPCC.

4.2.2 Sensitivity to Economic Variables

We tested the sensitivity of the index results to economic damages due to climate change (0.5% and 2% damages at a doubling), the rate of economic growth (1% and 5% per year growth), and λ (0 and 0.5), the coefficient of relative risk aversion (CRRA). We report in **Table 2** the sensitivity results and show in the first two lines of the table the GWP indices reported by the 1995 and 2001 IPCC. The sensitivities we report do not substantially affect the time path for the index values and so we focus on the single year 2010 as this is the first commitment period identified in the Kyoto Protocol. The basic result shown in Table 2 is that the effects on the calculated indices were relatively small for all of these sensitivities even though these values span fairly wide ranges relative to estimates in the literature. For example, worldwide GDP growth of as little as 1 percent or as much as 5 percent over a century would be extreme results by historical standards or as evidenced in long term projections. Economic damages of 0.5% to 2% of GDP at GHG doubling reflects the range in the literature (Nordhaus and Boyer, 2000) but these estimates remain highly uncertain (Reilly, 1998).

Table 2. Sensitivity of Year 2010 GHG Index to Economic Assumptions

	CH_4	N_2O	PFCS (CF_4)	SF_6	HFC-134a
1995 IPCC GWP [a]	21.0	310	6500	23900	1300
2001 IPCC GWP [b]	23.0	296	5700	22200	1300
Reference [c]	17.0	230	5330	18000	1590
Low Economic Growth (1%/yr)	16.2	220	5040	17000	1500
High Economic Growth (5%/yr)	17.8	248	6080	20500	1680
Low Damages (0.5%)	15.4	235	6210	20900	1440
High Damages (2%)	16.6	230	5430	18300	1560
Low CRRA (0):	17.0	230	5350	18100	1600
High CRRA (0.5):	16.6	226	5210	17600	1550

[a] As reported by FCCC/SBSTA/1999/L.5
[b] IPCC, 2001
[c] Reference is 3.0 percent GDP growth, damages at 1% of GDP at an equivalent doubling, a CRRA of 0.2, and a declining 5% discount rate (*i.e. Case 2* assumptions described in the text)

The sensitivity to the CRRA was negligible for the low case, often rounding to no difference. For the high case, the sensitivity was on the order of 3 percent. These changes are quite small relative to other uncertainties. Sensitivity to economic growth was greater. It was on the order of 5% for CH_4 and N_2O and 14% for other gases. The index value is lower for all gases with low economic growth and higher with high economic growth. These results are traceable to the strong CO_2 saturation effect, a weaker saturation effect for CH_4 and N_2O, and no saturation effect for the other gases. More rapid economic growth leads to higher emissions and higher near-term concentrations of all gases. With CO_2 saturating quickly the value of abating emissions of CO_2 today is less because a molecule of CO_2 remaining in the more CO_2-saturated atmosphere will have less radiative effect. Thus, the indices we calculate with higher GDP growth place higher value on mitigating other gases subject to less saturation (CH_4 and N_2O) or no saturation.

The damage sensitivities are the greatest among the economic variables we examined, although results are not nearly as sensitive as they are to the discount rate formulations. The somewhat surprising aspect of these sensitivities is that for CH_4 and HFCs (the short-lived gases) either a higher or a lower damage estimate reduces the index value. In contrast, for the longer-lived gases both a higher and lower damage estimate increases the index value. Two opposing factors generate this non-monotonic behavior. One effect is that with higher damages the optimal path is for greater reductions in radiative forcing. Greater reductions are achieved quickly with the short-lived gases so that one effect of rising damages is to increase the value of reducing short-lived gases. This effect dominates when estimates of damages are in the 0.5 to 1.0% of GDP range. The other effect involves the fact that damages are non-linear with respect to increases in ***emissions*** even though we represent damages as linear with respect to ***radiative forcing***. The non-linearity of emissions and damages occurs because of the strong saturation effect of CO_2 as concentrations rise particularly in the New GISS radiation code. As a result, marginal damages due to emissions of CO_2 fall with increasing emissions. Marginal damages for other GHGs ***relative to those*** from CO_2, the numeraire gas, are thus rising. This occurs even though marginal costs fall absolutely for CH_4 and N_2O where the saturation effect is weaker than that of CO_2. At higher marginal damages, the non-linearity of damages with respect to emissions outweighs the need for more action. This effect dominates once damages approach 2% of GDP. These two effects combine to give and inverted U-shape for the short-lived gases and the U-shaped for long-lived gases for indices as a function of damage based on the data in Table 2.

5. DISCUSSION AND POLICY IMPLICATIONS

The model we have developed integrates economic and physical components of the climate issue, providing a basis for comparing GHGs for policy purposes. The approach we developed is a significant advance over previous economic modeling of the GHG index problem buts some caveats remain, particularly in our representation of the physical science aspects of the index problem. These caveats and our finding that the optimal indices vary widely under reasonable assumptions (the optimal GHG index can vary by a factor of 2 or 3) suggest some directions for further research. Even with these caveats and uncertainties there are some important policy implications.

First, what can we say about the appropriateness of the GWPs specified in the Kyoto Protocol? The appropriate discount rate to use for climate policy decisions has been a subject of much disagreement (IPCC, 1996; Lind and Schuler, 1998; Cline, 1998). There have been two competing bases for establishing appropriate discount rates, termed the descriptionist and prescriptionist approaches. The former would consider the opportunity cost of investing in GHG reduction as the return on investment elsewhere in the economy. While there are many difficulties in empirically evaluating the opportunity cost, this camp tends to conclude that a discount rate on the order of 5 percent is appropriate as this rate is consistent with saving and investment behavior in the economy. The latter camp points out that the observed market rate is the sum of the pure rate of time preference and the marginal return on capital times the growth rate of per capita income. This camp points out that the pure rate of time preference is the current generations willingness to forego income for future generations and, on equity grounds, make a case for this component of the discount rate to be zero. That the choice of the discount rate affects how much we should do currently was the concern of the IPCC (1996), Lind and Schuler (1998), and Cline (1998). Our work shows that choice of discount rate also strongly affects whether one should emphasize reductions in long-lived or short-lived gases. The 5 percent discount rate is consistent with the descriptionist view. Adopting this view, the current 100-year GWP index for CH_4 of 21 is far too low; our estimate (*Case 1*) is 32, increasing the value of CH_4 reductions by over 50 percent. The prescriptionist view of the discount rate makes a case for a far lower discount rate. Our discount rate of 2 percent (*Case 4*) is illustrative, although cases are made for discount rates of 1 percent or lower. If the right discount rate is 2% or lower, the IPCC GWP for CH_4 overvalues methane reductions by 60 percent or more. Instead, more weight should be place on longer-lived gases because these reductions will benefit future generations more.

The Weitzman (1998) case for a declining discount rate is in many respects much simpler. He recognized that the algebra of calculating the rate means that, with uncertainty, lower values dominate the further ahead in time one looks. Our *Case 2* represents the Weitzman (1998) discount rate story, declining to zero by 2050 from 5 percent. The result is that the index value for

CH_4 falls (*Case 2* compared with *Case 1*) and the value of long-lived gases increase. The year 2000 value for CH_4 of 20 under the declining discount rate is very close to the IPCC GWP for CH_4. The values we estimate for HFCs of 1750, PFCs of 6800, and SF_6, 24000, are also similar to the IPCC GWPs for these gases. This similarity is not too surprising as one way to interpret the 100-year IPCC GWPs is that the discount rate is zero for the first one hundred years (similar to our assumption of zero for the last 50 years) and we truncate the our model at 100 year horizon.[2] One cannot, however, use our *Case 2* and the Weitzman (1998) discount rate argument to justify the IPCC estimates. As *Case 3* illustrates, the apparent agreement is a result of terminating the horizon at 2100. Extending it to 2200 in these cases increases the index for long-lived gases (PFCs and SF_6) by 25% and decreases the value for short-lived gases (CH_4 and HFCs) by 25%.

A second broad result is that the optimal index for each GHG changes over time. The Kyoto Protocol includes a provision that the GWP index currently prescribed for comparing gases can be revised for future commitment periods. Our findings indicate that for a given set of assumptions (discount rate, damages) the optimal index values chosen now would need to be adjusted over time even if there were no revisions to our scientific understanding of the radiative properties or the persistence of these gases in the atmosphere. The change over time varies across the gases depending on the discounting approach used. The change can be as much as 30 percent over 30 years and is particularly pronounced in the declining discount rate cases. If the index value indeed needs to be adjusted by these magnitudes it would have implications for decisions about GHG reductions by firms. For example, a firm that invested in a project with a 20-year lifetime that reduced methane emissions might, according to our calculation be able to value credits generated at the end of the period 30 percent less (relative to a CO_2 credit) than those generated at the beginning. Put another way, such a methane project would have to generate 43% greater [1/(1–0.3)] methane reductions at the end of the project to offset the same amount of CO_2 as at the beginning of the project. Revisions in our understanding of science of greenhouse gases may also lead to revisions in GHG indices as has occurred between the 1995 and 2001 IPCC reports or as indicated by the sensitivity of the indices to equations specifying radiative forcing.

One might dismiss the difference between 30 and 20 for the index value for CH_4 as a small given that the differences among indices for the different GHGs vary by orders of magnitude. But the comparison among different GHGs is not the comparison that is important for investment decisions. A firm making a decision to invest in emissions reduction of a particular GHG is concerned with the price path of that GHG. Revisions in GHG indices of the magnitude we estimate will have important effects on the value of emissions reduction investments. Some firms and countries would gain from revisions in one direction while others would lose. There will thus be a need to assure that the institution charged with evaluating and revising these indices is insulated from pressure that might provide special advantage to some countries or participants. In terms of economic consequences of such revisions should a trading system exist, one might liken the announcement of a change in indices to a central bank announcement of a change in

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[2] Our physical science component for trace gas lifetimes is highly simplified and thus another possible source of difference (although the simplified parameters are based on the IPCC summary data). We also consider saturation based on reduced form radiation codes and solve for an optimal path (whereas IPCC does not consider the future path dependence of their calculations) instead estimating the values based on a pulse emitted today with current background concentrations of other gases.

interest rates. Such changes immediately make some investments more valuable and others less, and are watched closely and anticipated. For central bank decisions, there are also strong efforts to guard against the use of inside information for personal gain and to make announcements widely available to all market participants at the same time. The current IPCC process does not appear to have such safeguards but these will have to be attended to if serious economic policies are put in place that depend on these indices.

A third general consideration is that the very long-lived gases may require special considerations. There has been a tendency to consider the so-called industrial gases (PFCs, HFCs, and SF_6) together because they are high GWP gases. Their high GWPs values result from the high radiative forcing of a molecule of each gas rather than from a consideration of their atmospheric lifetime (GWP calculations truncate any effect beyond 100 years so very long lifetimes are irrelevant to the IPCC calculation). By focusing on the discount rate and the time horizon problem more specifically our results show that the relatively short-lived HFCs are more readily compared with CH_4. Because of the fundamental difficulties of valuing impacts of a pollutant that remains in the environment for tens of thousands of years, the long-lived nature of PFCs and SF_6 is perhaps a reason to consider them on a different basis than the shorter-lived greenhouse gases. A high radiative forcing rate per molecule does not, by itself, give reason to identify the gas for unique policy treatment as considerations of widely different radiative effects involves little more than application of a multiplicative factor. The central issue of difficulty in comparing gases is the widely different lifetimes.

One of the caveats of our work is that we have represented persistence of these gases in a highly simplified manner. For CO_2 and CH_4, in particular, there are quite complex methods by which these gases are removed from the atmosphere. CO_2 is taken up by the ocean and by terrestrial systems and uptake depends directly on the concentration of CO_2 in the atmosphere but also on the concentrations of all GHGs through the effect of changing climate on ecosystems and on ocean uptake. CH_4 is destroyed in the atmosphere and the rate of destruction depends on the concentration of CH_4 and both the natural level and anthropogenic emissions of other pollutants, many of which are related to fossil energy combustion (Reilly *et al.*, 1999). Thus, the lifetime of CH_4 depends on air pollution policy, details of projections of energy use and urbanization, and on the impact of climate policy on energy use and resultant changes in other air pollutants. It is not possible at this point to embed highly complex models of atmospheric chemistry, terrestrial and ocean sinks, and the coupled ocean-atmosphere needed to project climate change in a suitably complex forward-looking model of the world economy. Techniques for producing summary functions of these complex models have been developed and have been used for uncertainty analysis (*e.g.*, Webster and Sokolov, 2000). This suggests that suitable summary functions can be embedded in a forward-looking economic model such as we have developed here or in a more complex computable general equilibrium models. We have also represented the links between radiative effects and damages very simply such that the inertia effects of the ocean are not accounted for and this might have some effects on the results.

6. SUMMARY

The non-CO_2 GHGs are an important part of the climate problem and a critical component of a climate solution. Central to the issue of a strategy to control them is the issue of how to make trade-offs between reductions in one gas versus another. We re-examined the GWP issue, constructing economic measures of such an index based on a simplified description of the physical and economic system. The Intergovernmental Panel on Climate Change continues to develop GWPs as preferred indices for comparing greenhouse gases. This preference appears to be driven by the belief that physical properties are knowable or subject to scientific resolution whereas assessments of economic parameters such as discount rates or damages due to climate change are too problematic to assess. However, measures that avoid explicit consideration of these economic factors simply make implicit and arbitrary assumptions about the economic parameters. As pointed out by Reilly and Richards (1993) the current IPCC approach implicitly assumes a discount rate of zero for the first 100 years and infinity after 100 years. While there is substantial debate in the economics community with regard to the appropriate discount rate, there is no support in economics of which we are aware for using the discount rate implied in the IPCC formulation. Instead, the argument centers on what positive constant rate to use or, as argued in recent research, whether the discount rate should decline to very low levels in the long term. In other words, the IPCC's implicit discount rate is an extreme opposite formulation of that suggested by recent economic work.

It is also unavoidable, because of saturation of the radiative effects of greenhouse gases, that an accurate index must consider the future path of emissions. Here, we showed that this effect depends on the degree of saturation effect that occurs, where there remains differences among scientific specifications, as well the rate of emissions growth which depends on economic growth. This aspect of the problem raises the very difficult issue that the "correct" set of indices depends not only on the emissions projectory which is, itself, a policy decision. We modeled the optimal policy response for a given set of growth and damage assumptions and thus determined the set of indices consistent with that optimal policy. While the set of indices we derive are thus optimal if the optimal control policy is followed, they will not be accurate if the world chooses a different control policy.

The optimal policy and the set of indices consistent with it also depend on economic damages and assessment of damages remains highly uncertain. The Kyoto Protocol has focused much attention on the near-term emissions of greenhouse gases and much other discussion would like to simplify the problem as determining a long-run atmospheric concentration target. This narrowing of the discussion is neither consistent with the UN FCCC nor is it operational. GWPs themselves look beyond atmospheric concentrations to radiative forcing. We read the UN FCCC Article 2 objective to necessarily include a consideration of the damages of climate change and the gas index problem, fundamental to making climate policy work, must thus consider damages. A concentration target is only a means toward this end, and not well-defined without defining the end. Moreover, we read the concern with sustainable economic development to necessarily require a balancing of mitigation costs and effects of climate change. Thus, it would seem narrow to lose cite of the broader goals of the FCCC that are focused on avoiding damages. For that reason, we need to continue to examine the implications of using the IPCC GWP indices that ignore damages and to develop methods that are able to consider damages. The central issue about discount rate differences, which have large effects on our estimated indices, is how to compare near-term and far future effects of climate change. The climate change issue is often characterized as one of protecting against relatively far in the future damages. If this is, in fact, an accurate portrayal of the issue then we need to value the long-lived gases more highly and we need to avoid an index calculation that completely ignores the long-term effects of gases.

Our research is not the final answer on the GHG index issue. Much more effort is needed to successfully integrate the science and economic components of the problem. We believe, however, that our work suggests that the failure of IPCC calculations to include economic considerations leads to indices that over-value reduction (by perhaps one-third) in short-lived gases (CH_4 and HFCs) and undervalue reductions (by one-half or more) in the very long-lived gases (PFCs and SF_6). The long-lived gases present special problems because of the difficulties of evaluating very long-term problems. Rather than ignoring the far distant future by truncating GWP calculations at 100 years, the near permanency of these gases in the atmosphere need to be considered carefully in policy design. The efficiency of a trading system that allows trades reductions between a gas that lasts for 50,000 years and one that last 10 years depends on getting the exchange value right. Finally, both scientific and economic understanding will suggest the need to change these indices over time, a fact recognized in the Kyoto Protocol. Once a control regime is in place, however, any such change will have substantial economic effect. It will be necessary for an intergovernmental institution to announce such changes. We likened the announcement of changes in such indices to announcements by central banks to change interest rates. It will be necessary for market participants to have the same high degree of trust in the intergovernmental institutions that announce changes in GHG indices as they do in central banks as these indices become central in a global greenhouse gas control regime. It is not yet clear that the economic consequences that might be at stake in such changes are yet recognized by the IPCC, where these decisions are currently made.

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