Comparing Greenhouse Gases for Policy Purposes*

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In order to derive optimal policies for greenhouse gas emissions control, the discounted marginal damages of emissions from different gases must be compared. The greenhouse warming potential (GWP) index, which is most often used to compare greenhouse gases, is not based on such a damage comparison. This essay presents assumptions under which ratios of gas-specific discounted marginal damages reduce to ratios of discounted marginal contributions to radiative forcing, where the discount rate is the difference between the discount rate relevant to climate-related damages and the rate of growth of marginal climate-related damages over time. If there are important gas-specific costs or benefits not tied to radiative forcing, however, such as direct effects of carbon dioxide on plant growth, there is in general no shortcut around explicit comparison of discounted net marginal damages.

INTRODUCTION

David Wood understood early on both the high economic stakes involved in debates about global climate change and the potentially huge contribution that careful and objective economic analysis could make to those debates. While I was serving on the Council of Economic Advisers and concerned with climate change policy, David was actively and effectively building interest in climate change among energy economists at MIT and elsewhere. He and I talked about the economics of global change several times

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during 1990 and the early spring of 1991. We agreed about many things, including the ongoing fusion of energy and environmental policies that this issue exemplifies, but we argued about the subject of this paper. I like to think that David would have found my ideas more persuasive in their present form.

THE PROBLEM

In its first report, Working Group I of the Intergovernmental Panel on Climate Change (the IPCC) observed that

> The earth's climate is dependent upon the radiative balance of the atmosphere, which in turn depends upon the input of solar radiation and the atmospheric abundances of radiatively active trace gases (i.e., greenhouse gases), clouds and aerosols. (IPCC, 1990, p. 7)

Global anthropogenic emissions of the various greenhouse gases are not in fixed proportions.[1] Thus, for instance, the ratio of total methane (CH_4) emissions to total carbon dioxide (CO_2) emissions caused by human activity can be affected by a variety of governmental and intergovernmental policies. It follows that the design of an efficient global policy aimed at slowing the rate of climate change would necessarily involve decisions on how much, over time, to spend on the margin to reduce CH_4 emissions and how much to spend to reduce CO_2 emissions. This choice in turn must logically reflect the marginal damages associated with emissions of each kilogram of CH_4 and CO_2.

As the intensity, as well as the substance, of the debate on global climate change makes clear, future damages attributable to current greenhouse gas emissions are highly uncertain. This reflects uncertainty about at least (a) how changes in today's emissions would affect future atmospheric abundances of greenhouse gases and thus future radiative forcing, (b) how changes in the time-path of radiative forcing would affect future climates, and (c) how changes in future climates would affect some appropriate measure of human welfare. Perhaps because the second and third of these sources of uncertainty have seemed particularly important and intractable and because damage analysis involves difficult problems of economic valuation, a number of authors have proposed schemes for comparing the relative values of reducing emissions of greenhouse gases that reflect only atmospheric abundances and their radiative forcing implications.

1. Here and in what follows "greenhouse gases" should be understood to include both radiatively active gases and aerosols as well as other gases and aerosols that affect the formation or destruction of such gases and aerosols.

This essay argues that comparisons among greenhouse gases that are useful for analysis of abatement policies cannot be made without significant economic input; the physical sciences cannot supply all necessary information. If greenhouse gas comparisons are to inform policy design, they must be ultimately based on analysis of marginal costs and benefits. As the next section demonstrates, it follows that comparisons which begin and end with summaries of contributions to radiative forcing over time have no welfare-economic or policy-analytic justification. The section that follows then shows that under certain assumptions, comparisons of discounted marginal damages reduce to comparisons of appropriately discounted marginal effects on global radiative forcing. The welfare-economic foundations developed there can support rigorous evaluation of alternative discount rates.

The final section considers the implications of relaxing two key assumptions. First, if changing concentrations of individual greenhouse gases produce important costs or benefits that are unrelated to global radiative forcing, explicit calculations of discounted net marginal damages cannot in general be avoided. In particular, if the effects of changes in atmospheric concentrations of CO_2 on plant growth are economically important, it will generally be impossible to make policy-relevant comparisons between CO_2 and other greenhouse gases without explicit computation of gas-specific marginal discounted net damages, including those associated with CO_2 fertilization. Second, following essentially all the relevant literature, the formal analysis that follows does not explicitly consider uncertainty. Some of the issues that would be encountered in doing so are also discussed in the last section of this paper.

STARTING WITH RADIATIVE FORCING

Because none of the relevant physical, chemical, or economic relationships can be guaranteed to be linear, and some are clearly nonlinear, the analysis here focuses on derivatives with respect to gas-specific emissions evaluated along some baseline economic/environmental trajectory. Let $R(\tau)$ be instantaneous radiative forcing (the net radiative flux change at the tropopause, usually measured in watts per square meter) at time τ, let $E_i(0)$ be emissions of gas i (usually measured in kilograms) at time 0, perhaps the present, for $i = 1, \ldots, N$, and let

$$\partial R(\tau) / \partial E_i(0) \equiv \alpha_i(\tau), \qquad \tau \geq 0,\ i = 1, \ldots, N. \qquad (1)$$

For any i and τ, $\alpha_i(\tau)$ depends on the instantaneous radiative forcing associated with increases in the atmospheric concentration of gas i, on the dynamics of removal of gas i from the atmosphere, and on the impact of increases in the concentration of gas i on the concentration over time of other greenhouse gases and their precursors. These functions are often thought of as inputs to economic analysis, but this is incorrect. The marginal radiative forcing effect of increasing the concentration of any one gas depends on initial concentrations of that gas (because of saturation of absorption bands) and on initial concentrations of other gases (because of chemical interactions and overlap of absorption bands). Since these initial concentrations at any time depend on earlier emissions, *the* $\alpha_i(\tau)$ *functions inevitably depend to some extent on an explicit or implicit long-run economic forecast*. It also follows that the α_i functions may depend importantly on what date is taken as time zero and on the impact of any large-scale emissions reductions policies.

The most frequently-cited approach to comparing greenhouse gasses is the index of global warming potential (*GWP*) presented by Lashof and Ahuja (1990) and by the IPCC (1990, 1992):

$$GWP_i = \frac{\int_0^T \alpha_i(\tau)\, d\tau}{\int_0^T \alpha_1(\tau)\, d\tau}, \qquad i = 1, \ldots, N, \tag{2}$$

where T must be specified and, by convention, gas 1 is CO_2. Thus $GWP_1 \equiv 1$, and the idea is that if $GWP_2 = 2$, for instance, then one can argue that reducing emissions of gas 2 is twice as valuable, kilogram for kilogram, as reducing emissions of CO_2.

The most obvious problem with the *GWP* measure is that the horizon, T, is completely arbitrary. The choice of horizon can be important in this setting because the atmospheric lifetimes (half-lives) of the various greenhouse gases differ substantially. The second IPCC report (1992, p. 56), for instance, lists estimated lifetimes that vary from "days" (for NO_x) to "$>$500" years (for CFC-14 and CFC-116).

The first IPCC report (1990, p. 60) dealt with the lack of any well-defined, defensible procedure for choosing T by showing values of a set of GWP_i for $T = 20$, 100, and 500.[2] The corresponding *GWP*s for HCFC-123, which has an estimated lifetime much shorter than that of CO_2, are 310, 85, and 29. Considering only major greenhouse gases, the corresponding *GWP*s shown

2. The second IPCC report (1992) acknowledged the severity of uncertainties attached to the "indirect effects" of emissions of several greenhouse gases and did not present "total" GWPs comparable to those in the first report.

for methane (CH_4) are 63, 21, and 9.[3] Since 20 years is clearly too short an horizon for this problem, while 500 years seems an awfully long time in any context, the reader's attention is naturally drawn to $T = 100$ as some sort of reasonable compromise. This is an old trick: drafters of decision memoranda in the White House learn quickly to fight to have their preferred choice in the middle of the list of options presented. Any of a wide range of values of T can be made to appear a reasonable compromise in this fashion.

Moreover, some have argued that extreme values of T should be used instead of compromise values. Hammond, Rodenburg, and Moomaw (1990, p. 705) advocate treating one unit of gas i at time zero as equivalent to $\alpha_i(0)/\alpha_1(0)$ units of CO_2. They argue that using only very short-run changes in radiative forcing serves to tie "observable current results directly to policy actions...." At the other extreme, Smith and Ahuja (1990) seem to argue that it is most appropriate to consider the total effects over time of current emissions, and this seems to imply setting $T = \infty$. Nordhaus (1991) presents only this measure in his recent survey.

Lashof and Ahuja (1990, p. 531) note that "current radiative forcing may be considered more important from a policy viewpoint than radiative forcing occurring in the distant future..." Accordingly, they consider discounted *GWP* (*DGWP*, say) measures based on discounted integrals of the $\alpha_i(\tau)$ functions:

$$DGWP_i = \frac{\int_0^\infty \alpha_i(\tau)\, e^{-r\tau}\, d\tau}{\int_0^\infty \alpha_1(\tau)\, e^{-r\tau}\, d\tau}, \qquad i = 1, \ldots, N, \tag{3}$$

where r is a discount rate that must be specified. Nordhaus (1990) appears to have arrived independently at this same approach.

The use of a fixed horizon as in (2), with everything occurring before T treated identically and everything after T ignored, has no support in economic theory. Because of this, T is arbitrary in a fundamental sense: there are no sound economic arguments that could be used to fix its value.

On the other hand, discounting cash flows — either actual cash flows or values of costs and benefits of various sorts — or utility flows over an infinite horizon is commonplace and easily justified. Thus the main problem with (3) is

3. The second IPCC report (1992, p. 56) indicates that these numbers incorporate the effects of a typographical error. The corresponding numbers given there for the direct effects only of CH_4 are 35, 11, and 4.

different: it applies discounting to a physical quantity, incremental radiative forcing, that is only by coincidence proportional to either an actual or potential stream of cash or utility over time. As Eckaus (1992, p. 27) puts it, "Adding up physical measures of radiative forcing in different periods resulting from emissions at different times and places is, in an economic policy sense, like adding apples and oranges: it cannot be done." Because discounting has no economic rationale here, there is no way to apply economic analysis to the determination of an appropriate value of r. Thus, though (3) has a more familiar and defensible weighting than (2), it is in the end equally arbitrary because there is no principled way to fix r.

ENDING WITH RADIATIVE FORCING

This section considers comparisons based on the relation between changes in quantities of emissions at time zero, the $E_i(0)$, and $D(t)$, the dollar value of damages at time t caused by climate change. As above, the analysis deals with derivatives along some baseline economic/environmental trajectory; here the focus is on derivatives of discounted damages with respect to emissions. Nordhaus (1991), Reilly (1991), Uzawa (1991), Eckaus (1992), and others have analyzed the first-order conditions for optimality of such a trajectory.[4] While the approach taken here is formally somewhat more general because it considers derivatives along trajectories that may not be optimal, it should be clear that the same gas-specific derivatives are central to both approaches.

Suppose that the only external effects of greenhouse gas emissions are on the global climate and that the state of the global climate can be adequately summarized for cost-benefit purposes by M variables, where M is finite. Let $C_j(t)$ be the value of the j^{th} of these climate variables at time t. The most discussed such variable is global mean temperature, but other quantities, such as regional values of soil moisture and tropical storm frequencies may be considerably more important. We use the following notation for the marginal relations between climate and damages (conditional on whatever assumption regarding adaptation seems most reasonable):

4. Eckaus (1992) considers cost minimization subject to an exogenously-imposed time-path of radiative forcing, while the others treat radiative forcing as determined by the optimization. While the resulting formulae differ somewhat in form, there is no substantive difference relevant to the issues considered here.

$$\partial D(t)/\partial C_j(v) \equiv \beta_j(t,v), \qquad t \geq v,\ j = 1, \ldots, M. \tag{4}$$

Since climate variables depend on the historical time-path of radiative forcing (and, perhaps, other quantities that will be assumed to be exogenous), we can define

$$\partial C_j(v)/\partial R(\tau) \equiv \gamma_j(v,\tau), \qquad v \geq \tau,\ j = 1, \ldots, M. \tag{5}$$

Using (4) and (5), the marginal relation between radiative forcing and climate-related damages becomes:

$$\begin{aligned} \partial D(t)/\partial R(\tau) &= \sum_{j=1}^{M} \left[\int_0^{\infty} [\partial D(t)/\partial C_j(v)][\partial C_j(v)/\partial R(\tau)]\, dv \right] \\ &= \sum_{j=1}^{N} \left[\int_0^{\infty} \beta_j(t,v)\gamma_j(v,\tau)\, dv \right] \equiv \phi(t,\tau). \end{aligned} \tag{6}$$

Finally, the present discounted value of damages associated with a small unit increase in the emissions of gas i at time zero can be written as

$$\begin{aligned} \int_0^{\infty} [\partial D(t)/\partial E_i(0)]\, e^{-rt} dt &= \int_0^{\infty} \left[\int_0^{t} [\partial D(t)/\partial R(\tau)][\partial R(\tau)/\partial E_i(0)]\, d\tau \right] e^{-rt} dt \\ = \int_0^{\infty} \left[\int_0^{t} \phi(t,\tau)\alpha_i(\tau)\, d\tau \right] e^{-rt} dt &= \int_0^{\infty} \alpha_i(\tau) \left[\int_{\tau}^{\infty} \phi(t,\tau) e^{-rt} dt \right] d\tau \\ &\equiv \int_0^{\infty} \alpha_i(\tau)\delta(\tau)\, d\tau. \end{aligned} \tag{7}$$

That is, the discounted damage caused by a unit increase in $E_i(0)$ is equal to a weighted integral of $\alpha_i(\tau)$, where the weights do not depend on i. This follows because emissions of greenhouse gases are (for the moment) assumed to cause only climate-related net damages, and such damages are only caused by changes in radiative forcing. The quantity $\delta(\tau)$ is the derivative of the present discounted value of marginal damages with respect to radiative forcing at time τ.

Note that in (7) the discount rate, r, is applied to the dollar values of incremental damages over time. In this setting, as in general, the rationale for discounting of monetary values rests on some mixture of impatience and the productivity of investment, and the choice of an appropriate discount rate for public policy analysis involves choosing the right mixture, as well as adjustment for risk and the effects of taxes.[5] While a detailed analysis of this issue is beyond the scope of this essay, the important point is that the *economic* problem of choosing the "correct" r in (7) is well-defined, which it was not in the context of (3).

If $\delta(\tau)$ in (7) were known for all τ, the argument so far implies that it should be used to replace the discount factor in (3) to compute indices of global warming damage, and ratios of those indices could then be used to compare greenhouse gases. But this function is not known, importantly because great uncertainty surrounds the level of damages associated with any particular pattern of climate change. Nonetheless, under some assumptions, the *shape* of $\delta(t)$ takes on a familiar form, and uncertainties regarding the level of that function cancel out across gasses when comparisons are made in ratio form, as in (2) and (3). Sufficient conditions for this to be true are that following hold for $j = 1,\ldots, M$:

$$\begin{aligned} \beta_j(t,\upsilon) &= \beta_j^0 e^{gt} \text{ for } t = \upsilon, \ = 0 \text{ for } t > \upsilon; \\ \gamma_j(\upsilon,\tau) &= \gamma_j(\upsilon-\tau) \text{ for } \upsilon \geq \tau. \end{aligned} \qquad (8)$$

Setting the $\beta_j = 0$ for $t > \upsilon$ can be viewed as simply a convention on the measurement of damages. The assumption that the $\beta_j(t,t)$ grow at rate g for all j and t is quite restrictive in principle but less so in practice, given the sketchy nature of our knowledge of the likely costs of global change. Nordhaus (1991, p. 925), for instance, argues in effect that g should be set equal to the rate of economic growth in "resource steady state" — when "all physical flows in the global economy are constant even though (because of resource-augmenting technical change) the real value of economic activity may be increasing." Out of such an equilibrium, one might argue that g should be less than the rate of aggregate economic growth, since marginal physical damages to natural systems seem unlikely to grow as rapidly as the global economy, and the share of economic activity accounted for by agriculture and other climate-sensitive activities is secularly declining. On the other hand, the *value* of damages to natural systems may rise quite rapidly because environmental amenities are luxury goods, and, depending on the baseline pace of climate change, marginal sensitivity to climate-related damages may rise more rapidly than damages

5. In general, see Lind (1984) and the literature he cites. Heal (1991) and Cline (1992) focus on discounting issues that arise in the context of climate change.

themselves. At any rate, it is possible to have an intelligent *economic* argument about what value or values of g best summarize available information on likely future changes in the marginal effects of climate change.

The second line of (8) assumes local linearity of the important climate-determining natural processes. In the absence of discontinuous changes or sharp nonlinearities within the relevant range, this assumption should not be seriously misleading. It is, of course, a modest generalization of the single linear differential equation that determines climate in the models of Nordhaus (1991) and others.

Substituting from (8) into the definition of $\delta(\tau)$ given in (7), we obtain

$$\begin{aligned}\delta(\tau) &= \int_{\tau}^{\infty} \phi(t,\tau) e^{-rt} dt = \int_{\tau}^{\infty} \left[\sum_{j=1}^{N} \beta_j^0 \gamma_j(t-\tau) e^{gt} \right] e^{-rt} dt \\ &= e^{-(r-g)\tau} \sum_{j=1}^{N} \left[\int_{\tau}^{\infty} \beta_j^0 \gamma_j(t-\tau) e^{-(r-g)(t-\tau)} dt \right] = \lambda e^{-\theta\tau},\end{aligned} \tag{9}$$

where $\theta \equiv r\text{-}g$, and λ is a constant, independent of τ. Thus a comparison of greenhouse gases based on discounted climate-related damages, using what might be called a relative damage index (*RDI*), reduces to a comparison of discounted radiative forcing, with discount rate θ:[6]

$$RDI_i = \frac{\int_0^{\infty} [\partial D(t) / \partial E_i(0)] e^{-rt} dt}{\int_0^{\infty} [\partial D(t) / \partial E_1(0)] e^{-rt} dt} = \frac{\int_0^{\infty} \alpha_i(\tau) e^{-\theta\tau} d\tau}{\int_0^{\infty} \alpha_1(\tau) e^{-\theta\tau} d\tau}, \qquad i = 1, \ldots, N. \tag{10}$$

As discussed above, the economic problem of choosing r and g, and thus θ, is in principle well-defined. In contrast, simply writing down (3) provides no economic (or other) basis for selecting a particular discount rate.

6. This conclusion also follows from the steady-state optimal growth analysis of Nordhaus (1991).

SOME COMPLICATIONS

While the *RDI* developed above is an improvement on the *GWP* and the *DGWP*, there are at least two reasons why it is unlikely to be an adequate basis for policy decisions. First, as Reilly (1991) notes, the assumption that the only external effects of greenhouse gas emissions are climate-related is both strong and crucial to the sort of analysis performed above. CFC emissions have important effects on stratospheric ozone, for instance, and plant growth may be sensitive to atmospheric concentrations of CO_2. Efficient control strategies must take such effects into account if they surpass some threshold level of economic importance. Since external effects that are not climate-related do not operate via changes in radiative forcing, the presence of such effects in general rules out the sort of cancellation that produced (10). Specifically, even under assumptions (8), discounted net damages in general simplify only to

$$\int_0^\infty [\partial D(t)/\partial E_i(0)]e^{-rt}dt = \lambda \int_0^\infty \alpha_i(\tau)e^{-\theta\tau}d\tau + \gamma_i, \qquad i = 1, \ldots , N,$$

where γ_i is the discounted present value of the derivative of non-climate-related net damages with respect to emissions of gas i at time 0. In order to compare greenhouse gases for policy purposes in this case, both λ and the γ_i must be explicitly calculated.[7]

The second reason why (10) is unlikely to provide a sound basis for policy decisions is that an analytical framework that took full and explicit account of the uncertainties and irreversibilities that are important in the climate change context would likely imply a basically different approach to comparing greenhouse gases.[8] Over time, scientific and economic research will likely reduce uncertainties regarding natural climate-rated processes, damage functions, and costs of adaptation and abatement. Most climate-related policy actions that have been widely discussed, both those focused on abatement of greenhouse gas emissions and on adaptation to changed climates, would have long-lived effects, and changes in emissions of at least some greenhouse gases will have long-lived effects on radiative forcing.

All else equal, a policy that puts primary near-term emphasis on relatively long-lived gases (CO_2 in particular) would seem to be attractive because it provides insurance against learning that climate change is a more

7. See Reilly and Richards (forthcoming) for an illuminating development of this point and some interesting calculations of discounted net damages.

8. For explorations of the policy implications of two aspects of the uncertainty that is pervasive in this context, see Heal (1984, 1991) and Hendricks (1991).

serious problem than it now seems. This effect is necessarily absent from any analysis that neglects uncertainty. Of course, to go beyond this intuitive argument, or even to provide an adequate defense for it, would require a full-blown analysis of uncertainty in this context. Such an analysis would be quite valuable for a host of reasons that go well beyond the issues considered in this essay.

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