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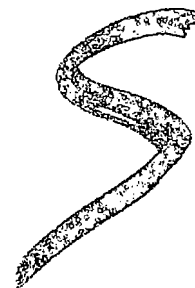
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["Evaluation Endpoints & Climate Policy: Atmospheric Stabilization, Benefit-Cost Analysis, & Near-Term Greenhouse-Gas Emissions"--James Hammitt Article, July 1998] [loose]

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HARVARD SCHOOL OF PUBLIC HEALTH

Department of Health Policy and Management



6 August 1998

Jeffrey A. Frankel
Council of Economics Advisers
314 Old EOB, Executive Office of the President
Washington DC 20502

Dear Dr. Frankel:

I found your comments at the NBER meeting this week very interesting. You mentioned you were aware of only one attempt (by Manne and Richels) to estimate least-cost paths to stabilization of atmospheric CO₂. I enclose another paper doing the same, which is in press at *Climatic Change*. In this paper, I derive least-cost stabilization paths and compare them with paths that are optimal if one attempts to maximize net benefits, where the monetary value of damages from climate change are related to the level or to the rate of change. I also examine the implications of path-dependence in abatement technology, such that abatement changes the subsequent uncontrolled emission path (i.e., if new technologies are adopted in response to abatement policy, they are not wholly discarded if the policies are subsequently relaxed).

I hope this paper is helpful to you. I also enclose a few other papers on climate policy that may be of interest.

Cordially,

James K. Hammitt
Associate Professor of
Economics and Decision Sciences

Enclosures:

- J.K. Hammitt, "Evaluation Endpoints and Climate Policy: Atmospheric Stabilization, Benefit-Cost Analysis, and Near-Term Greenhouse-Gas Emissions," *Climatic Change*, in press.
- J.K. Hammitt and J.L. Adams, "The Value of International Cooperation for Abating Global Climate Change," *Resource and Energy Economics* 18: 219-241, 1996.
- J.K. Hammitt, A.K. Jain, J.L. Adams, and D.J. Wuebbles, "A Welfare-Based Index for Assessing Environmental Effects of Greenhouse-Gas Emissions," *Nature* 381: 301-303, 1996.
- S. Garber and J.K. Hammitt, "Risk Premiums for Environmental Liability: Does Superfund Increase the Cost of Capital?" *Journal of Environmental Economics and Management*, in press.

**Evaluation Endpoints and Climate Policy:
Atmospheric Stabilization, Benefit-Cost Analysis,
and Near-Term Greenhouse-Gas Emissions**

James K. Hammitt
Harvard University

Center for Risk Analysis and
Department of Health Policy and Management
Harvard School of Public Health
718 Huntington Ave., Boston, MA 02115 USA
tel: 617 432 4030, fax: 617 432 0190
jkh@hsph.harvard.edu

July 1998

Abstract

The Framework Convention on Climate Change calls for stabilizing atmospheric concentrations of carbon dioxide and other greenhouse gases. In contrast, many economists espouse the goal of minimizing the present value of abatement costs and damages. The choice between evaluation endpoints--least-cost stabilization and maximization of benefits less costs--involves a tradeoff between accuracy and relevance. Atmospheric concentrations associated with candidate abatement policies can be more accurately predicted, for any level of confidence, than can the monetary values of climate damages associated with those policies. The monetary value of damages is more relevant to the question of what resources should be devoted to abatement, however, because atmospheric concentrations are of little interest except as they influence climate and its impacts on economic activities, ecosystems, and other elements of human concern. As demonstrated using both analytic and numerical models, the choice between endpoints is not solely a matter of analytic convenience but has substantive implications when comparing near-term abatement policies. For the next few decades, maximization of benefits less costs is likely to require greater abatement than will cost-effective stabilization of atmospheric concentrations.

Acknowledgment: The benefit-cost cases are partially based on scenarios developed by the Stanford University Energy Modeling Forum uncertainty subgroup, with primary contributions by W.D. Nordhaus, A.S. Manne, and H. Dowlatabadi. I thank the reviewers for constructive suggestions, and L.H. Goulder and S.C. Peck for helpful discussions. This work was supported by the U.S. Department of Energy (DE-FG02-95ER62109) and the National Science Foundation (SBR-9634292).

Keywords: optimal abatement, stabilization, benefit-cost analysis, path-dependence

1. Introduction

Decision making about actions to abate global climate change is complicated by daunting uncertainty about the consequences of choosing alternative emission paths of carbon dioxide and other greenhouse gases (GHGs). Several alternative objectives and corresponding endpoints for evaluating abatement policies have been considered, including limiting anthropogenic emissions of GHGs, stabilizing atmospheric GHG concentrations, limiting the magnitude or rate of increase of global mean surface temperature, and maximizing the difference between benefits and costs of abatement. The choice of evaluation endpoint requires making tradeoffs between desired criteria, notably the relevance of the endpoint (the extent to which it captures consequences that are of direct interest to policy makers) and the accuracy with which future levels of the endpoint can be projected under alternative policies.

The choice between endpoints is not simply one of analytic convenience; it may also affect the apparent merits of alternative policies. In particular, "optimal" policies based alternatively on benefit-cost analysis and on stabilizing GHG concentrations at least cost differ systematically, with policies based on benefit-cost analysis generally requiring larger near-term reductions in GHG emissions.¹

The systematic effect of the evaluation endpoint on the assessed merits of alternative policies is examined here using a simple analytic model and the magnitude of the effect is evaluated using a numerical integrated-assessment model. The intuition is straightforward: the present value of abatement costs is likely to be reduced by deferring emission reductions to the future, due to discounting future costs to reflect the opportunity cost of capital, anticipated improvements in abatement technologies, avoidance of premature depreciation of existing physical and human capital, and the existence of oceanic and other sinks that remove greenhouse gases from the atmosphere (Wigley et al., 1996). Under a stabilization objective, emissions are harmful only to the extent that they interfere with achieving the stabilization goal. Within limits, higher near-term emissions can be offset by greater subsequent emission reductions. In contrast, both near-term and future damages from climate change are accounted for under a benefit-cost objective. Near-term damages from climate change cannot be prevented by future emission reductions (although the monetary value of near-term damages may be compensated by

¹Grubb (1997) makes a similar observation.

decreasing future damages). In short, near-term and future abatement costs are counted under both objectives, but near-term consequences of emissions are counted only under the benefit-cost objective.

Alternative evaluation endpoints and criteria for choosing among them are discussed in Section 2. The result that optimal near-term emission reductions are larger under a benefit-cost than a least-cost stabilization objective is established using an analytic model in Section 3. The magnitude of the difference in near-term emission paths for a variety of stabilization levels and climate-damage functions is evaluated using an integrated assessment model in Section 4. Conclusions are presented in Section 5.

2. Endpoints for Policy Evaluation

The Framework Convention on Climate Change calls for "stabilization of greenhouse-gas concentrations ... at a level that would prevent dangerous anthropogenic interference with the climate system." Although an appropriate level has not been identified, emission paths that stabilize carbon dioxide concentrations at several levels have been constructed (Schimel et al., 1995; Wigley et al., 1996).² An economic-welfare perspective suggests an alternative goal, maximizing the difference between the benefits of reducing climate change and the costs of abatement. This approach has been widely used in integrated-assessment modeling (Cline, 1992; Nordhaus, 1992, 1994a; Peck and Teisberg, 1992; Manne and Richels, 1995). Other endpoints that have been proposed include the maximum change or rate of change of global annual mean surface temperature, which is frequently used as an index of climate change (Krause et al., 1989; Rijsberman and Swart, 1990; Wirth and Lashof, 1990; Hammitt et al., 1992); the magnitude of sea-level rise (Rotmans, 1990; Wigley and Raper, 1992); and the GHG emission rate. As a control variable, GHG emissions are a natural focus of the policy debate (WMO, 1988; Framework Convention on Climate Change); as an endpoint, emissions are not relevant except as they may be viewed as a proxy for the rate of change of atmospheric concentrations. The Global Warming Potential (GWP), an index developed for comparing the effects of emitting different

²Except for chlorofluorocarbons, where concentrations have stabilized and are expected to begin falling (Montzka et al., 1996), stabilizing the concentration of other greenhouse gases has received less attention.

GHGs, uses discounted or cumulative radiative forcing through a specified horizon as the evaluation endpoint (Houghton et al., 1990; Lashof and Ahuja, 1990), while an alternative, the Economic Damage Index (EDI), uses the present value of incremental economic welfare loss as its endpoint (Eckaus, 1992; Reilly and Richards, 1993; Schmalensee, 1993; Kandlikar, 1995; Hammitt et al., 1996).

These alternative evaluation endpoints correspond to different stages in the causal chain linking anthropogenic GHG emissions to climate-change damages, illustrated in Fig. 1 (not all of the important linkages can be represented as part of a linear chain, but the metaphor captures the most important aspects of the problem). The causal chain extends from anthropogenic emissions to atmospheric concentrations of anthropogenic GHGs (e.g., CO₂, N₂O, CH₄, CFCs), other radiatively active gases whose concentrations are influenced by anthropogenic emissions (e.g., O₃), and other atmospheric constituents (e.g., sulfate aerosols). Changes in atmospheric composition in turn influence radiative forcing, clouds, water vapor, atmospheric circulation, and other factors. These atmospheric changes influence global climate, including regional and temporal patterns of temperature, precipitation, and wind. Changes in climate may produce a wide range of impacts, including effects on the composition and growth of unmanaged ecosystems, agriculture, other economic activities, human health, and sea level. Changes in atmospheric composition also produce direct impacts, such as carbon dioxide fertilization of plants. (There are also interactions among the impact categories; e.g., sea level change affects unmanaged ecosystems and land availability.) These impacts influence human welfare by altering economic opportunity sets, e.g., through changes in environmental conditions, agricultural productivity, and biodiversity. The welfare losses associated with climate impacts depend on human preferences and opportunities for adaptation. The damages from climate change are the monetary value of direct losses and induced expenditures on adaptation (benefits of climate change are represented as negative damages).

In choosing an endpoint for evaluating the merits of alternative abatement policies, there is a tradeoff between relevance of the endpoint and the confidence with which it can be forecast. (For ongoing evaluation of the effectiveness of an abatement policy, the accuracy with which the current value of the endpoint can be monitored is also important.) For evaluating climate

policies, endpoints farther down the causal chain (Fig. 1) are most relevant but least confidently quantified. Relative to the other endpoints, GHG emissions are most confidently projected, although they are influenced by uncertainties about future population, magnitude and composition of economic growth, technological innovation, and human consumption patterns (Leggett et al., 1992). Projections of successive endpoints depend on the preceding endpoint and on additional, uncertain factors: atmospheric composition is sensitive to uncertainties about emissions, the global carbon cycle, and atmospheric chemistry; climate to uncertainties about atmospheric concentrations and climate-feedback processes; impacts to uncertainties about global and regional climate, natural and human adaptation, and the structure of future economic activity; and damages to human preferences over economic activity and changes in ecosystems. The relevance of the endpoints to description of future environmental conditions and to decision makers varies inversely with stage in the causal chain: GHG emissions and concentrations are of little or no interest as endpoints; impacts of climate change and damages are of great interest. (Emissions are of interest as a control variable, and concentrations are of interest for monitoring the effects of abatement policies.)

The tradeoff between uncertainty and relevance of endpoints is ubiquitous in environmental policy. Environmental and health risks are often evaluated by defining an "acceptable-risk" level without assessing preferences over possible end states. In the United States, for example, chemicals that may cause cancer are often regulated so as to reduce the predicted excess-cancer incidence to one-per-million lifetimes without regard to the type of cancer, its lethality, age of onset, or efficacy of treatment (Rosenthal et al., 1992). In evaluating policies toward CFCs and stratospheric-ozone depletion, total column ozone loss (an idealized annual global average) was the standard endpoint used from the emergence of the issue in the mid-1970s through negotiation of the Montreal Protocol (the international agreement restricting CFC emissions) in the mid-1980s. This endpoint was relied on even though more relevant endpoints (e.g., skin-cancer incidence, the monetary value of increased cancer risk) were sometimes evaluated as well; indeed, the U.S. Regulatory Impact Analysis for the Montreal Protocol quantified the monetary benefits of controlling CFC emissions (EPA, 1987). (EPA did not quantify all the benefits, since it was able to show that health benefits alone justified the costs of regulation.³)

The primary reliance on total column ozone depletion reflected an implicit balancing of relevance and uncertainty. Subsequent to the discovery of the Antarctic ozone hole, evaluations have used an endpoint corresponding to an earlier link in the causal chain, atmospheric chlorine concentration. The shift reflects a perception that total column ozone depletion was neither as relevant nor as accurately predicted as previously believed, since the discovery of the hole (which was not explained by contemporary theories) revealed both the great seasonal and geographic variation in ozone depletion and the weakness of current theories to predict ozone depletion (Hammitt, 1997). Stratospheric chlorine concentration is not directly relevant to human health or ecosystem impacts but is thought to be a (causal) indicator of the appearance of the Antarctic ozone hole. The existence of the ozone hole affects seasonal ultraviolet radiation levels, which in turn have implications for human health and ecosystems (Smith et al., 1992).

Benefit-cost analysis provides a framework for determining the appropriate level of abatement when benefits (and costs) can be accurately assessed. When benefits are highly uncertain, as for global climate change, several approaches are available for determining an appropriate abatement level. The most direct approach is to formally characterize the uncertainty about benefits using subjective probability methods (Raiffa, 1968; Morgan and Henrion, 1990; Cooke, 1991) and to maximize the expected difference between benefits and costs. Alternatively, a less relevant but more accurately predicted endpoint may be adopted, and an "acceptable" level of the endpoint somehow determined. The determination of an "acceptable" level is fundamentally a matter of judgment, and may incorporate several types of information. Most directly, the judgment may represent a holistic summary of available information about the uncertain benefits, including judgment about the relationship between the selected endpoint and the magnitude of salient consequences. Such a judgment may provide an informal substitute for using subjective probabilities to characterize uncertainty and integrating with respect to the probabilities to find the expected benefit. Whether a holistic judgment is more or less accurate than a formal probability analysis is unclear, but a formal analysis has the advantage of making

³By comparing alternative control levels, EPA concluded that the degree of emission reduction required by the Montreal Protocol was approximately the level that maximized benefits minus control costs. If benefits other than reduced skin cancer had been more comprehensively evaluated, a larger degree of control might have been justified.

the use of available knowledge, assumptions, and logic underlying the conclusion accessible so they can be more readily evaluated.

In some cases, it may be possible to determine the acceptable level by consideration of only the benefits or the costs of control. One frequently-espoused criterion is based on judgment about the benefits: it selects a level of control such that the magnitudes of adverse consequences are negligibly small, in the sense that they would have no practical significance or would be undetectable (against a naturally variable background or below limits of detection). This negligible-impact criterion is probably an important implicit justification for the one-per-million lifetime cancer-risk standard often mentioned in the U.S. (Rosenthal et al., 1992, Kelly, 1995). It is not likely to be a useful guide when, as for climate change, the marginal cost of reducing the hazard to a negligible level is likely to be high.

Alternatively, the acceptable level may be determined using only information about the costs of control, by selecting the level beyond which the marginal cost of further control begins to increase sharply. So-called "knee-of-the-curve" analysis rests on the assumption that the marginal control cost is smaller than the marginal benefit at low control levels but is higher than the marginal benefit at high control levels. As illustrated by Fig. 2, the approach may work well in cases where the abatement-cost curve has a sharp bend; in other cases, the point beyond which marginal control costs are likely to exceed the marginal benefits is not well defined.

In summary, alternatives to formal assessment of marginal benefits and costs that are likely to provide useful guidance rely on judgment about the uncertain benefits; alternatives like the negligible-impact criterion and "knee-of-the-curve" analysis are unlikely to prove useful in difficult cases. Whether and when a holistic-judgment approach is superior to more formal and disaggregated analysis is uncertain.

3. Comparison of Benefit-Cost and Least-Cost-Stabilization Paths: An Analytic Model

The choice between endpoints based on atmospheric concentrations and on quantified benefits has implications for the shape of the optimal abatement path, including the optimal degree of near-term emission reductions. As shown by the following example, optimal emissions based on the benefit-cost criterion require larger emission reductions in the near term (the next few decades) than do corresponding emission paths that stabilize concentrations at least

cost. Optimal emissions under the different objectives may also differ over the long term, but that difference is of limited interest for decision making because any emission path selected in the near term will subsequently be altered in response to future changes in information and other conditions (Hammitt et al., 1992; Manne and Richels, 1992; Peck and Teisberg, 1993; Kolstad, 1996).

For simplicity, divide the future into two periods, the next several decades and the distant future. For consistency with other work on atmospheric stabilization (Schimel et al., 1995; Wigley et al., 1996), restrict attention to a single GHG, carbon dioxide. Without controls, anthropogenic CO₂ emissions in each period are B₁ and B₂. Let x₁ and x₂ represent abatement levels (i.e., emission reductions) in the two periods. The present value of abatement costs $K = K_1(x_1) + \delta K_2(x_2)$, where abatement costs in each period are positive and increasing in emission reductions ($K'_t > 0$ and $K''_t > 0$ for $t = 1, 2$; ' and '' denote first and second derivatives, respectively). The discount factor $\delta < 1$ accounts for the opportunity cost of diverting economic resources from other activities. The above-background atmospheric concentration of CO₂ in each period is represented as $C_1(x_1) = (B_1 - x_1)$ and $C_2(x_1, x_2) = \rho(B_1 - x_1) + (B_2 - \epsilon x_1 - x_2)$, where ρ ($0 \leq \rho \leq 1$) is the fraction of first-period emissions remaining in the atmosphere in the second period and ϵ ($0 \leq \epsilon \leq 1$) reflects any reductions in uncontrolled second-period emissions that result from first-period abatement, such as by stimulating the development and diffusion of economically competitive low-emission technologies that supplant technologies that would have been used in the baseline scenario.

Least-cost stabilization can be determined by minimizing abatement costs K subject to the constraint that concentrations remain below a specified stabilization level. Consider a stabilization level C^* that will be exceeded in the second period (but not in the first period) if no abatement is undertaken, i.e., $C_1(0) < C^* < C_2(0, 0)$. The first-order condition for cost minimization is

$$K'_1(x_1) + \delta K'_2(x_2) \frac{dx_2}{dx_1} = 0.$$

Since the stabilization constraint is binding, $dx_2/dx_1 = -(\rho + \epsilon)$, yielding

$$K'_1(x_1^s) = \delta(\rho + \epsilon)K'_2(x_2^s) \quad (1)$$

where the superscript s denotes the optimal emission reduction for atmospheric stabilization. Holding the marginal cost of abatement in the second period fixed, the optimal marginal-abatement cost and abatement level in the first period are higher if δ , ρ , or ϵ are larger, i.e., if abatement costs in the second period are discounted less, the fraction of first-period emissions persisting in the atmosphere is larger, or the effect of first-period abatement in reducing future emissions is greater.

To evaluate the emission path minimizing the sum of abatement costs and climate damages, let $D_t(C_t)$ denote the monetary value of damages associated with atmospheric concentration C_t (lags between changes in atmospheric concentrations, climate, and impacts are neglected for simplicity). The first-order conditions are obtained by differentiating the sum of discounted abatement costs and damages, $\sum_{t=1}^2 \delta^{t-1} [K_t(x_t) + D_t(C_t)]$, with respect to x_1 and x_2 and setting the results equal to zero to obtain:

$$\begin{aligned} K'_1(x_1) &= \frac{dD_1}{dC_1} \frac{dC_1}{dx_1} + \delta \frac{dD_2}{dC_2} \frac{dC_2}{dx_1} \\ &= \frac{dD_1}{dC_1} + \delta(\rho + \epsilon) \frac{dD_2}{dC_2} \end{aligned} \quad (2a)$$

$$\begin{aligned} K'_2(x_2) &= \frac{dD_2}{dC_2} \frac{dC_2}{dx_2} \\ &= \frac{dD_2}{dC_2}. \end{aligned} \quad (2b)$$

Substitution of (2b) into (2a) yields

$$K'_1(x_1^b) = \frac{dD_1}{dC_1} + \delta(\rho + \epsilon) K'_2(x_2^b) \quad (2c)$$

where the superscript b denotes the optimal emission reduction using the benefit-cost criterion. As in the stabilization case, holding second-period marginal-abatement cost constant, larger values of δ , ρ , and ϵ increase the optimal first-period marginal-abatement cost and abatement level.

The stabilization level C^* should be set so that the marginal cost of abatement in the second period is equal to the marginal benefit of reducing second-period atmospheric concentration below C^* ,

$$K'_2(x_2) = \frac{dD_2}{dC_2} \frac{dC_2}{dx_2} = \frac{dD_2}{dC_2}, \quad (3)$$

where $C_2 = C^*$. If it is not, welfare in the second period can be enhanced by increasing or decreasing the stabilization level.⁴ Comparing eqns. (3) and (2b) reveals that the optimal stabilization level is equal to the optimal second-period concentration under the benefit-cost criterion, and so the optimal marginal-abatement costs in the second period are equal under the alternative criteria [$K_2'(x_2^s) = K_2'(x_2^b)$]. Further, comparison of eqns. (1) and (2c) shows that the optimal marginal-abatement cost in the first period under the benefit-cost criterion exceeds the optimum under the stabilization criterion by dD_1/dC_1 , the monetary value of the marginal damages incurred in the period before stabilization is achieved. The higher optimal marginal cost implies a larger optimal emission reduction, $x_1^b > x_1^s$ (because $K_1'' > 0$).

Under the stabilization criterion, higher near-term emissions can be offset by greater subsequent reductions as atmospheric CO_2 approaches the stabilization level. Wigley et al. (1996) describe several factors that suggest that postponing emission reductions will often be cost-effective for stabilization; these include (a) the existence of sinks for atmospheric CO_2 which imply that the share of CO_2 remaining in the atmosphere as the stabilization date approaches is smallest for the earliest emissions, (b) technological progress which is expected to reduce the cost of future abatement technologies, (c) avoidance of premature retirement of existing capital stock, and (d) the availability of alternative productive investments (which implies that future costs should be discounted). In contrast, the benefit-cost approach incorporates damages that occur before stabilization is reached; these damages can be reduced by early emission reductions but not by delayed reductions. The magnitude of the difference in optimal emission paths depends on the relative size of the damages for atmospheric concentrations below and at the stabilization level (represented by $D_1[C_1]$), on preference tradeoffs between damages in the near and distant future (represented by δ), on the atmospheric persistence of GHG emissions (represented by ρ), and on the extent to which abatement yields subsequent reductions in uncontrolled emissions (represented by ϵ).

⁴According to the Bellman principle of optimality in dynamic programming, the optimal action at any time depends only on current and future conditions, not on how the current situation was reached (Bellman and Dreyfus, 1962). Consequently, optimal emissions in the second period depend only on the costs of second-period abatement and the benefits of smaller second-period atmospheric concentrations, not on previous emission levels.

4. Comparison of Benefit-Cost and Least-Cost-Stabilization Paths: A Numerical Model

To evaluate the magnitude of the differences between emission paths that optimally stabilize atmospheric CO₂ and those that optimally balance benefits and costs, emission paths are derived using a simple integrated-assessment model. The model simulates globally aggregated CO₂ emissions, atmospheric concentrations, climate, damages, and abatement costs, using parameterized relationships that capture the major features of more complex models. The model yields results that are consistent with those of simple and more elaborate models that have been compared through the Stanford University Energy Modeling Forum (Weyant et al., 1996). As in all such models, quantitative results are sensitive to parametric assumptions but the qualitative results are more robust.

For a CO₂ emission path $E(t)$, the atmospheric CO₂ concentration in year t , denoted $C(t)$, is given by an impulse-response function (Maier-Reimer and Hasselmann, 1987)

$$C(t) = C_0 + \int_{1750}^t E(\tau) \left[\sum_{i=1}^5 \alpha_i \exp\left(-\frac{\tau-t}{\lambda_i}\right) \right] d\tau$$

where $C_0 = 280$ ppmv is the pre-industrial (1750) concentration, $\alpha_{1-5} = 0.131, 0.201, 0.321, 0.249, 0.098$, and $\lambda_{1-5} = \infty, 362.9, 73.6, 17.3, \text{ and } 1.9$ years.⁵

The increase in annual mean surface temperature $\Delta T(t)$ is simulated using a two-box model (Schneider and Thompson, 1981)

$$\frac{d}{dt} \Delta T(t) = \frac{1}{R} \{ Q(t) - \lambda \Delta T(t) - \frac{R_d}{\tau_d} [\Delta T(t) - \Delta T_d(t)] \}$$

$$\frac{d}{dt} \Delta T_d(t) = \frac{1}{\tau_d} [\Delta T(t) - \Delta T_d(t)]$$

where $\Delta T(t)$ and $\Delta T_d(t)$ are the temperature of the atmosphere/land/ocean-mixed-layer and the deep-ocean boxes (relative to their values in 1990), respectively; $Q(t) = 6.3 \ln[C(t)/C_0]$ w/m² is the radiative forcing from atmospheric CO₂; $\lambda = 6.3 \ln(2)/\Delta T_{2x}$ w/°C-m² is the climate-feedback factor, with climate sensitivity ΔT_{2x} the equilibrium increase in ΔT for a doubling of pre-industrial CO₂; $R = 20.83$ and $R_d = 223.7$ w-yr/°C-m² are the thermal inertia of the

⁵The impulse-response function represents a release of 25% of the preindustrial CO₂ concentration to the preindustrial atmosphere. Use of an alternative function representing a 100% release yields qualitatively similar results, with optimal emissions differing from those reported here by no more than a few percent of the uncontrolled emission rate.

mixed-layer and deep-ocean boxes; and $\tau_d = 500$ years is a parameter describing the rate of heat transfer between the mixed layer and deep ocean (Nordhaus, 1994a).

Climate-change-related damages (including adaptation and its costs) are represented by

$$D(t) = \mu P(t) \left[\frac{\Delta T(t)}{2.5} \right]^\theta \quad (4)$$

where $P(t)$ is Gross World Product, $\theta = 2$ is an exponent reflecting incremental damages that increase in the magnitude of climate change, and μ is a scaling constant equal to damages at $\Delta T = 2.5^\circ \text{C}$, measured as a fraction of world product (Cline, 1992; Nordhaus, 1992, 1994a; Peck and Teisberg, 1992, 1993).

Carbon dioxide emissions depend on the abatement level $A(t)$, where $0 \leq A(t) \leq 1$. To reflect path-dependence in the development and diffusion of CO_2 -emitting activities, emissions depend on past abatement even if there is no abatement in the current period. Specifically, a small fraction ε of the emission reductions due to abatement in each period is assumed to persist indefinitely, yielding uncontrolled emissions somewhat smaller than the "business as usual" or never-regulated emission path $\text{BAU}(t)$:

$$E(t) = \text{BAU}(t) [1 - A(t)] \prod_{\tau=1990}^{t-1} [1 - \varepsilon A(\tau)]. \quad (5)$$

Here, $\text{BAU}(t)$ is set equal to IPCC Scenario IS92a (Schimel et al., 1995) and $\varepsilon = 0$ in the base case. Uncontrolled emissions in year t conditional on a historical abatement path, $E_u(t)$, are given by eqn. (5) with $A(t) = 0$.

The abatement cost $K(t)$ increases in both the magnitude and rate of emission reduction compared with unregulated emissions, $\Delta E(t) = E_u(t) - E(t)$. Abatement costs are given by

$$K(t) = \kappa (1 + \delta)^{(1990-t)} [\Delta E(t)]^\beta \left\{ 1 + \text{abs} \left[\frac{d \Delta E(t)}{dt E_u(t)} \right] \right\}^\gamma.$$

Emission reductions that persist from previous abatement [$\text{BAU}(t) - E_u(t)$] impose no costs in the current period. The coefficient κ is set so that the 1990 marginal-abatement cost is \$200/t C (carbon mass of CO_2 in metric tons) for a 50% emission reduction (Nordhaus, 1991; Manne and Richels, 1992) assuming a base transition rate of 1%/yr (consistent with historical rates of substitution in the energy sector reported by Hafele, 1981) and no persistence of abatement ($\varepsilon = 0$ in eqn. (5)). The productivity of abatement technology is assumed to improve exogenously at δ

= 1%/yr. The exponent $\beta = 2$ yields abatement cost that is proportional to the square of the emission reduction (marginal-abatement cost is proportional to the emission reduction). The final term represents transition costs which depend on the rate at which abatement increases (or decreases); setting $\gamma = 10$ yields an increase in the cost by a factor of 2.35 if emission reductions occur at 10 times the base transition rate (i.e., at 10%/yr). Cumulative abatement costs and damages are measured as present values, using a 5%/yr discount rate.⁶

Least-cost paths to stabilize atmospheric CO₂ are shown in Fig. 3. Optimal emissions, atmospheric concentrations, increase in mean surface temperature, and marginal-abatement cost are presented in panels A-D, respectively. Optimal paths to stabilize concentrations at 450, 550, 650, and 750 ppmv are nearly identical to emission paths (not shown) that optimally stabilize ΔT at 1.0, 1.5, 2.0, and 2.5° C, respectively (for $\Delta T_{2x} = 2.5^\circ \text{C}$). Although very-low cost abatement measures are adopted immediately, significant emission reductions are postponed a decade or more. The least-cost emission paths do not fall more than 2% below never-controlled emissions (BAU) before 2000, 2010, 2050, and 2070, respectively. During this period, the marginal cost of abatement is less than \$10/t C. Thereafter, it rises over a 50-70 year period to about \$300-500/t C, depending on the stabilization level.⁷

Unlike the stabilization scenarios presented by IPCC (Schimel et al., 1995) and by Wigley et al. (1996), the date of stabilization is not constrained here; these scenarios minimize the simulated abatement cost of maintaining atmospheric CO₂ below the stabilization level. The optimal stabilization date⁸ is 2060, 2100, 2120, and 2160 for stabilization at 450, 550, 650, and 750 ppmv, respectively, somewhat earlier than the corresponding dates specified for the IPCC

⁶The present model is similar in structure and parameter values to DICE (Nordhaus, 1992, 1994a) but differs in some components. The principal difference is that the present model relies on a partial- rather than a general-equilibrium economic structure (in DICE, damages from climate change influence economic growth and the levels of current consumption and investment are determined endogenously). The climate model and damage function are similar. The emissions and abatement cost functions are similar except the dependence of costs on the rate of change in abatement and the effect of abatement on future uncontrolled emissions have no parallels in DICE. The present model also uses a five-box representation of atmospheric CO₂ in contrast to the one-box representation in DICE.

⁷The marginal-abatement cost is equivalent to the tax on carbon emissions that would induce the specified emission reductions.

⁸Defined here as the date by which atmospheric CO₂ concentrations come within 2 ppmv of the corresponding stabilization level.

(Schimel et al., 1995) and Wigley et al. (1996) scenarios, which are 2100, 2150, 2200, and 2250, respectively (Enting et al., 1994). The earlier stabilization dates allow larger cumulative emissions and smaller abatement costs. Atmospheric CO₂ cannot be maintained below 350 ppmv, since it already exceeds that value. The illustrated scenario minimizes the simulated abatement cost of maintaining atmospheric CO₂ below 350 ppmv beginning in 2150, the date considered by IPCC and by Wigley et al. (1996).

Panels E-H of Fig. 3 present scenarios that minimize total abatement costs plus damages and illustrate their dependence on the climate sensitivity ΔT_{2x} and damage-function coefficient μ . For the base case, $\Delta T_{2x} = 2.5^\circ \text{C}$ (the IPCC best estimate; IPCC, 1996) and $\mu = 0.02$ (Cline, 1992; Peck and Teisberg, 1992), optimal emissions increase over the next century but at a rate slightly smaller than BAU. Optimal emissions fall 3% below BAU by 2010, 5% below BAU by 2025, and about 20% below BAU by 2100. Atmospheric CO₂ continues to rise, reaching 780 ppmv in 2150. The marginal-abatement cost increases slowly from \$10/t C in 2000 to \$40 in 2050, \$110 in 2100 and \$190 in 2150.

For larger values of ΔT_{2x} or μ , the optimal emission path departs more rapidly from BAU and may fall absolutely. As high values of the parameters, consider $\Delta T_{2x} = 4.5^\circ \text{C}$ (the upper end of the IPCC range; IPCC, 1996) and $\mu = 0.15$ (a high but not implausible value; Nordhaus, 1994b). In the high-sensitivity case ($\Delta T_{2x} = 4.5^\circ \text{C}$, $\mu = 0.02$), optimal emissions rise slowly to 8% below BAU by 2010, plateau at a level about 40% above their 1990 value for 2050-2100, then gradually decline. The optimal marginal-abatement cost is \$25/t C in 2000, rising to \$90 in 2050 and \$230 in 2100. For the high-damage case ($\Delta T_{2x} = 2.5^\circ \text{C}$, $\mu = 0.15$), optimal emissions are approximately stable at 1990 levels until 2050, when they begin to fall to near zero by 2100. The marginal-abatement cost rises rapidly from \$70/t C in 2000 to \$220 in 2050 and \$500 in 2100. Finally, for the high-sensitivity, high-damage case ($\Delta T_{2x} = 4.5^\circ \text{C}$, $\mu = 0.15$), optimal emissions fall about 20% from 1990 to 2000, plateau until 2020, then fall to zero in 2070. Marginal cost increases from \$170 in 2000 to almost \$400 in 2050 and \$500 in 2100.

As examined in Section 3, if near-term abatement reduces future uncontrolled emissions (by stimulating the development and diffusion of low-emission practices, for example), the ratio of optimal near-term to future marginal-abatement costs increases (eqns. (1), (2c)). This effect

shifts the optimal allocation of abatement to earlier dates. In addition, the persistence of abatement reduces the cumulative cost of reducing emissions, which has different implications under the alternative evaluation criteria. Under the net-benefit criterion, the reduced cost of emission control leads to greater reductions and smaller cumulative emissions; under the stabilization criterion, cumulative emissions are not substantially affected but cumulative abatement costs fall.

The effect of path-dependent technological diffusion is illustrated in Fig. 4. Panels A-D illustrate the least-cost stabilization paths for atmospheric concentration limits of 750, 550, and 350 ppmv with and without persistent abatement.⁹ The solid lines correspond to the case without persistence, and are identical to those presented in Fig. 3. The dashed lines represent least-cost stabilization when 1% of the emission reduction in each year persists indefinitely ($\epsilon = 0.01$ in eqn. (5)). Introducing this level of persistence has minimal effect on the optimal emission paths; in particular, it remains optimal to postpone significant abatement (for stabilization levels above 350 ppmv). The primary effect of persistent abatement is to sharply reduce the marginal cost once abatement begins (panel D). The effect of persistence on cumulative emission costs offsets the effect of shifting abatement to earlier periods, so the optimal near-term marginal-abatement cost is smaller than in the case without persistence. The required increase in the ratio of optimal near-term to future marginal-abatement costs results from an even larger decrease in the future marginal-abatement cost.

In contrast, under the benefit-cost criterion persistence of abatement increases the optimal near-term emission reduction and marginal-abatement cost. Unlike the stabilization objective, the benefit-cost criterion rewards reductions in atmospheric concentrations below the levels that are optimal when abatement is not persistent, and so emission paths generally remain lower than the corresponding paths in the absence of persistence. The optimal paths for $\epsilon = 0.01$ are illustrated in panels E-H of Fig. 4 and compared with the optimal paths without persistence from Fig. 3. For the base case ($\Delta T_{2x} = 2.5^\circ \text{C}$, $\mu = 0.02$), the optimal marginal-abatement cost in 2000 increases from \$10/t C without persistence to \$19/t C with persistence, and in 2010 from \$12 to

⁹Results for stabilization levels of 650 and 450 ppmv are qualitatively similar but are omitted for clarity.

\$19/t C. For the high-sensitivity and high-damage cases, the optimal marginal-abatement cost in 2000 increases from \$26 to \$41/t C and from \$70 to \$107/t C, respectively.¹⁰

If damages from climate change are more closely related to the rate of change than to its magnitude, it may be optimal to shift emission reductions to earlier periods, increasing the difference in results between least-cost stabilization and benefit-cost perspectives. Even without emission controls, the rate of increase in $\Delta T(t)$ may rise little, if at all, in future periods. For BAU emissions, the rate of increase of $\Delta T(t)$ is nearly constant (Figs. 3 and 4); for other unrestricted emission scenarios, IPCC (1996: 39) shows the rate of change rising slowly for high-emission scenarios and falling slowly for low-emission scenarios. If emissions are restricted, the maximum rate of increase in $\Delta T(t)$ is likely to occur in the next few decades, which suggests the largest (marginal) damages may also occur then.

To examine the effect of rate-dependent damages, replace the damage function (eqn. 4) with a function in which damages depend solely on the rate of climate change

$$D_r(t) = \mu_r P(t) \left[\frac{d}{dt} \Delta T(t) \right]^{\theta_r} \quad (4')$$

where $\theta_r = 2$ to reflect increasing marginal damages in the rate of change. Optimal emission paths for rate-dependent damages are compared with those for level-dependent damages in Fig. 5. The coefficient μ_r is selected to yield cumulative abatement levels comparable to those obtained using the level-dependent damage function (4). The values that yield emission paths comparable to the base, high-sensitivity, and high-damage cases imply annual damages of 0.12%, 0.15%, and 1.0% of Gross World Product, respectively, for $d/dt[\Delta T(t)] = 1^\circ \text{C/century}$. As anticipated, when damages are dependent on the rate of climate change, optimal emission reductions and marginal-abatement costs are larger in early decades and smaller in later decades than for level-dependent damages that yield comparable cumulative emission reductions (as represented by atmospheric concentration in panel B).¹¹

¹⁰For the high-sensitivity, high-damage case (omitted from Fig. 4 for clarity) the increase in marginal-abatement cost in 2000 is from \$170/t C to \$230/t C.

¹¹Although they do not remark upon it, Peck and Teisberg (1994) also find the optimal marginal-abatement cost is larger in the near-term and smaller in the distant future when damages are proportional to the cubed rate rather than to the cubed level of climate change.

5. Conclusions

The tradeoff between predictability and relevance of the evaluation endpoint is common in environmental-policy analysis. In climate change, the choice between the two prominent alternatives--quantified damages of climate change and limiting the atmospheric concentration of GHGs to levels that are not dangerous--leads to qualitatively different policy implications. Least-cost stabilization of atmospheric concentrations implies that, if the desired stabilization level is neither too near nor below the current level, it is optimal to delay significant reductions in GHG emissions, relative to their uncontrolled level, for a decade or more. A corollary implication is that the optimal marginal-abatement cost for the next few decades is nearly zero. In contrast, minimizing the sum of abatement costs and damages, as suggested by benefit-cost analysis, implies that GHG emissions should be immediately reduced below their uncontrolled, "business as usual" levels; the current optimal marginal-abatement cost is larger than for least-cost stabilization paths (except for low stabilization levels). For example, comparing the optimal benefit-cost path for the base case ($\Delta T_{2x} = 2.5^\circ \text{C}$, $\mu = 0.02$) with the least-cost paths for stabilization at 450, 550, 650, and 750 ppmv shows that the optimal emission reductions (and marginal-abatement costs) are higher under the benefit-cost endpoint than under the stabilization endpoint until 2002, 2024, 2069, and 2107, respectively. For larger values of the climate sensitivity, larger damages, damages that depend on the rate of climate change, and for path-dependent development and diffusion of abatement technologies, the benefit-cost endpoint implies even more stringent abatement compared with the stabilization objective.

The dependence of optimal emissions over the next few decades on the choice between atmospheric stabilization and quantified-benefit endpoints can be understood by comparing the forms of the objective function and constraint. Under stabilization, higher near-term emissions can be offset by greater subsequent reductions as atmospheric CO_2 approaches the stabilization level. As noted in Section 1, Wigley et al. (1996) describe several factors that contribute to making early emission reductions cost-ineffective for stabilization (CO_2 sinks, technological progress, depreciation of capital stock, and discounting); these can be offset by the (very uncertain) cost of rapid change from increasing to decreasing emissions if departure from BAU is delayed too long. If the optimal stabilization level is sure to exceed 550 ppmv, uncertainty about

its value does not affect the choice of near-term emission path as optimal emissions for the next few decades coincide for higher stabilization levels. (Stabilization at 350 ppmv or below requires rapid emission reductions to return to a level that has already been exceeded, and least-cost stabilization below 550 ppmv requires departures from BAU by 2010.) In contrast, the benefit-cost approach incorporates (very uncertain) damages that occur in the near term as well as the distant future; near-term damages can be reduced by near-term emission reductions, but not by delayed reductions.

The appropriate stabilization level, the climate sensitivity, and the relationship between climate change and damages are presently unknown. Consequently, an appropriate near-term emission path involves hedging, and falls somewhere between the paths that would be appropriate if the stabilization level or climate sensitivity and damage function were known (Manne and Richels, 1995; Peck and Teisberg, 1993). Because the optimal paths for least-cost stabilization at CO₂ concentrations of 550 ppmv and above virtually coincide with the BAU emission path, optimal near-term emissions for stabilizing atmospheric concentrations will not depart from BAU if the probability that the appropriate stabilization level is less than about 550 ppmv is negligible. In contrast, the appropriate hedging policy under the benefit-cost approach, whether damages depend on the magnitude or rate of climate change, implies some near-term emission reduction from BAU.

These conclusions may be sensitive to factors that have been omitted from the analysis. Political and institutional factors could make the delayed-reduction strategy for atmospheric stabilization less attractive, as it may be difficult to credibly commit to a policy of imposing emission reductions several decades in the future. Moreover, there may be additional near-term benefits of policies to reduce GHG emissions, such as improved health due to reduction in airborne particulates that could accompany changes in fossil-fuel combustion (Burtraw and Toman, 1997). Both benefit-cost and least-cost-stabilization perspectives imply that GHG emissions will eventually need to decline substantially relative to BAU emissions; achieving this reduction will require the development and diffusion of innovative technologies and changes in anticipated human living patterns. An important research issue is how the incentives to develop such changes depend on near-term policies (Grubb, 1997; Schneider and Goulder, 1997). It is

likely that near-term policies to reduce emissions--whether market incentives or restrictions on emissions or technologies--would accelerate the development of changes that will reduce the cumulative cost of responding to climate change.

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Figure Captions

Fig. 1 -- Causal chain linking greenhouse gas emissions to climate change and damages.

Endpoints near the top of the figure are less relevant to policy choice but can be projected with greater accuracy than endpoints toward the bottom of the figure. Dashed lines represent possible policy interventions.

Fig. 2 -- Hypothetical benefits and costs (top panel) and marginal benefits and costs (bottom panel) of control policies. If control costs have a sharp bend, as for C, the optimal control level is insensitive to variation in benefits within some range; for example, y is optimal for low and high benefit functions (b and B , respectively), although it is not optimal for marginal benefits outside this range. If control costs do not have such a sharp bend, as for c , optimal abatement is sensitive to benefits; x and z represent optimal control for low and high benefit functions, respectively.

Fig. 3--Emissions (Gt C/yr), atmospheric concentrations (ppmv), increase in global mean surface temperature ($^{\circ}\text{C}$, $\Delta T_{2x} = 2.5^{\circ}\text{C}$ except as noted), and marginal-abatement cost ($\$/\text{t C}$) for "Business as usual" (long dashes) and optimal control paths (solid lines). Panels A-D: minimize abatement cost subject to constraint that atmospheric CO_2 does not exceed 750 (7), 650 (6), 550 (5), 450 (4), and after 2150, 350 (3) ppmv. Panels E-H: minimize abatement costs plus climate-change-induced damages for base case (b) ($\Delta T_{2x} = 2.5^{\circ}\text{C}$, $\mu = 0.02$), high-sensitivity (s) ($\Delta T_{2x} = 4.5^{\circ}\text{C}$, $\mu = 0.02$), high-damage (d) ($\Delta T_{2x} = 2.5^{\circ}\text{C}$, $\mu = 0.15$), and high-sensitivity/high-damage (e) ($\Delta T_{2x} = 4.5^{\circ}\text{C}$, $\mu = 0.15$) cases.

Fig. 4--"Business as usual" (long dashes) and optimal control paths comparing cases with persistent abatement ($\epsilon = 0.01$, short dashes) and without persistent abatement ($\epsilon = 0$, solid lines). Panels A-D: minimize abatement cost subject to constraint that atmospheric CO_2 does not exceed 750 (7), 550 (5), and after 2150, 350 (3) ppmv. Panels E-H: minimize abatement costs plus climate-change-induced damages for base case (b) ($\Delta T_{2x} = 2.5^{\circ}\text{C}$, $\mu = 0.02$), high-sensitivity (s) ($\Delta T_{2x} = 4.5^{\circ}\text{C}$, $\mu = 0.02$), and high-damage (d) ($\Delta T_{2x} = 2.5^{\circ}\text{C}$, $\mu = 0.15$) cases.

Fig. 5--"Business as usual" (long dashes) and optimal control paths comparing cases with damages dependent on magnitude (solid lines) and rate (short dashes) of climate change. Panels A-D: minimize abatement costs plus climate-change-induced damages for base case (b) ($\Delta T_{2x} = 2.5^\circ \text{C}$, $\mu = 0.02$), high-sensitivity (s) ($\Delta T_{2x} = 4.5^\circ \text{C}$, $\mu = 0.02$), and high-damage (d) ($\Delta T_{2x} = 2.5^\circ \text{C}$, $\mu = 0.15$) cases.

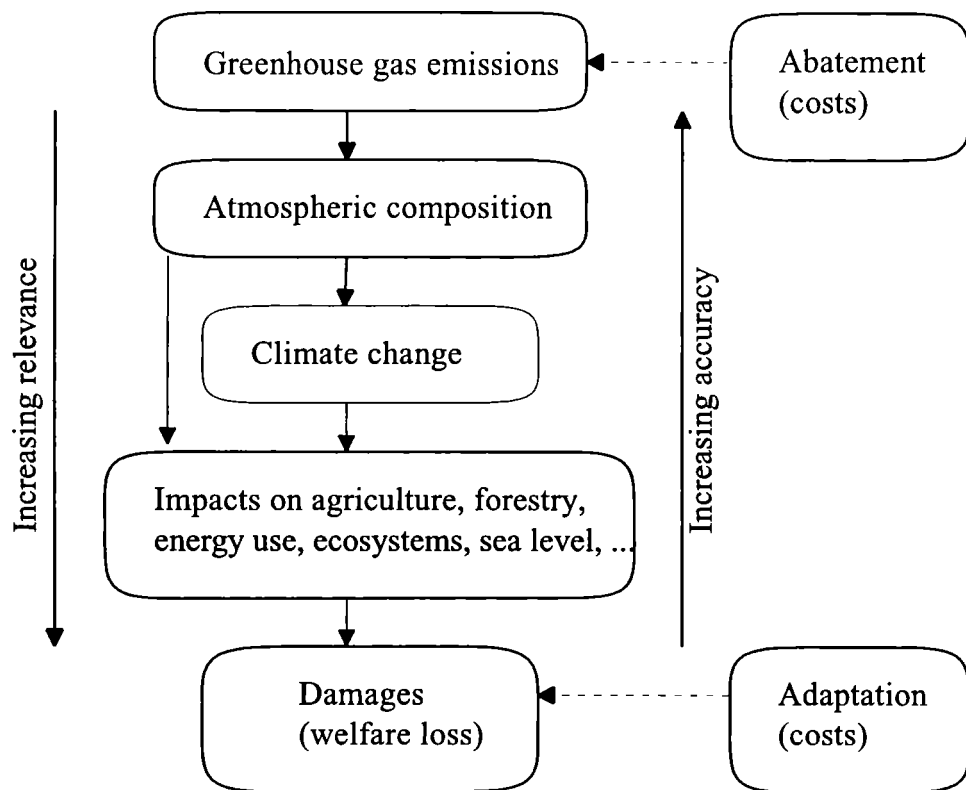
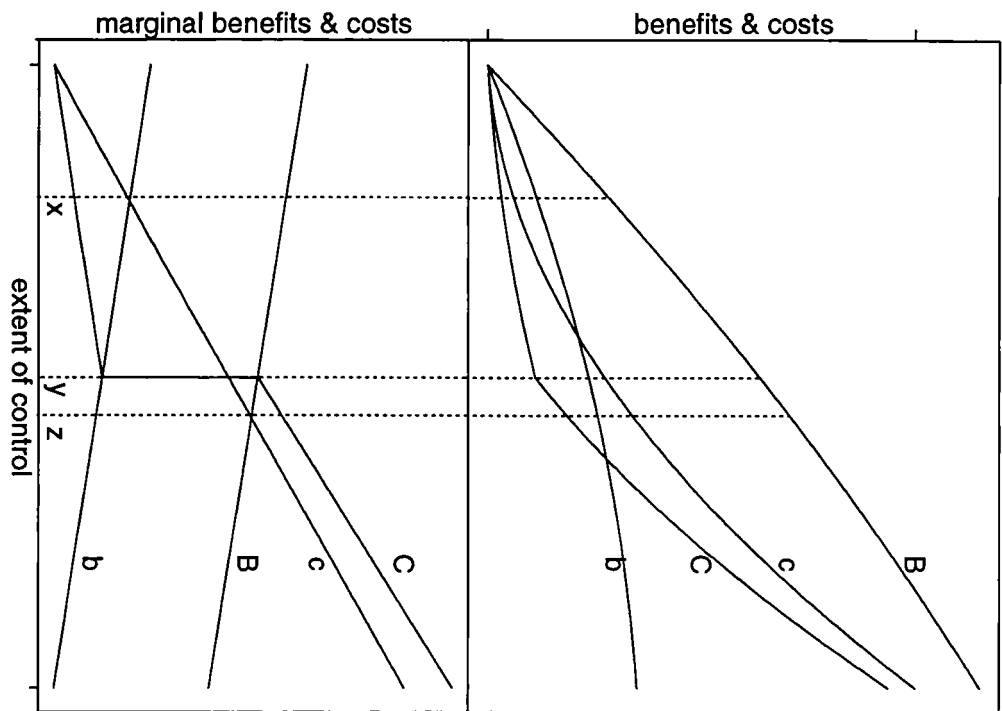


Fig. 2



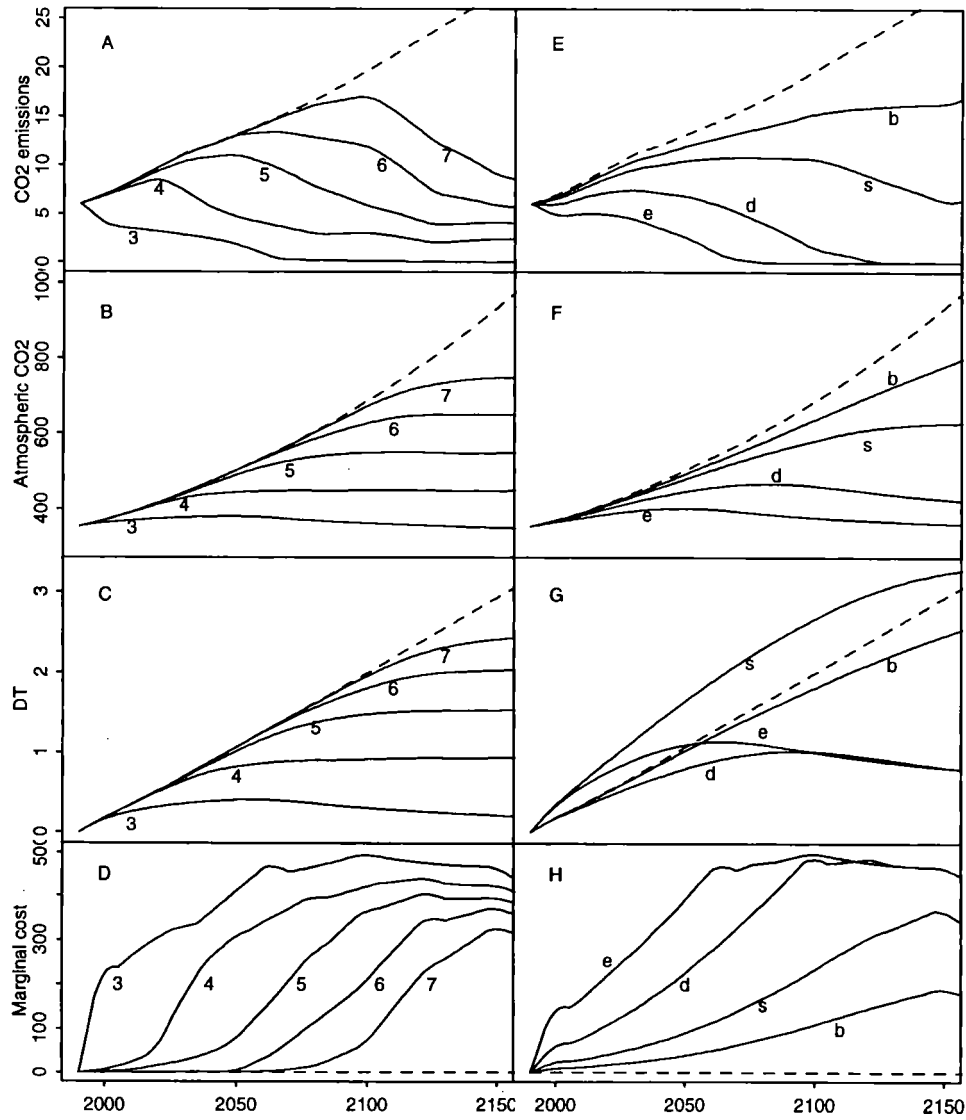


Fig. 4

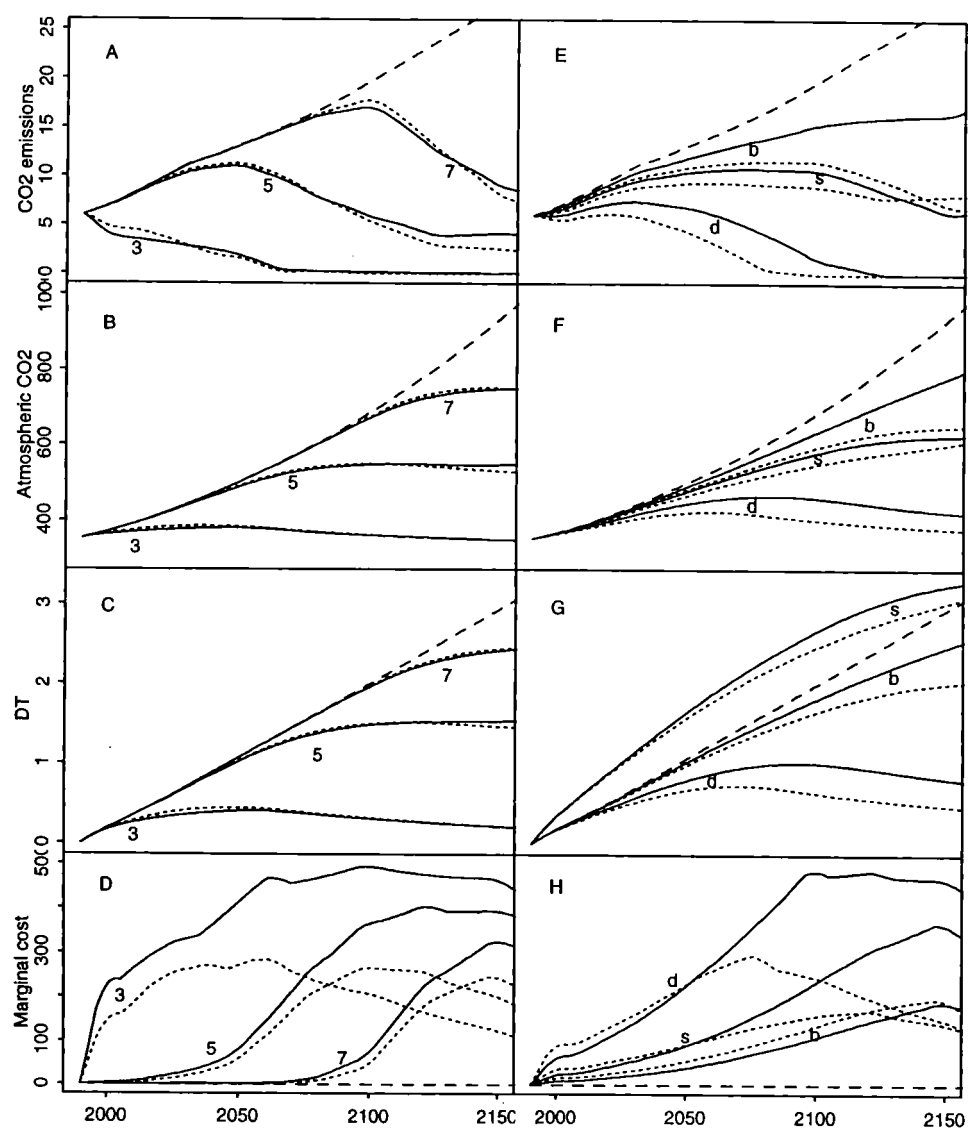
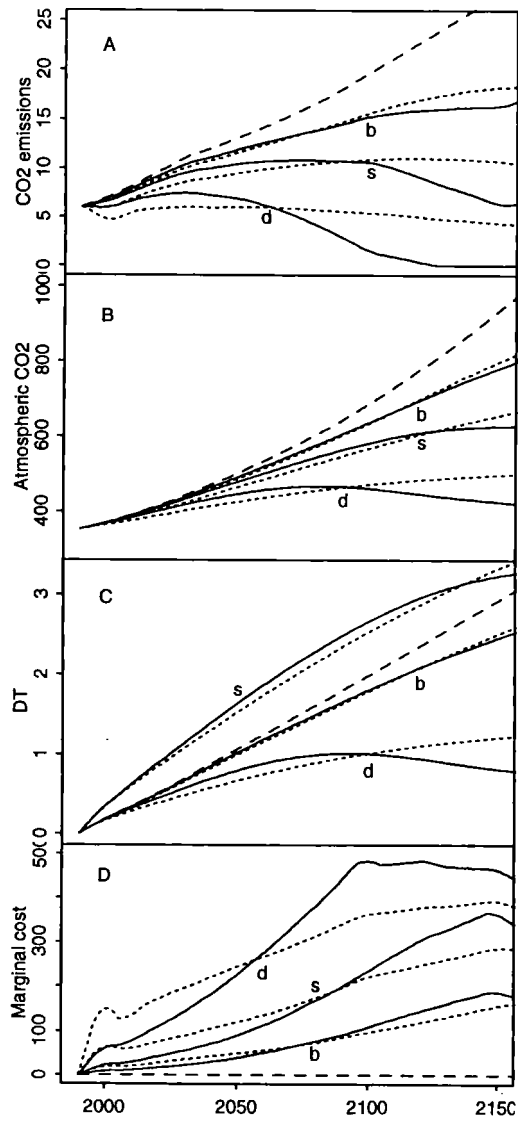


Fig 5



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RESOURCE and ENERGY ECONOMICS

Resource and Energy Economics 18 (1996) 219–241

The value of international cooperation for abating global climate change

James K. Hammitt ^{a,*}, John L. Adams ^b

^a *Harvard School of Public Health, 718 Huntington Ave., Boston, MA 02115, USA*

^b *RAND Corporation, Santa Monica, CA, USA*



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Resource and Energy Economics 18 (1996) 219-241

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The value of international cooperation for abating global climate change

James K. Hammitt^{a,*}, John L. Adams^b

^a Harvard School of Public Health, 718 Huntington Ave., Boston, MA 02115, USA

^b RAND Corporation, Santa Monica, CA, USA

Accepted 15 May 1996

Abstract

Because abatement of global climate change is a public good, independent national actions may not produce the efficient quantity. Using a numerical integrated-assessment model, abatement costs and damages induced by climate change are compared at the cooperative and noncooperative solutions to a set of two-party dynamic games between the industrialized and developing countries. Games with perfect and imperfect information about climate and economic factors are considered. Across 144 games with perfect information, incorporating different values of climate and economic parameters, the noncooperative solution usually yields global benefits comparable to those of the cooperative solution. In about one-fifth of these games, however, a second noncooperative solution exists which yields none of the benefits of the cooperative solution. In a game with imperfect information, where the state of nature is uncertain in the first but known in the second of two periods, the expected benefits of the noncooperative solution are 98% of the expected benefits of the cooperative solution. In contrast to single-agent studies which show little cost to delaying abatement, the benefits of cooperation are usually lost if cooperation is delayed 20 years.

JEL classification: C72; H41; Q28

Keywords: Climate change; Noncooperative games; International agreements

* Corresponding author. Tel: (+1) 617 432-4030; fax: (+1) 617 432-0190; e-mail: jkh@hsph.harvard.edu.

1. Introduction

Climate change may be viewed as a long-term global-commons problem. Human activities that release carbon dioxide and other greenhouse gases (GHGs) to the atmosphere may produce effects on climate that, if not irreversible, will persist at least for decades because of the century-long atmospheric residence times of many GHGs and the enormous thermal capacity of the oceans. Because GHGs are well-mixed in the global atmosphere, the effects of anthropogenic GHG emissions on climate do not depend on which nation emits them.

Numerical analyses of policies to prevent or limit global climate change often assume global cooperation. Several integrated-assessment models treat the world community as a single agent (Cline, 1992; Hammitt et al., 1992; Nordhaus, 1992, 1993, 1994; Peck and Teisberg, 1992, 1993). Models that incorporate multiple economic/political units are more complex, and are typically used to assess the consequences of following exogenously prescribed policies (e.g., Gaskins and Weyant, 1993, 1994; Edmonds et al., 1995; Manne et al., 1995) or to find the optimal policy for a single region assuming other regions do not consider climate-abatement policies (Peck and Teisberg, 1995). We extend this work by disaggregating the world into two regional actors, the industrialized 'North' and developing 'South', and determining their optimal abatement policies in the absence of cooperation, defined as the Nash solution to a noncooperative game. We contrast this noncooperative outcome to the cooperative, global-utility-maximizing solution to provide information about the value of cooperation in abating climate change.

Because abatement of global climate change is a public good, it is likely to be under-supplied. The under-supply may be mitigated if individual regions would bear substantial shares of the global costs of climate change (Olson and Zeckhauser, 1966) or expect to be compensated for unilateral abatement under a subsequent agreement. Regions might also undertake unilateral abatement to demonstrate the feasibility of particular abatement practices, to encourage others to abate, or to gain a lead in developing abatement technologies.

In the model presented here, whether the two regions achieve the global optimum without cooperation depends on the values of parameters, such as the costs of climate change, that are currently unknown. For parameter values consistent with 'best guess' estimates, the optimum response involves modest abatement, an outcome that can generally be achieved without cooperation. Even for parameter values where substantial abatement is optimal, the noncooperative solution often equals or at least approximates the cooperative solution. When the regions are uncertain about parameter values, the noncooperative response yields expected benefits that are almost as large as those of the cooperative response. In part, the small simulated benefits to cooperation reflect the aggregation of the diverse world community into only two agents in the model, so at least one bears a large share of global damages.

Several recent studies have modeled abatement of climate change as a noncooperative game of perfect information (e.g., Black et al., 1993; Dockner and Van Long, 1993; Hoel, 1991, 1993; Martin et al., 1993; Nordhaus and Yang, 1995; Tolwinski and Martin, 1995), although with the exception of Nordhaus and Yang (1995) they have not attempted to incorporate the economic and climate-system detail typical of integrated-assessment models. The study that is most comparable to the present work is that of Peck and Teisberg (1995), which uses a two-region numerical integrated-assessment model to compare cases in which the industrialized-nation region: (a) minimizes its own damages and abatement costs; (b) minimizes the sum of global damages and its own abatement costs; and (c) compensates the developing nations for cooperating in a globally optimal abatement program (except in case (c), the developing countries do not restrict their emissions). There is little abatement or environmental benefit in case (a), substantial benefits to developing countries and costs to industrialized countries in case (b), and larger benefits to both regions in case (c) (although the industrialized region is worse off than in case (a)).

The remainder of the paper is organized as follows. The analytic framework and integrated-assessment model are described in Section 2. Results for games with perfect and imperfect information are described in Section 3. Conclusions are in Section 4.

2. Analytic structure and the integrated-assessment model

The analysis is structured as a two-player, two-period game. Each of two world regions, denoted North (industrialized nations) and South (developing nations), selects a near-term GHG-abatement policy for an initial period (1990–2010). At the end of the initial period, each region selects a long-term policy for a second period (2010–2100). The allowable strategies in each period differ in GHG emissions and abatement costs. Payoffs to each region are defined as the sum of abatement costs and the reduction in damages from climate change, relative to a policy of no abatement. Three solution concepts are considered: cooperative, in which the regions choose strategies in both periods to maximize their joint benefits; non-cooperative, in which the regions select their Nash subgame-perfect, closed-loop, pure strategies to the two-period game; and 'delayed cooperative', in which the regions select their Nash strategies to the first-period game that is conditioned on cooperation in the second period.

Payoff matrices are presented for games with perfect and imperfect information. First, results are presented for a set of 144 games with perfect information, in which all parameter values are known in advance, and the dependence of the game outcomes on plausible alternative parameter values is assessed. Second, results are presented for a game with imperfect information and exogenous learning, in which knowledge about the parameter values in the first period is represented by a

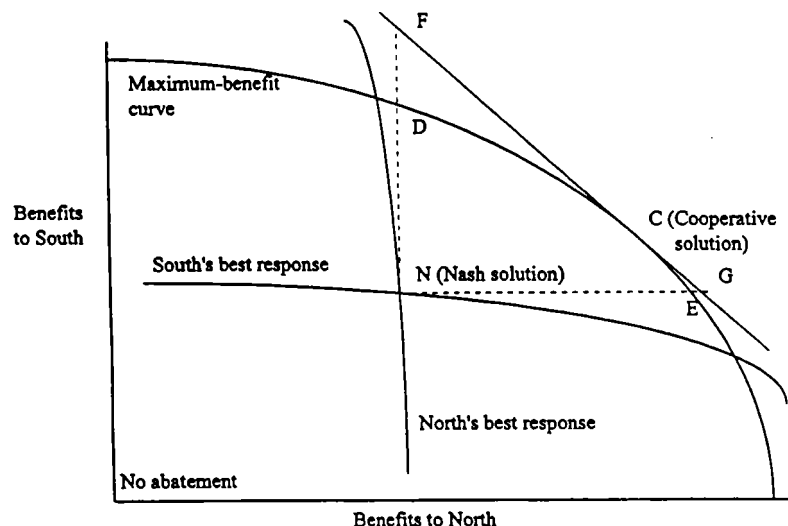


Fig. 1. Benefits to North and South for a hypothetical game with a continuous strategy space.

common-knowledge prior distribution and the parameter values become known before the second-period strategies are selected;¹ this case allows comparison of the cooperative and noncooperative solutions for the more realistic case with uncertainty and the expectation of improvements in information over time. It also allows evaluation of the expected value of having perfect information in the first period and its dependence on whether or not the regions cooperate (Hammitt, 1996).

The two-agent, two-period structure is an approximation to the many-agent, many-period or continuous-time game in which national governments, transnational and subnational organizations participate. It provides substantial computational efficiencies, allowing consideration of multiple games. The two-period limitation should not seriously affect the conclusions, but the limitation to two agents may, because at least half the global damages are internalized by a single agent.

Fig. 1 illustrates the payoff structure to a hypothetical game. Gains to each region are measured relative to the case in which neither region undertakes

¹ The games are modeled assuming 'nature' selects the vector of parameters describing climate and economic factors before the first period. In the games with perfect information, the result of nature's move is known to both regions; in the game with imperfect information, the result of nature's move is not known to the regions when they select first-period strategies but is known when they select second-period strategies.

abatement. The best-response functions describe each region's best action conditional on the other region's choice; their intersection (if any) is a pure-strategy Nash solution. The Nash equilibrium *N* may be considered the no-agreement solution (or threat point) because either region can withdraw from negotiations and expect to receive the benefits associated with this outcome (unless the other region is willing to reduce its own benefits to 'punish' the first). The Nash equilibrium may or may not be Pareto efficient. The Nash solution illustrated in Fig. 1 is inefficient: both regions' welfare would be improved if they could move to any point northeast of *N*. The sector *D-E* of the maximum-benefit locus represents the efficient bargaining range, i.e., the set of efficient outcomes that are Pareto superior to the Nash equilibrium. The regions can achieve any point in this range by coordinating their actions. The resulting gains from cooperation range from zero to *N-D* for South and from zero to *N-E* for North.

If the regions can make side-payments (e.g., direct aid, initial allocation of tradable emission permits), the range of feasible cooperative outcomes can be improved. The sum of the regions' benefits is maximized at point *C* in Fig. 1, where the slope of the maximum-benefit curve is -1 . In the modeling results that follow, this point is identified as the cooperative solution. If costs can be compensated without loss, all points on the tangent at *C* can be achieved by coordinating abatement actions to achieve *C* and making side-payments between regions as appropriate. To obtain an allocation between *C* and *F*, the North would transfer resources to the South; to achieve an outcome between *C* and *G*, the transfer would be reversed. (Note that the cooperative solution *C* may lie outside the range *D-E*; if so, all the points on the tangent that dominate the noncooperative solution require side-payments in a common direction and side-payments would be required to induce cooperation.) If side-payments are feasible, the efficient bargaining range is described by *F-G* and the possible gains from cooperation extend from zero to *N-F* for South and zero to *N-G* for North.

2.1. The integrated-assessment model

Abatement costs are simulated using a regionally disaggregated version of a model which simulates GHG emissions, atmospheric concentrations, an index of climate change, and abatement costs (Hammitt et al., 1992; Lempert et al., 1994). Net GHG emissions in year *t*, denoted $F(t)$, are modeled as the sum of emissions from each region

$$F(t) = F_N(t) + F_S(t),$$

$$F_N(t) = B_N(t) I_N(t) E_N(t),$$

$$F_S(t) = B_S(t) I_S(t) E_S(t),$$

where the subscripts *N* and *S* (dropped hereafter) denote North and South. For each region, $B(t)$ is a reference emission trajectory incorporating trends in

population, economic growth, energy use and GHG emission rates. $I(t)$ is an index of energy intensity (energy use per unit economic activity) and $E(t)$ is an index of emissions intensity (GHG emissions per unit energy). Abatement actions are represented through their effect on $I(t)$ and $E(t)$; in the absence of abatement, $I(t) = E(t) = 1$ for all t .

The model is based on the dominance of energy use among GHG sources: carbon dioxide accounts for 72% of the increase in radiative forcing between 1990 and 2100 under the 1990 Intergovernmental Panel for Climate Change (IPCC) 'business as usual' Scenario A (Houghton et al., 1990) and energy transformation contributes about three-quarters of current anthropogenic CO₂ emissions (Houghton et al., 1990). Other GHGs are incorporated by multiplying $F(t)$ by the 1990 ratio of anthropogenic GHG emissions (in units of equivalent CO₂) to CO₂ emissions (1.72) to approximate global emissions of the major GHGs. This choice implies that climate forcing by the other GHGs can be limited at comparable marginal cost to forcing by CO₂. Atmospheric concentration is modeled using a linear impulse-response function for CO₂ fit to the results of an ocean general circulation model (Maier-Reimer and Hasselmann, 1987).

Climate change is represented by the difference between global annual mean surface temperature in year t and its pre-industrial level, $\Delta T(t)$. Although the effects of climate change will depend on regional and seasonal changes in temperature, precipitation, and other climate dimensions, the magnitudes of such changes are likely to correlate with ΔT . $\Delta T(t)$ is simulated using an energy-balance, box-diffusion model (Hoffert et al., 1980; Cess and Goldenberg, 1981; Schneider and Thompson, 1981; Siegenthaler and Oeschger, 1984) calibrated to results of an upwelling-diffusion model (Schlesinger and Jiang, 1990, 1991). Uncertainties about climate change can be summarized by considering alternative values of the climate sensitivity ΔT_{2x} , defined as the equilibrium increase in global annual mean surface temperature accompanying a doubling of pre-industrial atmospheric CO₂. Two values, $\Delta T_{2x} = 2.5$ and 4.5°C , are considered; these correspond to the middle and upper values suggested by IPCC (Houghton et al., 1990).

Damages are modeled using regional damage functions. The appropriate specification is highly uncertain. It seems reasonable to assume that damages at time t are increasing and convex in $\Delta T(t)$, at least for the degree of climate change reasonably anticipated. However, negative damages (benefits) are possible for small climate change (especially if potential fertilization by increased atmospheric CO₂ is incorporated) and diminishing marginal damages presumably set in for sufficiently large changes (although perhaps not until after existing human infrastructure has become unsuitable to local climate and natural ecosystems have been destroyed). Damages may be more sensitive to the rate of change than the difference from pre-industrial climate, since given adequate time, humans can adapt their activities to a broad range of climatic conditions and wildlife may become reestablished in suitable locations.

For comparability with other work, damages at time t are represented here by a simple geometric function

$$D(t) = \mu \text{GDP}(t) [\Delta T(t) - \Delta T(1990)]^\gamma$$

where $\Delta T(1990) = 0.5^\circ\text{C}$ (Houghton et al., 1990) and $\text{GDP}(t)$ is the time path of regional Gross Domestic Product (Gaskins and Weyant, 1994). Damages are assumed to depend on the magnitude of climatic change relative to the 1990 level, since the economy is presumably adapted to the current rather than to pre-industrial climate.

Alternative values of the exponent $\gamma = 1.3, 2.0$, and 3.0 are considered, and alternative values of μ are selected so that damages at $\Delta T = 3.0^\circ\text{C}$ correspond to 2%, 4% and 8% of gross world product. The value $\gamma = 1.3$ corresponds to Cline's (1992) base case, $\gamma = 2$ to Nordhaus' (1992, 1993) base case and Cline's (1992) high case, and $\gamma = 3$ to Peck's and Teisberg's (1992, 1993) high case, respectively. The lowest value of μ is based on Nordhaus' (1991) estimate that global damages for $\Delta T = 3.0^\circ\text{C}$ are unlikely to exceed 2% of gross world product. Cline (1992) used 2% as his high case (his base case is 1%) and Peck and Teisberg (1992, 1993) use 2% as their base case. (In more recent work, Nordhaus (1992, 1993) uses a value of 1.3%.) The alternative values of μ represent arbitrary doubling and redoubling of the benchmark. In addition, to reflect the possibility that damages will be proportionally greater in the currently developing countries than in the industrialized nations (Lave and Vickland, 1989; Nordhaus, 1991; Strzepek and Smith, 1995), an unequal damage case is considered in which damages at $\Delta T(t) = 3^\circ\text{C}$ equal 1% of gross regional product in the North and 3% of gross regional product in the South. Under this specification, global damages at $\Delta T = 3.0^\circ\text{C}$ are approximately 2% of gross world product.

Two classes of abatement activity are incorporated, which differ in cost per unit emission reduction, capacity, and rate of implementation. 'Energy conservation' represents a class of activities that are relatively inexpensive, quickly implemented, and limited in scope. Conservation is represented by a reduction in energy intensity $I(t)$ from 1.0 to ρ . $I(t)$ follows a logistic path with rate characterized by the transition half-life r_c , representing the time from initiation of conservation until $I(t) = (1 + \rho)/2$. The logistic time path is characteristic of technological diffusion (Mansfield, 1961; Fisher and Pry, 1971; Hafele, 1981). Costs are assumed to be incurred in the year of operation and are linear in energy savings.

Additional emission reductions require 'fuel switching', which represents a set of higher-cost, more slowly implemented actions. Cost and effectiveness are simulated assuming that all emissions are produced by long-lived capital equipment using either emitting (fossil fuel) or non-emitting (e.g., nuclear, solar, biomass) technologies; for both technologies, construction and operating periods are 10 and 30 years, respectively. The carbon intensity or fraction of energy use reliant on emitting technologies $E(t)$ is also constrained to follow a logistic path.

The transition half-life r_f is a choice variable and eventual complete substitution of non-emitting technologies is assumed ($E[\infty] = 0$).

The abatement cost due to fuel switching is the difference between policy-induced and base-case expenditures on vintaged capital equipment. Fuel switching is divided between low-cost and high-cost components, reflecting increasing marginal abatement costs. $E(t)$ can be reduced from 1.0 to 0.5 using only low-cost non-emitting capital; additional reductions require high-cost non-emitting equipment. Operating costs are incurred each year the equipment is in use and capital costs are uniformly divided over the ten-year construction period. Sufficient capital equipment to satisfy increased energy demand and to replace equipment that will retire a decade later is assumed to enter construction each year, with the appropriate share of non-emitting capital to satisfy the desired trajectory for $E(t)$. For rapid emission reductions, marginal abatement costs increase with the rate of abatement because emitting equipment must be retired prematurely (oldest first).

2.2. Regional emission and cost parameters

Alternative emission and cost parameters are obtained by calibrating model outputs to the results of two energy-economy models: the Edmonds–Reilly Model (Edmonds and Reilly, 1985) and Global 2100 (Manne and Richels, 1992). These are among the most prominent of the models used for estimating the costs of reducing future CO₂ emissions, and are the only models participating in a recent model-comparison study (Stanford Energy Modeling Forum EMF-12; Beaver,

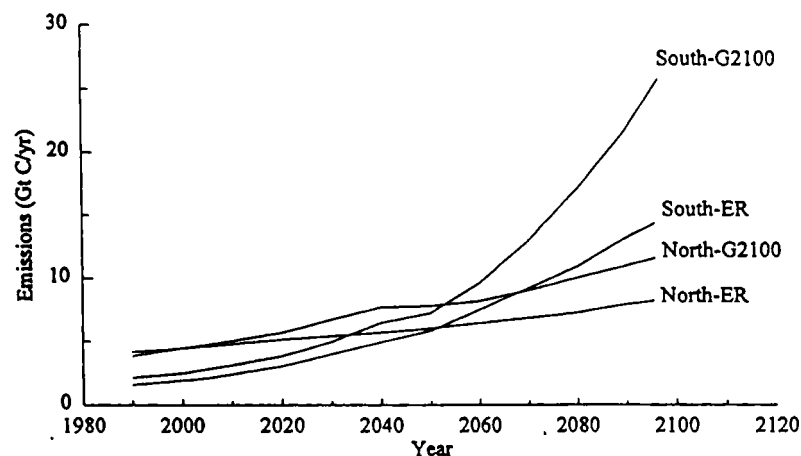


Fig. 2. Baseline emission trajectories for North and South calibrated to Edmonds–Reilly and Global 2100 model results.

Table 1

Cost parameters (\$/ton avoided carbon emissions)

Abatement technology	Edmonds–Reilly		Global 2100		Hammit et al. (1992)
	North	South	North	South	
Conservation	0	52	0	74	5
Low-cost non-emitting	320	130	230	110	50
High-cost non-emitting	999	570	399	334	200

1993; Gaskins and Weyant, 1993, 1994) that provide the regional detail and distant time horizon required for this analysis.

Parameters are estimated independently for each region and model. First, the reference emission trajectory $B(t)$ is set equal to the EMF-12 reference-case emissions. As shown by Fig. 2, base-case emissions grow more rapidly in the South than the North, and are higher for Global 2100 than for the Edmonds–Reilly model.² Second, five sets of capacity (ρ) and rate (r_c , r_f) parameters are estimated so that the emission model used here approximates the emission trajectory simulated by the energy-economy models for each of the five EMF-12 policy scenarios (stabilization by 2000, 20% reduction by 2010, 50% reduction by 2050, 2%/yr reduction, and phased-in carbon tax). Third, for each of the five policy scenarios, cost parameters are estimated so that the average cost of emission reduction approximates the average cost calculated by the EMF-12 models. Both emission-reduction- and cost-parameter values are obtained using nonlinear-least-squares regression, taking each year as an independent observation.

Capital and operating costs are estimated as a common multiple of the capital and operating costs of CO₂-emitting energy-using equipment, subject to the constraint: $0 \leq \text{cost of conservation} \leq \text{cost of low-cost non-emitting equipment} \leq \text{cost of high-cost non-emitting equipment}$. Estimated cost parameters do not vary systematically with the policy scenario from which they are estimated. Consequently, the median values across scenarios for each region/model pair, reported in Table 1, are used for simulation. The conservation capacity parameter ρ , derived by fitting the emissions path to the EMF policy scenarios, is 0.8 for all cases. This corresponds to satisfying 20% of energy demand through conservation.

Marginal abatement costs estimated from the Edmonds–Reilly Model are greater than those estimated from Global 2100 (except conservation costs in the South). Moreover, both sets of estimates are substantially larger than the values used in prior work with the globally aggregated version of this model (Hammit et

² The regions are defined as aggregates of the five regions used in the EMF study so that the emission constraints of each EMF scenario (which differ between EMF regions) are common to each component of the aggregate regions. North includes the USA, Other OECD, and the former USSR, and South includes China and the Rest of World.

al., 1992; Lempert et al., 1994) which are based on estimates by Nordhaus (1991) and the backstop (unlimited capacity) costs of Global 2100 (\$208/ton carbon; Manne and Richels, 1992). The high costs relative to the backstop have been attributed to the rapid emission reductions incorporated in the EMF scenarios (Gaskins and Weyant, 1993, 1994).

For both sets of parameter values, the cost of conservation is lower in the North and the cost of fuel switching is lower in the South. This suggests that the North is the least-cost emission avoider in the near term (during which conservation is the only mechanism with significant effect) and the South is the least-cost avoider over the longer term (when conservation opportunities are saturated and incremental reductions are achieved by fuel switching).

3. Simulated payoff matrices

Games with perfect and imperfect information about the values of the climate sensitivity, damage function, and other parameters are examined in the following subsections.

3.1. Games with perfect information

Payoff matrices are calculated for the set of 144 games summarized in Table 2. The games differ in their damage function, climate sensitivity, baseline emissions, cost parameters, and discount rate. The payoff matrices for three representative games are described below, followed by a summary of how the cooperative and noncooperative solutions vary with changes in parameter values.

Each region is allowed to choose from the finite set of first-period strategies described in Table 3. In the second period, each region can modify its first-period fuel-switching rate and adopt conservation if it had not previously done so.

The payoff matrices for four games are illustrated in Fig. 3. Panels A and B illustrate the best-response functions and efficient frontier for the game with climate sensitivity $\Delta T_{2x} = 2.5^\circ\text{C}$, the damage function with damages proportional to $[\Delta T(t)]^3$ and equal to 2% of GDP at $\Delta T = 3^\circ\text{C}$ ($\gamma = 3$, $\mu = 2\%$), discount rate $r = 5\%$, and the reference emission and cost specification based on Global 2100 results. Panel A illustrates the game in strategy space: points in the upper-right corner of the panel represent rapid first-period emission reductions; points in the lower-left corner represent minimal first-period abatement. Panel B shows the same points plotted in payoff space: points in the upper-right corner represent larger benefits to both regions.

For this game, the cooperative and Nash solutions coincide. As illustrated by the reaction functions, the minimal-abatement Strategy 1 is dominant for South; it is the best response to any action North could choose. The minimal-abatement action is also North's best response to any action by South, except North should

Table 2
Game parameters^a

Category	Parameter	Description	Values	Prior ^b
Emissions	$B(t)$	Uncontrolled GHG emission path	Edmonds–Reilly, Global 2100	1/2, 1/2
Abatement costs	Cost parameters	Unit conservation and fuel-switching costs	Edmonds–Reilly, Global 2100	1/2, 1/2
Climate	ΔT_{2x}	Sensitivity of climate to GHG concentrations	2.5, 4.5°C	2/3, 1/3
Damages	γ	Damage function exponent	1.3, 2.0, 3.0	1/3, 1/3, 1/3
	μ	Damage function coefficient	2, 4, 8%, 3.1%	1/4, 1/4, 1/4, 1/4
Welfare	r	Discount rate	0, 3, 5%/yr	1/5, 2/5, 2/5

^a 144 games with perfect information = 2 (coupled) emissions and abatement-cost specifications $\times$ 2 climate sensitivities $\times$ 3 damage-function exponents $\times$ 4 damage-function coefficients $\times$ 3 discount rates.

^b Game with imperfect information: marginal prior probabilities of each parameter value; parameters are assumed to be probabilistically independent.

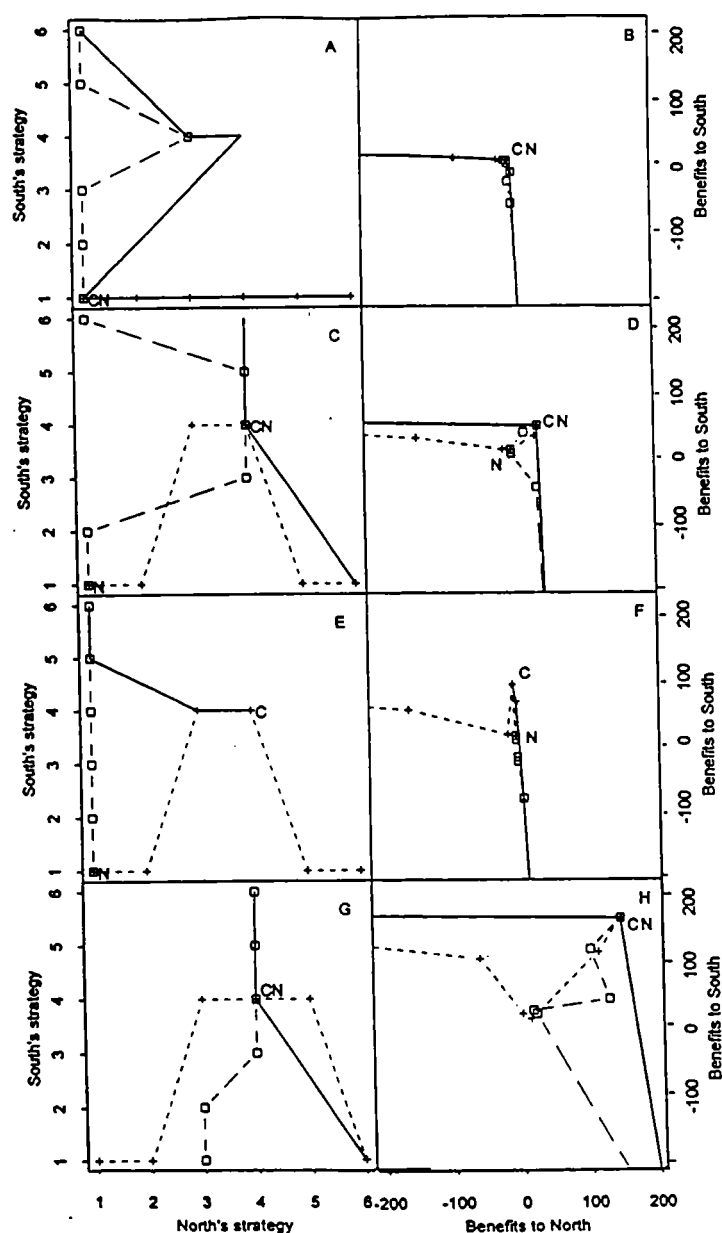


Table 3

First-period strategies

Strategy	Initiate conservation?	Fuel-switching rate ^a
1	No	140
2	No	100
3	Yes	140
4	Yes	100
5	Yes	40
6	Yes	20

^a Years from initiation to 50% completion.

adopt Strategy 3 if South adopts Strategy 4. The efficient frontier approximates the union of the best-response functions.

Qualitative aspects of the game are sensitive to the cost parameters, damage function, and other parameters. The parameters of the game illustrated in Panels C and D are identical to those of the first game, except the discount rate is reduced to 3%. This change increases the importance of future damages relative to near-term abatement costs. Comparison of Panels C and A shows that the efficient frontier requires substantially more abatement in the second game, and the cooperative solution requires both regions to adopt Strategy 4. The cooperative solution is a Nash equilibrium, but the minimal-abatement solution (where both regions adopt Strategy 1) is also a Nash equilibrium. The global benefits of the first equilibrium (the cooperative solution) are \$76 billion/yr (annualized at 3%) greater than those of the second equilibrium, 0.14% of the annualized world GDP of about \$54 trillion.

The game illustrated in Panels E and F is the same as that in Panels C and D, except the damage function is changed to the asymmetric case ($\mu = 3:1\%$) for which damages, as a fraction of GDP, are three times larger for South than North, but remain about 2% of global GDP at $\Delta T = 3^\circ\text{C}$. The effect of this change is to reduce (strictly, not increase) North's and increase (not decrease) South's optimal abatement action (note that North's best-response function is shifted to the left relative to the corresponding function in Panel C). Because global damages are approximately the same as in the previous game, the cooperative solution is unchanged, with global annualized benefits of \$73 billion/yr relative to the

Fig. 3. Payoff matrices for illustrative games with strategies described in Table 3. Panels in the left-hand column are plotted in strategy space; panels in the right-hand column are plotted in payoff space. Both columns illustrate the efficient frontier (solid line), best-response functions (North – long dashes with $\square$, South – short dashes with $+$), Cooperative (C) and Nash (N) solutions. Panels A–F: Global 2100 emission and abatement-cost parameters, $\Delta T_{2x} = 2.5^\circ\text{C}$ and $\gamma = 3$ with: $\mu = 2\%$, $r = 5\%$ (Panels A and B); $\mu = 2\%$, $r = 3\%$ (Panels C and D); $\mu = 3:1\%$, $r = 3\%$ (Panels E and F). Panels G and H: Imperfect first-period information with common-knowledge prior distribution specified in Table 2.

minimal-abatement Nash equilibrium. The cooperative solution is not a Nash equilibrium, however, because of the shifts in the best-response functions. Moreover, comparison of Panels C and E shows that the efficient frontier shifts from a situation where it is efficient for North but not necessarily for South to undertake substantial abatement (i.e., to adopt Strategy 4, 5, or 6) to a situation where it is efficient for South but not necessarily for North to do so.³

Comparison among the 144 simulated games with perfect information suggests several general results. The following subsections describe how the cooperative and noncooperative solutions depend on assumed parameter values.

3.1.1. Cooperative solutions

The cooperative solution minimizes the sum of regional abatement costs and climate damages (point C in Fig. 1). For parameter values consistent with 'best guess' estimates of climate sensitivity and economic damages, optimal abatement is limited. For example, of the 24 games with $\Delta T_{2x} = 2.5^\circ\text{C}$, damage functions with $\mu = 2\%$ or the asymmetric 3:1%, and discount rate $r = 3\%$ or 5% , the cooperative solution requires minimal abatement in 14 cases (58%). This result is consistent with globally integrated analyses (Nordhaus, 1992, 1993, 1994; Peck and Teisberg, 1992, 1993).

Shifts in the cooperative solution induced by changes in parameters are in the expected directions. Increases in the damage-function coefficient, decreases in the discount rate, and increases in the climate sensitivity increase the present-value damages of climate change and never shift the cooperative solution toward less stringent first-period abatement. Increases in the damage-function exponent often produce less stringent first-period abatement because, although such changes increase the damages that occur for large ΔT , they reduce damages in the near term (when $\Delta T < 3^\circ\text{C}$) and can thereby reduce the present value of damages (especially for the larger discount rates considered).

The distribution of abatement between regions is suggestive of the pattern of marginal abatement costs implicit in the model specification. For the Edmonds–Reilly cost parameters, where the cost of fuel switching is substantially smaller in the South than the North, South is the long-run least-cost abater: the second period fuel-switching rate for South is almost always as fast or faster than the rate for North. The pattern of first-period abatement depends on the stringency of the damages. For games with high damage functions (when the cooperative first-period solution requires, at a minimum, conservation by both regions), South undertakes at least as much abatement as North. For games where less first-period abatement

is optimal, South generally undertakes no more rapid abatement than does North. For the Global 2100 cost parameters, where the regional cost parameters are more similar, North is often the least-cost abater in the long run: the second-period fuel switching rates are frequently 120 yrs for North and 140 yrs for South, although for high damage cases (e.g., $\mu = 8\%$ and discount rate = 0%), South can have a faster second-period rate than North.

3.1.2. Noncooperative solutions

Of the 144 simulated games, 117 (81%) have one pure-strategy Nash equilibrium and the remaining 27 games have two. In the games with two Nash equilibria, one is always the minimal-abatement solution, in which both regions undertake minimal abatement in both first and second periods. The other Nash solution dominates the minimal-abatement equilibrium and corresponds, in all but one of these games, to the cooperative solution. Thus, for 26 of these 27 games, even if the regions could not agree to explicit cooperation, an agreement to coordinate their actions to achieve the Pareto-superior of the two Nash equilibria would be as effective.

The fraction of the global benefits of cooperation that is achieved by the Nash solution varies widely across games. Of the 24 games with 'best-guess' parameter values ($\Delta T_{2x} = 2.5^\circ\text{C}$, $\mu = 2\%$ or $3:1\%$, $r = 3\%$ or 5%), the Nash solution coincides with the cooperative solution in 19 games (79%), including the 14 cases where the cooperative solution requires minimal abatement.

As summarized in Table 4, the cooperative solution requires minimal abatement in 19 (13%) of the 144 games evaluated; not surprisingly, it is also the unique Nash equilibrium in these cases. Counting only the dominant Nash solution in games with multiple equilibria, the cooperative and noncooperative solutions

Table 4
Comparison of Nash and delayed-cooperative solutions with cooperative solution

Cooperative solution is minimal abatement?	Equals cooperative solution? ^a	Benefits ^b	Noncooperative		Delayed cooperative	
			Games	%	Games	%
Yes	Yes	na ^c	19	13	19	13
No	Yes	100%	62	43	77	53
No	No	90–100%	22	15	10	7
No	No	60–90%	11	8	14	10
No	No	40–60%	8	6	2	1
No	No	0%	22	15	22	15
Total			144	100	144	100

^a Noncooperative or delayed-cooperative solution (dominant one in games with two equilibria) coincides with cooperative solution.

^b Benefits of noncooperative or delayed cooperative solution divided by benefits of cooperative solution (both measured relative to minimal abatement strategy pair).

^c na = not applicable (ratio is 0/0).

³ In the game with the asymmetric damage function, the strategy pair in which North adopts its Strategy 6 and South adopts its Strategy 1 is just dominated by the cooperative solution. If the benefits to South were slightly larger for this strategy pair, the efficient frontier in Panel F would include a line segment extending to the left from the cooperative solution, as it does in Panels B and D.

coincide in 62 games (43%) in which some abatement is optimal. In the remaining 63 games (44%), the cooperative solution is not a Nash equilibrium. The extent to which the noncooperative solution captures the benefits of cooperation can be quantified as the ratio of the global benefits of the noncooperative solution to the global benefits of the cooperative solution, both measured relative to the minimal-abatement solution. The median value of this ratio across the 63 games for which the cooperative and noncooperative solutions differ is 68%. Of these games, the Nash equilibrium is the minimal-abatement solution in 22 cases; none of the benefits of cooperation are achieved and the ratio is zero. The global benefits of the noncooperative solution are between 90% and 100% of their value at the cooperative solution in 22 games, between 60% and 90% in 11 games, and between 40% and 60% in eight games.

Setting aside the 19 cases in which the cooperative solution requires minimal abatement, the 62 games in which the Nash and cooperative solutions coincide are disproportionately those with larger climate damages and smaller marginal abatement costs ($\Delta T_{2x} = 4.5^\circ\text{C}$, $r = 0\%$, $\gamma = 1.3$, Global 2100 emissions and cost parameters⁴). In these games, self-interested action often entails significant abatement. In contrast, the 22 games in which the cooperative solution requires abatement but the noncooperative solution is the minimal-abatement point are disproportionately those with low damages and higher marginal abatement costs ($\Delta T_{2x} = 2.5^\circ\text{C}$, $r = 3$ or 5% , $\mu = 2\%$ or 3.1% and Edmonds–Reilly emissions and cost parameters).

Of the 63 games where the cooperative solution is not a Nash equilibrium, the cooperative solution dominates the Nash equilibrium in only three cases. In the other games, sidepayments are required for both regions to benefit from cooperation. In 41 games, South requires compensation from North in order to benefit from cooperation; in 19 games, North requires compensation from South. The direction of the side-payments is sensitive to the damage function: the asymmetric case (where South's damages are three times larger than North's, as a fraction of GDP) accounts for 9 of the 19 cases in which South must pay North, but only one of the 41 cases where North must pay South. Required sidepayments are substantial, relative to the gains from cooperation. For the games where South requires compensation, the median ratio of its minimum demand to North's maximum offer is 54%; the quartiles of the ratio are 36% and 74%. Similarly, the median ratio of North's minimum demand to South's maximum offer in the games where North requires compensation is 50%; the quartiles are 25% and 80%.

The games with multiple Nash solutions all use the Global 2100 reference emissions trajectories and cost parameters, and cases with low damages ($\mu = 3:1$ or 2% , $r \neq 0\%$) are disproportionately represented. When two Nash equilibria

exist, they are at the points indicated in Panel C of Fig. 3, where both regions adopt Strategy 1 and where both adopt Strategy 4. These points represent the corners of a plateau in the global benefit function. The factors producing these multiple Nash solutions may be elucidated by considering how the benefit surface depends on the damage function and discount rate.

When the present-value damages are small relative to the abatement costs (that is, for small damage-function coefficients and large discount rates), the minimal-abatement solution is generally optimal and is the only Nash solution (as in Panel A of Fig. 3). As the damages become larger relative to abatement costs (that is, as the damage function coefficient increases or the discount rate decreases), the plateau rises and the cooperative solution shifts to the point where both regions adopt Strategy 4. Both the cooperative solution and the minimal-abatement point may be Nash solutions (as in Panel C of Fig. 3). As the damages become even larger relative to abatement costs, the plateau continues to rise, the cooperative solution remains at the 100 yr point and is often a Nash solution, but the regions' best-response functions shift away from their minimal actions and the minimal-abatement point is no longer a Nash solution.

3.1.3. Delayed-cooperative solutions

Negotiating a global mitigation agreement may be difficult and time consuming. Consequently, it is of interest to consider a game in which the regions do not cooperate in the first period, but anticipate doing so in the second. The payoff matrices for these games are constructed assuming the regions adopt the cooperative solution to the second-period game that results from each combination of first-period strategies.

The delayed-cooperative solutions to each game are similar to the Nash solutions described above. As shown in Table 4, the proportion of games for which the cooperative solution is a delayed-cooperative equilibrium is slightly

Table 5
Expected values of information and cooperation (\$ billion/yr)

Expected value of cooperation	First-period information	
	Perfect	Imperfect
Global	12	6
North	17	10
South	–5	–4
Expected value of information	Solution	
	Cooperative	Noncooperative
Global	14	19
North	6	13
South	8	6

⁴ Recall that the Global 2100 parameters yield higher reference-case emissions and lower marginal abatement costs than the Edmonds–Reilly parameters.

larger than the corresponding proportion for which the cooperative solution is a Nash equilibrium: in addition to the 19 games for which the minimal-abatement solution is globally optimal, the delayed-cooperative solution coincides with the cooperative solution in 77 games (53%). The similarity between the Nash and delayed-cooperative solutions suggests that the costs of delaying cooperation to the second period are nearly as large as the costs of never cooperating.

In contrast, the opportunity costs of delaying cooperation to the second period are somewhat more balanced than the costs of failing to cooperate: to ensure Pareto improvement by moving from delayed to immediate cooperation, North would need to compensate South in 24 games and South would need to compensate North in 22 games. The cooperative solution dominates the delayed-cooperative solution in only two games.

3.2. Games with imperfect information

The values of the climate sensitivity, damage function, and other parameters are not accurately known at present, but it is likely that information about them will improve as research and observation continue. Consequently, it is of interest to consider a game in which the parameter values are uncertain in the first period, but their values become known before second-period strategies are selected. First-period information about the parameter values is represented by a prior probability distribution that is common knowledge – both regions have equal access to current scientific understanding of climate change. The parameters are probabilistically independent and assigned marginal probabilities as shown in Table 2. For each parameter, the prior distribution assigns equal probability to all values considered, except the high climate sensitivity (4.5°C) is assigned smaller probability than the alternative (2.5°C), as these are the upper and middle values of the IPCC uncertainty range, respectively (Houghton et al., 1990), and the positive discount rates (3, 5%) are each assigned larger probability than the less defensible 0% rate.

Each region is assumed to minimize its expected damages plus abatement costs. The resulting payoff matrix is summarized in Fig. 3, Panels G and H. In the first period, the cooperative solution and the unique Bayesian Nash solution both require the regions to adopt Strategy 4. As shown by the best-response functions in Panel G, it is in North's interest to undertake significant abatement regardless of South's action, and it is in South's interest to undertake significant abatement unless North adopts its weakest or strongest abatement strategies. Although the first-period actions coincide at the cooperative and Nash solutions, the expected benefits depend on whether or not the regions cooperate in the second period: as summarized in Table 5, the expected global benefits of cooperation are \$6 billion/yr. These benefits are unequally allocated between regions: North would need to compensate South between \$4 billion/yr and \$10 billion/yr for cooperation to produce an expected gain for both regions. The \$6 billion/yr difference between the expected global benefits of cooperation and noncooperation is small

compared with the \$284 billion/yr difference in expected benefits between the cooperative and minimal-abatement solutions: the noncooperative solution provides 98% of the expected benefits of cooperation. Because the first-period actions for the cooperative and noncooperative solutions coincide, the delayed-cooperative solution yields the same expected benefits as the cooperative solution.

Depending on the parameter values that are revealed at the second period, the first-period abatement may prove *ex post* to have been stronger or weaker than what would have been optimal if the parameter values were known in the first period. The expected reduction in abatement costs plus damages that could be achieved if the parameter values were known *ex ante* (the Expected Value of Perfect Information or EVPI) depends on whether the regions act cooperatively or noncooperatively. If the regions cooperate, EVPI must be non-negative for the global community – a unitary decision maker cannot be made worse off in expectation by improved information (Hammitt, 1995). In contrast, EVPI can be negative for a single region, and perhaps for the global community if the regions do not cooperate (Hammitt, 1996). As shown in Table 5, the global expected value of information is \$14 billion/yr if the regions cooperate and somewhat larger, \$19 billion/yr, if they do not. With cooperation, the expected value of information is about equally distributed between the regions; without cooperation, the value of information to the North is about twice the value to the South, reflecting greater sensitivity of North's than South's best-response function to parameter values.

4. Conclusions

Structuring the problem of abating climate change as a noncooperative game provides insight into regional interests, the value of international cooperation, and the abatement policies that nations or supra-national organizations (e.g., OECD) might adopt in the absence of an international agreement.

For the games analyzed, the difference in benefits between cooperative and noncooperative solutions is often modest, relative to the differences associated with alternative states of nature. Among the games with perfect first-period information, more than half the noncooperative solutions coincide with the cooperative, globally efficient, solutions. The cooperative and noncooperative solutions often coincide for games using 'best guess' estimates of climate sensitivity and damages. This is not surprising as, consistent with single-agent optimization studies, the cooperative solution requires little abatement for these parameter values. Even for states of nature where substantial abatement is optimal, however, the Nash equilibrium when it is unique, or one of the multiple Nash solutions, often equals or approximates the cooperative solution. Over 144 games with perfect information (which are biased toward more severe damages and larger climate sensitivity than 'best guess' values), the noncooperative solution captures

at least 90% of the global benefits of the cooperative solution in 103 games (71%). This result extends to a game with first-period uncertainty about the parameter values, with the uncertainty resolved in time for second-period decisions. For this game, the expected benefits at the noncooperative solution are 98% of the expected benefits at the cooperative solution, with the difference entirely due to differences in second-period actions.

The frequently small simulated difference between cooperative and noncooperative solutions suggests that global agreements to limit climate change may not be as important as is often assumed. However, some cases with substantial cost differences were identified. In 22 (15%) of the games with perfect information, the Nash equilibrium yields none of the benefits of cooperation. In an additional 27 games (19%), two Nash equilibria exist, with one providing none of the benefits of cooperation.

The delayed-cooperative solutions, in which the regions adopt Nash strategies in the first period conditioned on the knowledge that they will cooperate in the second, are similar to the noncooperative solutions. Single-agent studies have typically shown that delaying abatement a decade or two imposes little additional cost (Hammit et al., 1992; Lempert et al., 1994; Nordhaus, 1993). In this case, however, most of the cost savings that may be achieved through cooperation are lost if cooperation is delayed 20 years.

In evaluating these results, several caveats should be recognized. The discrete strategy space limits the resolution with which differences between cooperative and Nash solutions can be identified (and may influence the location of the solutions), but it does not seriously limit the ability to detect small cost differences (because the cost surface is sufficiently flat in the relevant regions). The possibility that 'leakage' (increased GHG emissions from one region induced by abatement policies in another; Felder and Rutherford, 1993) may significantly reduce the cost-effectiveness of independent regional abatement programs has not been incorporated.

The optimistic conclusion that, for many parameter values, the global costs of the Nash equilibrium equals or approximates that of the cooperative solution appears to result from the division of the world into only two regions, so at least one region bears a large share of global damages (Olson and Zeckhauser, 1966). This analysis differs from the canonical commons problem, in which each of a large number of atomistic agents bears a negligible share of community damages (Hardin, 1968). Peck and Teisberg (1995) also find evidence that a large region may incur substantial abatement costs in its own interest. In their analysis of games with perfect information, the optimal carbon tax or marginal control cost in the North, when the North controls its emissions and the South does not, is about half the level of the optimal carbon tax at the cooperative solution (for the 21st Century, falling in the 22nd Century when the North's ability to control climate damages falls with its share of global emissions). They also find that the optimal tax for this case is larger when the North includes the former Soviet Union, and

thus internalizes a larger share of global damages, than when it does not. (Despite the substantial carbon tax, unilateral action by North yields small emission reductions because the Peck and Teisberg model provides limited opportunities for low-cost abatement.) In contrast, Nordhaus and Yang (1995) find that the Nash solution yields almost no abatement in their game with perfect information and ten regions (several of which are structured so as not to internalize their full regional damages). In their analysis, the average carbon tax increases with time from about \$6 to \$30/ton carbon in the cooperative solution, but does not exceed \$1/ton carbon for the Nash solution. Because current and likely future GHG emissions are concentrated in a relatively small number of countries, the relevant case probably lies between the two-agent and atomistic-agent cases.

Acknowledgements

This work was partially supported by the National Oceanic and Atmospheric Administration and the Harvard Center for Risk Analysis. The authors thank C. Kolstad, A. Manne, W. Martin, E. Parson, S. Peck, J. Reilly, and the referees for helpful comments.

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A welfare-based index for assessing environmental effects of greenhouse-gas emissions

James K. Hammitt, Atul K. Jain, John L. Adams
& Donald J. Wuebbles

A welfare-based index for assessing environmental effects of greenhouse-gas emissions

James K. Hammitt*, Atul K. Jain†, John L. Adams‡
& Donald J. Wuebbles†

* Center for Risk Analysis and Department of Health Policy and Management, Harvard School of Public Health, 718 Huntington Avenue, Boston, Massachusetts 02115, USA

† Department of Atmospheric Sciences, University of Illinois, 105 South Gregory Avenue, Urbana, Illinois 61801, USA

‡ RAND Corporation, 1700 Main Street, Santa Monica, California 90407 USA

The global warming potential (GWP) index¹⁻³ is a measure of the relative contribution of the emissions of different greenhouse gases to the radiative forcing of the atmosphere—and thus to climate change—over a given time period. But this index does not represent the effects of climate change, and therefore does not provide an adequate basis for policy decisions about emissions reductions. This inadequacy has led to the proposal of an alternative, the economic-damage index (EDI)⁴⁻⁷. This index compares the effect of different greenhouse-gas emissions on global economic welfare. Here we use a simple climate model to calculate the EDIs for a range of climate-change/greenhouse-gas emission scenarios, and compare the values to the corresponding GWPs. Although the values of these indices are, at this stage, broadly similar in both magnitude and uncertainty, the prospects of reducing these uncertainties by future research are better for the EDI.

An index of the relative effects on economic welfare of unit mass emissions of alternative greenhouse gases (GHGs) is useful for evaluating trade-offs between GHG emissions for policy making, international negotiation, and for determining the most cost-effective means for limiting contributions to climate change. Such an index can also be used in a decentralized regulatory mechanism that limits the total effect of a nation's or firm's emissions, but permits the nation or firm to allocate its emissions among GHGs and to trade emission credits with others. (In an analogous fashion, the Montreal Protocol permits nations to reallocate their consumption of ozone-depleting substances, within classes, subject to a limit on total consumption weighted by ozone depletion potential). Because decentralized mechanisms do not require the regulator to know national or firm-specific costs of emission reductions, such mechanisms can substantially reduce abatement costs⁸ if difficulties in measuring GHG sources and sinks can be overcome⁹.

The GWP for GHG_{*i*} is defined as the ratio of the partial derivative of the time-integrated radiative forcing with respect to GHG_{*i*} relative to the partial derivative with respect to a standard GHG (by convention, CO₂)¹⁻³

$$\text{GWP}_i = \frac{\frac{\partial}{\partial e_i} \left[\int_0^h F(t) dt \right]}{\frac{\partial}{\partial e_0} \left[\int_0^h F(t) dt \right]} = \frac{\int_0^h \Delta C_i(t) R_i(t) dt}{\int_0^h \Delta C_0(t) R_0(t) dt} \quad (1)$$

where e_i and e_0 denote unit mass emissions of GHG_{*i*} and of CO₂ at time 0, h is a specified time horizon, and $F(t)$ denotes total radiative forcing at time t , respectively. In the second formulation, $\Delta C_i(t)$ and $\Delta C_0(t)$ are the differences in atmospheric concentration of GHG_{*i*} and of CO₂ between scenarios with and without incremental emissions of each GHG at time 0, and $R_i(t)$ and $R_0(t)$ are the incremental radiative forcing per unit of each GHG (the dependence of radiative forcing on atmospheric composition, and

hence t , can be neglected when GWP is evaluated for a constant-composition atmosphere¹⁻³). The GWP calculation treats GHGs as if their effects depend only on cumulative radiative forcing before the time horizon h . In an alternative formulation, the contribution to the index of future incremental forcing is reduced by exponential discounting and the horizon is extended to infinity¹⁰.

From a policy or economic-welfare perspective, radiative forcing *per se* is not important; what is significant is the effect of the associated climate change on human and natural systems that affect economic welfare (the 'damages', positive or negative, associated with climate change). To illustrate this, we consider a simple example in which climate-induced damages depend only on the maximum global annual-mean surface temperature reached¹¹. An incremental emission of a gas with a short atmospheric-residence time like CH₄ has negligible effect compared with an emission of a long-lived GHG like CO₂ if the emissions occur far enough before the year in which mean temperature peaks. As the emission date approaches the year of the peak, the emission of CH₄ becomes more important relative to that of CO₂. Neither GWP nor exponentially discounted radiative forcing¹⁰ properly account for the relative importance of short- and long-lived GHGs in this example, or in more realistic settings.

The EDI takes account of relative increments in economic welfare. In addition to climate-induced effects, EDI can incorporate effects that occur through other pathways including stratospheric-ozone depletion by halocarbons and enhanced plant growth by CO₂ fertilization⁵. EDI depends on future GHG emissions, because atmospheric composition affects incremental radiative forcing, some atmospheric-removal processes, and the economic effects of incremental climate change. (GWP also depends on future GHG emissions¹², although it is conventionally evaluated for a constant atmosphere.) Unlike GWP, EDI also depends on other factors that affect climate change (for example, H₂O feedback and sulphate aerosols) and factors that influence climate-induced effects and their value to humans. Along a socially optimal GHG-emission trajectory, the values of EDI correspond to ratios of the optimal marginal social costs or shadow prices of GHG emissions^{4,5}.

The EDI for GHG_{*i*} is defined as the reduction in emission of a standard GHG (CO₂) required to offset the incremental damage that would otherwise accompany an increased emission of GHG_{*i*}. Equivalently, EDI_{*i*} is the partial derivative of the present value of economic welfare loss with respect to emissions of GHG_{*i*} relative to the partial derivative with respect to CO₂ emissions

$$\text{EDI}_i = \frac{\frac{\partial}{\partial e_i} W[C(t)]}{\frac{\partial}{\partial e_0} W[C(t)]} = \frac{\int_0^\infty \Delta C_i(t) \lambda_i(t) dt}{\int_0^\infty \Delta C_0(t) \lambda_0(t) dt} \quad (2)$$

where $W[C(t)]$ represents economic welfare loss due to the time path of GHG concentrations $C(t)$. In the second formulation, $\lambda_i(t)$ denotes the marginal social cost or shadow price of an additional unit concentration of GHG_{*i*}.

For simplicity and consistency with current integrated-assessment models¹³⁻¹⁵, we neglect non-climate effects of GHG emissions and assume that damages due to climate change (net of adaptation costs) can be represented by

$$W[\Delta T(t)] = \int_0^\infty \left(\frac{1}{1+r} \right)^t \alpha \text{GDP}(t) D[\Delta T(t)] dt \quad (3)$$

where r is the discount rate, α is a scaling constant, $\text{GDP}(t)$ is gross world product and $\Delta T(t)$ is the increase in global annual-mean surface temperature from its value in 1990. The level and shape of the damage function are highly uncertain. The constant α cancels in EDI, so uncertainty about its value (assuming it to be positive) is unimportant. (If non-climate impacts such as CO₂

TABLE 1 EDI for selected parameter values, atmospheric lifetime and GWP

EDI		CO ₂	N ₂ O	CH ₄	CFC-11	CFC-12	HCFC-22
Middle case*		1	354.8	11.0	3,123	9,067	773
Discount rate, r	1% yr ⁻¹	1	322.2	3.73	1,833	7,950	261
	5% yr ⁻¹	1	366.2	23.70	4,317	9,596	1,688
Damage-function exponent, γ	1	1	354.7	27.21	4,182	9,279	1,962
	3	1	340.1	5.10	2,334	8,527	353
	'Hockey-stick'†	1	319.4	6.07	2,043	7,910	428
Climate sensitivity, ΔT_{2x}	1.5 °C	1	353.4	10.03	3,047	9,028	702
	4.5 °C	1	356.6	12.33	3,229	9,142	871
Emission/GDP scenario	IS92c	1	345.2	22.16	4,010	8,934	1,520
	IS92e	1	399.2	8.01	2,979	10,272	565
Maximum‡		1	403.6	49.69	5,154	10,507	3,664
Minimum‡		1	296.7	2.92	1,895	7,286	206
Emission year	2005	1.013	364.0	6.78	3,438	9,423	1,003
	2015	1.007	373.5	3.96	3,739	9,779	1,228
Atmospheric lifetime§ (yr)		50–200	120	14.5 ± 2.5	50 ± 5	102	13.3
GWP§, integration horizon	20 yr	1	290	62.0	5,000	7,900	4,300
	100 yr	1	320	24.5	4,000	8,500	1,700
	500 yr	1	180	7.5	1,400	4,200	520

* Middle case r , 3% yr⁻¹; γ 2; ΔT_{2x} , 2.5 °C; emission/GDP scenario, IS92a; emission year, 1995. Other cases: one parameter set as specified; all others equal to their middle-case values.

† Defined by equation (4); $\chi = 0.1$, $\Delta T_m = 4.25$ °C.

‡ Maximum and minimum values over 81 combinations of $r = 1, 3, 5\%$ yr⁻¹; $\gamma = 1, 2, 3$; $\Delta T_{2x} = 1.5, 2.5, 4.5$ °C; emission/GDP scenario, IS92a, c, e.

§ GWP and atmospheric lifetimes from ref. 3. No single lifetime for CO₂ can be defined because of the different rates of uptake by multiple sink processes.

fertilization were included, α would not cancel and information about the level as well as the shape of damages would be required.) For the shape we consider simple geometric functions $D_\gamma[\Delta T(t)] = [\Delta T(t)]^\gamma$ with $\gamma = 1, 2$, and 3 and a more nonlinear 'hockey-stick' damage function (A. S. Manne, personal communication)

$$D_h[\Delta T(t)] = 1 - \left[1 - \left(\frac{\Delta T(t)}{\Delta T_m} \right)^2 \right]^\chi \quad (4)$$

where ΔT_m is a catastrophic level of ΔT and χ is a parameter between 0 and 1. For $\chi = 1$, D_h reduces to the quadratic damage function D_2 ; as χ approaches 0, D_h becomes increasingly convex with damages equal to 100% of GDP when ΔT reaches ΔT_m (D_h is undefined for $\Delta T > \Delta T_m$). Damage functions incorporating additional climate dimensions (for example, meridional temperature gradients and precipitation) could be substituted.

EDI depends on future GHG concentrations, climate sensitivity ΔT_{2x} (the equilibrium change in ΔT accompanying a doubling of the pre-industrial level of atmospheric CO₂), and the date of the incremental emission. We consider three GHG-emission/GDP scenarios (IS92a, c, and e; these are IPCC middle, low and high cases, respectively¹⁶) with emissions extrapolated linearly and GDP exponentially at their 2075–2100 rates through our integration horizon of 2200; $\Delta T_{2x} = 1.5, 2.5$ and 4.5 °C (refs 17, 18); discount rate $r = 1, 3$ and 5% yr⁻¹; and incremental emissions in 1995, 2005 and 2015.

We calculate EDI by comparing scenarios with and without incremental GHG emissions using the Integrated Science Assessment Model¹⁹. The carbon-cycle component^{19,20} is representative of current global carbon-cycle models^{21,22}. It includes an upwelling-diffusion ocean, six-box biosphere, temperature-dependent buffer factor, and logarithmic CO₂ fertilization²³.

Atmospheric N₂O and halocarbon concentrations are calculated using a mass-balance model with removal rates inversely proportional to the atmospheric lifetimes. Tropospheric CH₄ is calculated by simulating the main chemical processes influencing global levels of CH₄, CO and OH radicals. CH₄ and CO removal rates take account of oxidation by OH radicals, soil uptake and stratospheric transport. Calculated OH radical concentrations depend on CH₄, CO, NO_x, non-methane hydrocarbons,

tropospheric O₃, and H₂O concentrations. Indirect radiative effects of CH₄ and halocarbons due to their influence on H₂O and O₃ are not incorporated.

Global-mean surface and ocean temperatures are calculated using an upwelling-diffusion climate model with ocean-mixing parametrization consistent with the model used by IPCC^{18,24}. In addition to ΔT_{2x} , the advection velocity, diffusive coefficient and polar-temperature feedback parameter determine the simulated rate of ocean heat transfer.

Illustrative values of EDI are given in Table 1. Compared with the GWP with 100-yr horizon, the 'middle case' ($\Delta T_{2x} = 2.5$ °C, emission/GDP scenario IS92a, $\gamma = 2$, $r = 3\%$ yr⁻¹, and emission year 1995) EDI is ~10% larger for long-lived N₂O and CFC-12; 55% smaller for short-lived CH₄ and HCFC-22, and 20% smaller for intermediate-lived CFC-11.

The sensitivity of EDI to parameter values is inversely correlated with atmospheric residence time; over all 81 combinations of r , γ , ΔT_{2x} , and emission/GDP scenario considered, the ratios of the maximum to minimum EDI values are 1.36, 1.44, 2.72, 17.0 and 17.8 for N₂O, CFC-12, CFC-11, CH₄ and HCFC-22, respectively. The relative sensitivity to parameters also varies with residence time: CH₄, HCFC-22 and CFC-11 are proportionately most sensitive to r , γ and the emission/GDP scenario; CFC-12 to r , the emission/GDP scenario and γ ; and N₂O to the emission/GDP scenario, r and γ . Smaller discount rates yield smaller EDIs for all GHGs considered, as these GHGs have shorter residence times than CO₂ and a smaller discount rate gives greater weight to the distant future. For short-lived CH₄ and HCFC-22, larger γ and higher emission and GDP growth also yield smaller EDIs, as these parameter changes increase the incremental damages more in the distant than the near future. Conversely, higher emission and GDP growth increase the EDI for N₂O and CFC-12, although larger γ decreases them. The EDIs are least sensitive to changes in ΔT_{2x} , as its effect on incremental damages is more linear than the effect of changes in γ and emission scenario.

To explore further the sensitivity to nonlinearity in damages, we evaluate EDIs using an extreme 'hockey-stick' specification, setting $\chi = 0.1$ and $\Delta T_m = 4.25$ °C (just greater than the maximum $\Delta T(t) = 4.24$ °C for $\Delta T_{2x} = 2.5$ °C and scenario IS92a at our integration horizon 2200). For CH₄ and HCFC-22, the resulting EDI is between the values obtained using $\gamma = 2$ and 3, as these

GHGs are largely removed from the atmosphere by the time ΔT reaches values where the 'hockey-stick' damage function is sharply nonlinear. For the longer-lived GHGs, the resulting EDI is modestly smaller than the EDI with $\gamma = 3$.

The timing of GHG emissions is of central interest for policy^{11,25}. The EDI can be used to compare incremental emissions at different dates, for example 2005 and 2015, using CO₂ emissions in 1995 as the base. The EDI for CO₂ increases then decreases with decadal CO₂ emission delays, reflecting the opposing effects of increasing the incremental forcing in future years when incremental damages are larger but discounting is greater. EDIs for CH₄ decrease with emission year as emissions are delayed; those for the other GHGs considered increase with emission year. These results suggest that the welfare loss from climate change associated with IS92a emissions could be reduced by incrementally reallocating CO₂ emissions from 2005 to 1995 and 2015, delaying CH₄ emissions from 1995, and advancing emissions of N₂O, CFC-11, CFC-12 and HCFC-22 from 2005 and 2015 to 1995.

As the effects of climate change may depend more on its rate than its magnitude, damage functions based on $d[\Delta T(t)]/dt$ have been proposed²⁶. Application of such functions to EDI is problematical, because the effect of an incremental emission is to first increase then decrease $d[\Delta T(t)]/dt$ as a function of t ; for typical parameter values, the integrated incremental damages are negative. Viewing EDI as a function of the integration horizon, it starts positive, turns negative if either numerator or denominator changes sign before the other, then turns positive when both terms become less than zero (with a singularity when the denominator equals zero). For long integration horizons, EDIs calculated using a damage function equal to $\{d[\Delta T(t)]/dt\}$ typically approximate the corresponding EDIs using D_{γ} .

Neither the GWP nor the EDI as defined here incorporate the effect of uncertainties on policy choice. Because information about climate change, its consequences, and mitigation approaches will change over time, near-term policies should be designed to accommodate sequential change¹¹. With uncertainty, emissions of long-lived GHGs like CO₂ are more costly than emissions of shorter-lived GHGs like CH₄, because they constrain the set of achievable future climate states more severely. It may be useful to characterize uncertainty about ΔT_{2x} and other parameters using probability distributions, and to incorporate the economic value of the option to decrease future radiative forcing that is lost by emitting longer-lived GHGs in an extended EDI.

Values of EDI are broadly comparable in magnitude and in range of uncertainty to GWP. Nevertheless, EDI offers significant advantages for policy analysis. Because EDI is defined in terms of economic welfare, it is directly relevant to policy choice; moreover, questions about the damage function and discount rate are clearly defined and may be addressed by research on climate impacts and preferences for impacts at different dates. EDI can also incorporate non-climate effects of GHG emissions on welfare, such as CO₂ fertilization and stratospheric-ozone depletion. In contrast, GWP does not measure welfare changes, non-climate effects cannot be incorporated, and the appropriate time horizon cannot be determined by analysis⁴⁻⁷. Uncertainty about the appropriate values of EDI may be an accurate reflection of uncertainty about the consequences for welfare of climate change, rather than a limitation of the index. □

Received 13 October 1995; accepted 17 April 1996.

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ACKNOWLEDGEMENTS. This work was supported by the US Department of Energy, Office of Health and Environmental Research.