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 Mangement, 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) index[1-3] 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 costs[8] if difficulties in measuring GHG sources and sinks can be overcome[9].

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, CO$_2$)[1-3]

$$\mathrm{GWP}_i = \frac{\dfrac{\partial}{\partial e_i}\left[\displaystyle\int_0^h F(t)\,\mathrm{d}t\right]}{\dfrac{\partial}{\partial e_0}\left[\displaystyle\int_0^h F(t)\,\mathrm{d}t\right]} = \frac{\displaystyle\int_0^h \Delta C_i(t)R_i(t)\,\mathrm{d}t}{\displaystyle\int_0^h \Delta C_0(t)R_0(t)\,\mathrm{d}t} \qquad (1)$$

where e_i and e_0 denote unit mass emissions of GHG$_i$ and of CO$_2$ 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 CO$_2$ 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 atmosphere[1-3]). 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 infinity[10].

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 reached[11]. An incremental emission of a gas with a short atmospheric-residence time like CH$_4$ has negligible effect compared with an emission of a long-lived GHG like CO$_2$ 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 CH$_4$ becomes more important relative to that of CO$_2$. Neither GWP nor exponentially discounted radiative forcing[10] 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 CO$_2$ fertilization[5]. 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 emissions[12], although it is conventionally evaluated for a constant atmosphere.) Unlike GWP, EDI also depends on other factors that affect climate change (for example, H$_2$O 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 (CO$_2$) 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 CO$_2$ emissions

$$\mathrm{EDI}_i = \frac{\dfrac{\partial}{\partial e_i}W[C(t)]}{\dfrac{\partial}{\partial e_0}W[C(t)]} = \frac{\displaystyle\int_0^\infty \Delta C_i(t)\lambda_i(t)\,\mathrm{d}t}{\displaystyle\int_0^\infty \Delta C_0(t)\lambda_0(t)\,\mathrm{d}t} \qquad (2)$$

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 models[13-15], we neglect non-climate effects of GHG emissions and assume that damages due to climate change (net of adaptation costs) can be represented by

$$W[\Delta T(t)] = \int_0^\infty \left(\frac{1}{1+r}\right)^t \alpha\mathrm{GDP}(t)D[\Delta T(t)]\,\mathrm{d}t \qquad (3)$$

where r is the discount rate, α is a scaling constant, 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 CO$_2$

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

EDI		CO_2	N_2O	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, $\Delta T_{2\times}$	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§, integraton 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; $\Delta T_{2\times}$, 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}; $\gamma = 1, 2, 3$; $\Delta T_{2\times} = 1.5, 2.5, 4.5$ °C; emission/GDP scenario, IS92a, c, e.

§ GWP and atmospheric lifetimes from ref. 3. No single lifetime for CO_2 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)

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

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 $\Delta T_{2\times}$ (the equilibrium change in ΔT accompanying a doubling of the pre-industrial level of atmospheric CO_2), 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, respectively[16]) with emissions extrapolated linearly and GDP exponentially at their 2075–2100 rates through our integration horizon of 2200; $\Delta T_{2\times} = 1.5$, 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 Model[19]. 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 CO_2 fertilization[23].

Atmospheric N_2O and halocarbon concentrations are calculated using a mass-balance model with removal rates inversely proportional to the atmospheric lifetimes. Tropospheric CH_4 is calculated by simulating the main chemical processes influencing global levels of CH_4, CO and OH radicals. CH_4 and CO removal rates take account of oxidation by OH radicals, soil uptake and stratospheric transport. Calculated OH radical concentrations depend on CH_4, CO, NO_x, non-methane hydrocarbons, tropospheric O_3, and H_2O concentrations. Indirect radiative effects of CH_4 and halocarbons due to their influence on H_2O and O_3 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 $\Delta T_{2\times}$, 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' ($\Delta T_{2\times} = 2.5$ °C, emission/GDP scenario IS92a, $\gamma = 2$, $r = 3\%$ yr^{-1}, and emission year 1995) EDI is ~10% larger for long-lived N_2O and CFC-12; 55% smaller for short-lived CH_4 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, $\Delta T_{2\times}$, 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 N_2O, CFC-12, CFC-11, CH_4 and HCFC-22, respectively. The relative sensitivity to parameters also varies with residence time: CH_4, 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 N_2O 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 CO_2 and a smaller discount rate gives greater weight to the distant future. For short-lived CH_4 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 N_2O and CFC-12, although larger γ decreases them. The EDIs are least sensitive to changes in $\Delta T_{2\times}$, 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 $\Delta T_{2\times} = 2.5$ °C and scenario IS92a at our integration horizon 2200). For CH_4 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 CO_2 emissions in 1995 as the base. The EDI for CO_2 increases then decreases with decadal CO_2 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 CH_4 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 CO_2 emissions from 2005 to 1995 and 2015, delaying CH_4 emissions from 1995, and advancing emissions of N_2O, 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 proposed[26]. 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 $\{d[\Delta T(t)]/dt\}^{\gamma}$ 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 change[11]. With uncertainty, emissions of long-lived GHGs like CO_2 are more costly than emissions of shorter-lived GHGs like CH_4, because they constrain the set of achievable future climate states more severely. It may be useful to characterize uncertainty about $\Delta T_{2\times}$ 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 CO_2 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 analysis[4–7]. 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.

1. Shine, K. P., Derwent, R. G., Wuebbles, D. J. & Morcrette, J.-J. in *Climate Change: The IPCC Scientific Assessment* (eds Houghton, J. T., Jenkins, G. J. & Ephraums, J. J.) 41–68 (Cambridge Univ. Press, 1990).
2. Isaksen, I. S. A., Ramaswamy, V., Rodhe, H. & Wigley, T. M. L. in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (eds Houghton, J. T., Callander, B. A. & Varney, S. K.) 47–67 (Cambridge Univ. Press, 1992).
3. Albritton, D. L., Derwent, R. G., Isaksen, I. S. A., Lal, M. & Wuebbles, D. J. in *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emissions Scenarios* (eds Houghton, J. T. et al.) 205–231 (Cambridge Univ. Press, 1995).
4. Eckaus, R. S. *Energy J.* **13,** 25–35 (1992).
5. Reilly, J. M. & Richards, K. R. *Envir. Resourc. Econ.* **3,** 41–61 (1993).
6. Schmalensee, R. *Energy J.* **14,** 245–255 (1993).
7. Kandlikar, M. *Energy Policy* **23,** 879–883 (1995).
8. Cropper, M. L. & Oates, W. E. *J. econ. Literat.* **30,** 675–740 (1992).
9. Victor, D. G. *Policy Sci.* **24,** 199–222 (1991).
10. Lashof, D. A. & Ahuja, D. R. *Nature* **344,** 529–531 (1990).
11. Hammitt, J. K., Lempert, R. J. & Schlesinger, M. E. *Nature* **357,** 315–318 (1992).
12. Wuebbles, D. J., Jain, A. K., Patten, K. O. & Grant, K. E. *Clim. Change* **29,** 265–297 (1995).
13. Nordhaus, W. D. *Science* **258,** 1315–1319 (1992).
14. Peck, S. C. & Teisberg, T. J. *Energy J.* **13,** 55–77 (1992).
15. Manne, A., Mendelsohn, R. & Richels, R. *Energy Policy* **23,** 17–34 (1995).
16. Leggett, J., Pepper, W. & Swart, R. in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (eds Houghton, J. T., Callander, B. A. & Varney, S. K.) 69–95 (Cambridge Univ. Press, 1992).
17. Mitchell, J. F. B., Manabe, S., Meleshko, V. & Tokioka, T. in *Climate Change: The IPCC Scientific Assessment* (eds Houghton, J. T., Jenkins, G. J. & Ephaums, J. J.) 131–172 (Cambridge Univ. Press, 1990).
18. Gates, W. L., Mitchell, J. F. B., Boer, G. J., Cubash, U. & Meleshko, V. P. in *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment* (eds Houghton, J. T., Callander, B. A. & Varney, S. K.) 97–134 (Cambridge Univ. Press, 1992).
19. Jain, A. K., Kheshgi, H. S. & Wuebbles, D. J. *Integrated Science Model for Assessment of Climate Change* (UCRL-JC 116526; Lawrence Livermore National Lab., Livermore, CA, 1994).
20. Jain, A. K., Kheshgi, H. S., Hoffert, M. I. & Wuebbles, D. J. *Global biogeochem. Cycles* **9,** 153–166 (1995).
21. Schimel, D. S. *et al.* in *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emissions Scenarios* (eds Houghton, J. T. *et al.*) 35–71 (Cambridge Univ. Press, 1995).
22. Enting, I. G., Wigley, T. M. L. & Heimann, M. *Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses* (Division of Atmospheric Res., CSIRO, Australia, 1995).
23. Bacastow, R. & Keeling, C. D. in *Carbon in the Biosphere* (eds Woodwell, G. M. & Pecan, E. V.) 86–135 (NTIS, Springfield, Virginia, 1973).
24. Bretherton, F. P., Bryan, K. & Woods, J. D. in *Climate Change: The IPCC Scientific Assessment* (eds Houghton, J. T., Jenkins, G. J. & Ephaums, J. J.) 173–193 (Cambridge Univ. Press, 1990).
25. Schlesinger, M. E. & Jiang, X. *Nature* **350,** 219–221 (1991).
26. Peck, S. C. & Teisberg, T. J. *Clim. Change* **28,** 289–315 (1994).

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

Occurrence patterns of foreshocks to large earthquakes in the western United States

Rachel E. Abercrombie*† **& Jim Mori**‡

* Department of Earth Sciences, University of Southern California,
Los Angeles, California, 90089, USA
‡ US Geological Survey, Pasadena, California, USA

OBSERVATIONS of foreshocks preceding large earthquakes provide one of the few well documented cases of premonitory events that are clearly related to a subsequent earthquake. Unfortunately, the apparent randomness of foreshock occurrence—they precede some events and not others—has severely hampered their use in reliable earthquake prediction. Understanding the factors that control foreshock occurrence is critical for determining how large earthquakes initiate and whether reliable short-term prediction will ever be possible[1]. Here we report the results of a comprehensive study of the occurrence patterns of foreshocks to large earthquakes in the western United States. The incidence of foreshocks decreases with increasing depth of the mainshock, and also depends on the mainshock slip orientation. This pattern of occurrence may be explained by a decrease in small-scale crustal heterogeneity with increasing depth, and suggests that increasing normal stress (both regional tectonic stress and lithostatic load) inhibits the occurrence of foreshocks. No relationship is observed between any aspect of foreshock occurrence and the magnitude of the subsequent mainshock, suggesting that

---

† Present address: Institute of Geological and Nuclear Sciences, Kelburn Research Centre, 32 Salamanca Road, PO Box 1320, Wellington, New Zealand.