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

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The global warming potential (GWP) index 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). 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 if difficulties in measuring GHG sources and sinks can be overcome.

The GWP for GHG, is defined as the ratio of the partial derivative of the time-integrated radiative forcing with respect to GHG, relative to the partial derivative with respect to a standard GHG (by convention, CO₂) is

\[
\text{GWP} = \left( \frac{\partial}{\partial e} \int_{0}^{h} F(t) dt \right) / \left( \int_{0}^{h} \Delta C(t) R(t) dt \right) \cdot \int_{0}^{h} \Delta C(t) R(t) dt
\]

where \(e\) and \(e_0\) denote unit mass emissions of GHG, 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, \(\Delta C(t)\) and \(\Delta C_0(t)\) are the differences in atmospheric concentration of GHG, and of CO₂ between scenarios with and without incremental emissions of each GHG at time 0, and \(R(t)\) 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). 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.

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. 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 forcing 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 fertilization. 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, 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.

The EDI for GHG 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. Equivalently, EDI is the partial derivative of the present value of economic-welfare loss with respect to emissions of GHG, relative to the partial derivative with respect to CO₂ emissions

\[
\text{EDI} = \frac{\partial}{\partial w} W[C(t)] = \int_{0}^{\infty} \Delta C(t) \lambda(t) dt / \int_{0}^{\infty} \Delta C(t) \lambda_0(t) dt
\]

where \(W[C(t)]\) represents economic welfare loss due to the time path of GHG concentrations \(C(t)\). In the second formulation, \(\lambda(t)\) denotes the marginal external cost or shadow price of an additional unit concentration of GHGs.

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

\[
W[\Delta T(t)] = \int_{0}^{\infty} \left( \frac{1}{1+r} \right)^{\tau} z \cdot GDP(t) D[\Delta T(t)] dt
\]

where \(r\) is the discount rate, \(z\) 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 \(z\) 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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CO₂</th>
<th>N₂O</th>
<th>CH₄</th>
<th>CFC-11</th>
<th>CFC-12</th>
<th>HCFC-22</th>
</tr>
</thead>
<tbody>
<tr>
<td>*<em>Middle case</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discount rate, r</td>
<td>1% yr⁻¹</td>
<td>1</td>
<td>322.2</td>
<td>3.73</td>
<td>1,833</td>
<td>7,950</td>
</tr>
<tr>
<td>Damage-function exponent, γ</td>
<td>5% yr⁻¹</td>
<td>1</td>
<td>366.2</td>
<td>27.30</td>
<td>4,317</td>
<td>9,596</td>
</tr>
<tr>
<td>Climate sensitivity, ΔT₂⁻</td>
<td>1.5°C</td>
<td>1</td>
<td>354.7</td>
<td>11.0</td>
<td>3,123</td>
<td>9,067</td>
</tr>
<tr>
<td>Emission/GDP scenario</td>
<td>IS92e</td>
<td>1</td>
<td>345.2</td>
<td>22.16</td>
<td>4,010</td>
<td>8,934</td>
</tr>
<tr>
<td>Maximum‡</td>
<td>2005</td>
<td>1</td>
<td>359.1</td>
<td>19.54</td>
<td>4,010</td>
<td>8,934</td>
</tr>
<tr>
<td>Minimum‡</td>
<td>2015</td>
<td>1</td>
<td>319.4</td>
<td>6.07</td>
<td>3,793</td>
<td>9,028</td>
</tr>
<tr>
<td>Atmospheric lifetime§ (yr)</td>
<td>50–200</td>
<td>1</td>
<td>120</td>
<td>14.5 ± 2.5</td>
<td>50 ± 10</td>
<td>1,025</td>
</tr>
</tbody>
</table>

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* Middle case r, 3% yr⁻¹; γ; ΔT₂⁻, 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); γ = 0.1, ΔT₀ = 4.25°C.

‡ Maximum and minimum values over 81 combinations of r = 1, 3, 5% yr⁻¹; γ = 1, 2, 3; ΔT₂⁻ = 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.

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**Fertilization was included; s 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 \( D_0 | ΔT(t) | = | ΔT(t) | ^γ \) with \( γ = 1, 2, 3 \) and a more nonlinear ‘hockey-stick’ damage function (A. S. Manne, personal communication)

\[
D_0 | ΔT(t) | = 1 - \left( \frac{ΔT(t)}{ΔT_m} \right)^γ \tag{4}
\]

Where \( ΔT_m \) is a catastrophic level of \( ΔT \) and \( γ \) is a parameter between 0 and 1. For \( γ = 1 \), \( D_0 \) reduces to the quadratic damage function \( D_0 \); as \( γ \) approaches 0, \( D_0 \) becomes increasingly convex with damages equal to 100% of GDP when \( ΔT \) reaches \( ΔT_m \) (\( D_0 \) is undefined for \( ΔT > ΔT_m \)). Damage functions incorporating additional climate dimensions (for example, meridional temperature gradients, precipitation) could be substituted.

**EDI depends on future GHG concentrations, climate sensitivity \( ΔT_m \) (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) with emissions extrapolated linearly and GDP exponentially at their 2075–2100 rates through our integration horizon of 2200; ΔT₂⁻ = 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. The carbon-cycle component is representative of current global carbon-cycle models. It includes an upwelling-diffusion ocean, six-box biosphere, temperature-dependent buffer factor, and logarithmic CO₂ fertilization.

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, NOₓ, 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. In addition to ΔT₂⁻, 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’ (ΔT₂⁻ = 2.5°C; emission/GDP scenario IS92a, γ = 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 \( r, γ; ΔT_m \), and emission/GDP scenario considered, the ratio 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 near the 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 ΔT₂⁻, 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 \( γ = 0.1 \) and ΔT₀ = 4.25°C (just greater than the maximum ΔT(t) = 4.24°C for ΔT₂⁻ = 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 \( γ = 2 \) and 3, as these

302 NATURE • VOL 381 • 23 MAY 1996
GHGs are largely removed from the atmosphere by the time $\Delta T$ 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$^{12}$. 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$_2$O, 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$^{39}$. Application of such functions to EDI is problematic, 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 $D$.

Neither the GWPs 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 $\Delta T_{2100}$ and other parameters using probability distributions, and to incorporate the economic value of the option to decrease future radiative forcing that is lost by omitting 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$^{4,5}$. 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.

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

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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 useful 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