

Relative contributions of greenhouse gas emissions to global warming

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IN the past few years, many workers have noted that the combined effect on climate of increases in the concentrations of a large number of trace gases could rival or even exceed that of the increasing concentration of carbon dioxide¹⁻³. These trace gases, principally methane, nitrous oxide and chlorofluorocarbons, are present at concentrations that are two to six orders of magnitude lower than that of carbon dioxide, but are important because, per molecule, they absorb infrared radiation much more strongly than carbon dioxide. Indeed a recent study⁴ shows that trace gases are responsible for 43% of the increase in radiative forcing from 1980 to 1990 (Fig. 1). An index to compare the contribution of various 'greenhouse' gas emissions to global warming is needed to develop cost-effective strategies for limiting this warming. Estimates of relative contributions to additional greenhouse forcing during particular periods do not fully take into account differences in atmospheric residence times among the important greenhouse gases. Here we extend recent work on halocarbons^{5,6} by proposing an index of global warming potential for methane, carbon monoxide, nitrous oxide and CFCs relative to that of carbon dioxide. We find, for example, that methane has, per mole, a global warming potential 3.7 times that of carbon dioxide. On this basis, carbon dioxide emissions account for 80% of the contribution to global warming of current greenhouse gas emissions, as compared with 57% of the increase in radiative forcing for the 1980s.

In considering options for limiting global warming, the relative warming potential of given greenhouse gas emissions must be considered, rather than the relative radiative forcing of changes in atmospheric concentrations. This requires an estimate of the radiative impact of given emissions over time^{7,8}. Because greenhouse gases have different residence times, the relative cumulative impact of each gas may be quite different from its relative initial forcing. To evaluate the climate implications of current activities and proposed policies, it is desirable to have a single index for each gas⁹ that combines its radiative forcing per molecule in the atmosphere with its atmospheric residence time. Previous efforts to express emissions on a CO₂-equivalent basis have used simplified approaches that do not explicitly treat the time-dependence of CO₂ concentrations^{10,11,23}.

To provide a consistent basis for comparing emissions of different greenhouse gases, an index of global warming potential (GWP) can be defined as:

$$GWP_i = \frac{\int_0^{\infty} a_i(t)c_i(t) dt}{\int_0^{\infty} a_c(t)c_c(t) dt} \quad (1)$$

where $a_i(t)$ is the instantaneous radiative forcing due to a unit increase in the concentration of gas i , and $c_i(t)$ is the fraction of gas i remaining at time t . The corresponding values for CO₂ are in the denominator. In general, a_i is a function of the concentration of gas i and other greenhouses gases because of saturation and overlap of the respective absorption bands³. For example, the differential radiative forcing from an increase in CO₂ is about 30% greater at 350 p.p.m. than it is at 450 p.p.m. The integral can be approximated, however, by using a representative value for a_i based on a projection of concentration

changes over the residence time of gas i . Our calculations (Table 1, column 3) are based on the average radiative forcing from increasing the atmospheric concentrating CO₂ from 350 to 450 p.p.m., increasing CH₄ from 1.7 to 2.7 p.p.m., and increasing N₂O from 0.31 to 0.41 p.p.m.; the CFC radiative forcings vary in a nearly linear fashion with concentration^{3,4}.

Radiative forcing is expressed as the initial change in the Earth's radiation budget due to changes in greenhouse gas concentrations (W m⁻² p.p.m.⁻¹). Climate sensitivity is defined as the amount of global warming required to restore radiative balance and depends on uncertain climate feedbacks. Climate sensitivity is estimated to be 0.5-1.3 °C W⁻¹ m², corresponding to a warming of 2-5 °C for a doubling of CO₂ (ref. 12).

The definition of GWP given above is similar to that given by Fisher *et al.* for halocarbons⁶, which is analogous to the definition of ozone depletion potential (ODP) given by Wuebbles¹³. Both the latter definitions are based on reaching equilibrium following a step-function change in emissions, whereas our definition emphasizes the long-term implications of emissions in a given year. If residence times are constant and radiative forcing varies linearly with concentration, these definitions are identical⁶. Note that these formulations weight all future forcings equally, contrary to the case of instantaneous forcing, which neglects all future impacts. Intermediate cases in which future forcing is discounted are discussed below.

If gas i is removed from the atmosphere in proportion only to its concentration, then $c_i(t) = e^{-t/\tau_i}$, where τ_i is its average residence time. In this case, the cumulative forcing arising from this mole of gas over its atmospheric life is $a_i\tau_i$. The atmospheric retention of N₂O and the CFCs is reasonably well described by single residence times, so for these gases this approach can be used directly. Atmospheric retention of CO₂ is more complex. Rather than being destroyed, CO₂ is transferred into other reservoirs (for example, oceans and biota) from which it can return to the atmosphere. The result is that CO₂ removal cannot be described by a single residence time. Therefore, for CO₂ we follow Maier-Reimer and Hasselmann¹⁴ and let

$$c_c(t) = \sum_0^4 \alpha_j e^{-t/\tau_j} \quad ; \quad \sum_0^4 \alpha_j = 1 \quad (2)$$

The coefficients are based on Maier-Reimer and Hasselmann's fit of the response of their ocean general circulation model to an instantaneous injection of CO₂ of 25% of the current atmospheric burden (α_0 - α_4 = 0.131, 0.201, 0.321, 0.249 and 0.098; τ_0 - τ_4 = 1,000, 362.9, 73.6, 17.3 and 1.9). The original fit, however, set $\tau_0 = \infty$, which implies that $\int c_c(t) dt = \infty$. We have arbitrarily chosen $\tau_0 = 1,000$ years, which effectively discounts the very

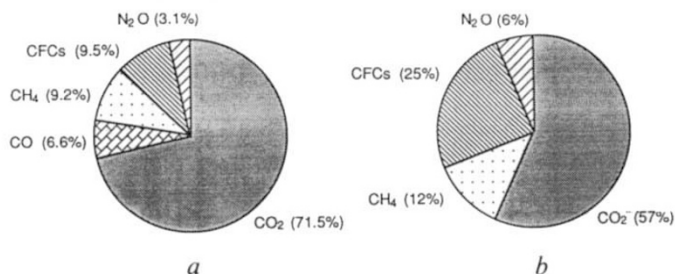


FIG. 1 *a*, Relative contributions to global warming potential in 1985 and *b*, relative contributions to greenhouse forcing added during the 1980s. The left pie is based on zero-discount rate GWPs from Table 1 and anthropogenic emissions estimates from ref. 18 as follows: 21 Pg CO₂; 800 Tg CO net carbon plus 300 Tg CO recycled carbon; 82 Tg CH₄ net carbon plus 250 Tg CH₄ recycled carbon; 5.2 Tg N₂O; 360 Gg CFC-12; 280 Gg CFC-11; 150 Gg CFC-113; 47 Gg CFC-14. Four other CFCs contributed a total of <1%. CFC residence times not given in ref. 12 were taken from refs 20 and 22, with values given as >500 years set to 500 years. The total contribution of CO₂, including net CO₂ produced from emissions originating as CO and CH₄, is ~80%. A surprisingly large contribution (1.7% of the total warming potential) was made by CFC-14 (CF₄) because of its very long residence time (set to 500 years). *b* is redrawn from ref. 4.

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TABLE 1 Global warming potentials for various greenhouse gases on mole and weight bases relative to carbon dioxide

Gas	Residence time (yr)	(Molar basis)			(Weight basis)	
		Instantaneous forcing (W m^{-2} p.p.m. $^{-1}$)	Cumulative forcing (W m^{-2} yr Pmol $^{-1}$)	Global warming potential	Cumulative forcing (W m^{-2} yr Pg $^{-1}$)	Global warming potential
CO ₂	230	0.015	19	1.0	0.42	1.0
CO	(2.1)	(0.65)	26	1.4	0.94	2.2
CH ₄	(14.4)	(0.65)	71	3.7	4.4	10
N ₂ O	160	3.8	3,400	180	77	180
HCFC-22	15	190	15,000	810	180	410
CFC-11	60	220	74,000	4,000	540	1,300
CFC-12	120	280	190,000	10,000	1,600	3,700

Residence times are derived as follows: CO₂ (ref. 14), CH₄ and N₂O (ref. 20) and CFCs (ref. 6). The residence times of CO₂ and CH₄ are adjusted as discussed in the text. CO is ascribed a residence time equivalent to 0.22 times that of methane (see text). The cumulative forcing and GWPs for CO and CH₄ are based on net carbon and therefore include the warming potential of CO₂. Instantaneous radiative forcings are based on the parameterized model given in ref. 3, except for HCFC-22 which is calculated from tables in ref. 4. Values that depend on concentration are based on increasing CO₂ from 350 to 450 p.p.m., increasing CH₄ from 1.7 to 2.7 p.p.m. with a 70% amplification (see text), and increasing N₂O from 0.31 to 0.41 p.p.m. Climate sensitivity is estimated to be 0.5–1.3 °C W⁻¹ m², corresponding to a warming of 2–5 °C for a doubling of CO₂ (ref. 12).

long-term retention of a small fraction of the original emissions. Results are quite sensitive to this choice for τ_0 . The integral of equation (2) is $\sum \alpha_j \tau_j$, which yields the effective residence time of 230 years for CO₂ given in Table 1. Adopting an effective residence time of 500 years as suggested by Edmonds and Wuebbles¹⁵ (equivalent to letting $\tau_0 = 3,000$ years) would reduce the GWPs in Table 1 by a factor of two. Shorter effective residence times would be obtained if future warming is discounted (see below).

The GWP of methane is influenced by chemical interactions in the atmosphere that should be taken into account. First, we note that all carbon emitted into the atmosphere as methane is eventually oxidized to CO₂ and H₂O. For methane emitted from the decomposition or burning of renewably produced organic matter, the CO₂ generated recycles carbon that was removed from the atmosphere during photosynthesis (recycled carbon). The entries in Table 1, however, are based on net carbon emissions (from fossil fuels or from net deforestation), for which the cumulative forcing from one mole of CO₂ adds to the cumulative forcing from one mole of methane *per se*. In addition, methane emissions tend to increase tropospheric ozone and stratospheric water vapour concentrations, perhaps enhancing the direct radiative forcing from methane by ~70% (ref. 16). Finally, to account roughly for increases in the residence time of methane resulting from CH₄-CO-OH coupling, we assume that each mole of methane emitted increases the residence time of one mole of methane by 50% (refs 16, 17).

The GWP of CO is closely related to that of methane. Carbon monoxide itself is not a greenhouse gas, but it too is oxidized to CO₂ in the atmosphere, implying that for net carbon its GWP must be at least 1. Additional forcing is contributed through the coupling of CH₄-CO-OH as CO emissions increase the residence time of methane and therefore its atmospheric burden. Model calculations¹⁷ suggest that each mole of CO emissions increases the residence time of one mole of CH₄ by approximately 20%. Each mole of 'net-carbon' CO emissions is therefore ascribed the cumulative forcing of 0.2 times that of one mole of CH₄ plus the cumulative forcing which arises from one mole of CO₂.

Estimates of cumulative radiative forcing caused (or averted) by each petamole (10¹⁵ mole) of gas emitted (or removed) in order of increasing global warming potential are shown in column 4 of Table 1. Column 5 shows the GWPs; for CO₂ the GWP is 1 by definition. The warming potential of carbon monoxide is 40% higher than that of CO₂ and, despite the adjustments which increase the forcing from methane emissions, we find that the GWP of methane is only 3.7, much lower than the ratio of instantaneous radiative forcings shown in column 3 (which have been adjusted as described above). Nitrous oxide is 180 times as effective as CO₂, and HCFC-22 oxide is 180

times as effective as CO₂, in causing cumulative global warming. HCFC-22, which is a leading potential substitute for other CFCs because of its relatively low capacity to destroy ozone, has a GWP of 810, much higher than the naturally occurring greenhouse gases, but lower than CFC-11 (~4,000) and CFC-12 (~10,000)—the two most commonly used CFCs that it might replace. Our results for the halocarbons are consistent with the values in Fisher *et al.*² to within 20%, when common reference residence times are used.

Results based on emissions of one petagram (Pg) of each gas are shown in column 6 of Table 1, with the corresponding weight-based index in column 7. This index will be higher than the GWP for those gases that have a lower molecular weight than CO₂ and vice versa. Although the GWP is a physically

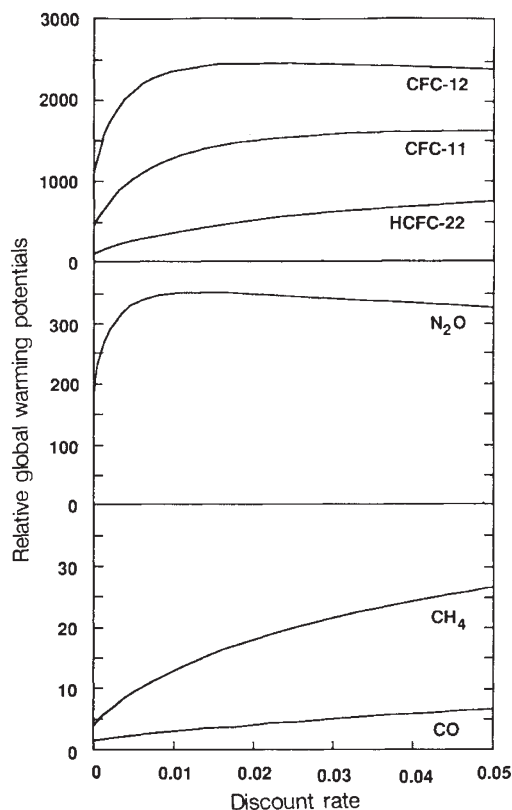


FIG. 2 Global warming potentials relative to CO₂ as a function of discount rate. The effective residence time of CO₂ decreases disproportionately with increasing discount rate because it is expressed as the sum over multiple exponentials. The GWPs of CO and CH₄ are based on net carbon emissions.

more meaningful index (accurately reflecting the implications of burning rather than venting one mole of methane, for example) we have presented both results because emissions data are frequently reported on a weight basis. (For consistency we have used the full molecular weight of CO₂ in columns 6 and 7, rather than the carbon weight which is commonly used in the carbon-cycle literature. For the carbon cycle gases the molar GWPs are identical to GWPs on a carbon weight basis.)

Current radiative forcing may be considered more important from a policy viewpoint than radiative forcing occurring in the distant future because, for example, of the possibility that new technologies will emerge to solve the problem. Intergenerational equity issues and the likelihood that the value placed on limiting climate change will grow with economic output, however, argues against discounting future forcing. Discounting can be accommodated by multiplying future forcing by e^{-rt} , where r is called the discount rate and is analogous to an interest rate. For a gas with a single decay time, τ , its effective residence time reduces to $\tau/(1+r\tau)$. For a gas with multiple decay rates like CO₂, discounting reduces the equivalent residence time disproportionately, from $\sum \alpha_j \tau_j$ to $\sum \alpha_j \tau_j / (1+r\tau_j)$. Applying a discount rate of 1% per year, for example, reduces the effective residence time of CO₂ from 230 to 45 years. As higher discount rates are assumed, the significance of residence time diminishes and the GWP approaches the respective relative scaled radiative forcing per molecule for each gas (Fig. 2). A similar result can be obtained by integrating equation (1) over a finite time interval, but this implies a discontinuity in weighting future forcing.

Neglecting for the time being the contributions from NO_x and ozone, this framework can be used to calculate the contributions to global warming potential by different gases, regions and activities. Using data compiled by the US Environmental Protection Agency¹⁸, we have estimated the relative contributions of the various greenhouse gases for the year 1985 using the zero discount rate GWPs from Table 1. These differ substantially from the contributions calculated on the basis of concentration increases during the 1980s (Fig. 1)³. The contribution of CO₂ dominates, in spite of its low radiative forcing, because of the magnitude of its emissions and atmospheric residence time. Indeed, the total contribution of CO₂, including net CO₂ produced from emissions originating as CO and CH₄, is ~80% of the warming potential generated in 1985.

The largest source of uncertainty in our results stems from the assumed effective residence time of CO₂. The results are sensitive not only to the long-term behaviour of a small fraction of the initial emissions, but also to the underlying assumptions in the carbon-cycle model and the scenario of future CO₂ emissions¹⁴. There is also considerable variation in the estimated residence times of some of the other gases (for example, CH₄¹⁹, HCFC-22^{6,20}) and in how feedbacks may change these in the future. Uncertainty in the radiative forcings per unit change in concentration arises primarily from accounting for the warming amplification from ozone and stratospheric water vapour associated with methane oxidation, and from choosing representative future concentrations¹⁶. The impact of CH₄-CO-OH coupling on the residence time of methane is also nonlinear and depends on emissions of NO_x and other compounds²¹. The values presented here are intended to establish an order-of-magnitude comparison and stimulate further work to refine the GWP estimates. Analyses of different scenarios will continue to be necessary as a complement to the use of GWP point estimates.

The formulation developed here will help to address policy questions regarding the relative amounts of rational expenditures on different mitigating strategies. Suppose that one can estimate the cost of reducing, say, one Pmol of emissions of a greenhouse gas. Using information in column 4 of Table 1, the costs of averting a unit of cumulative forcing by that option can be calculated. As the potential for reduction in greenhouse gas emissions from any option is limited, a 'supply curve' is needed to rank in order the costs of different options along with the

quantity of radiative forcing each option can prevent. Then, for any given amount of expenditure the most cost-effective options can be undertaken first. Alternatively, if it were decided that an expenditure of \$1 is justifiable to reduce (remove or prevent), say, 1 kmol of CO₂ emissions in order to mitigate global warming, then it would be rational to spend \$1 × GWP_{*i*} to reduce emissions of gas *i* by 1 kmol. Higher discount rates will have the effect of justifying higher expenditures to reduce emissions of other greenhouse gases relative to those of CO₂. Estimates of the relative costs of different options must be developed with great caution, however, because the most attractive options will often be those that have significant other benefits besides reducing greenhouse gas emissions (for example, increasing energy efficiency).

The index of global warming potential developed here should prove useful in clarifying the relative contributions to global warming of different countries and different activities and should make it easier to develop cost-effective emissions policies at both national and international levels. A prerequisite for using this index as a basis for legal requirements, however, is the availability of reliable methods to establish current emissions and to monitor changes. □

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- Lacis, A., Hansen, J., Lee, P., Mitchell, T. & Lebedeff, S. *Geophys. Res. Lett.* **8**, 1035-1038 (1981).
- Ramanathan, V., Cicerone, R. J., Singh, H. B. & Kiehl, J. T. *J. Geophys. Res.* **90**, 5547-5566 (1985).
- Hansen, J. et al. *J. Geophys. Res.* **93**, 9341-9364 (1988).
- Hansen, J., Lacis, A. & Prather, M. *J. Geophys. Res.* **94**, 16417-16421 (1989).
- Rogers, J. & Stephens, D. *J. Geophys. Res.* **90**, 2423-2428 (1988).
- Fisher, D. et al. *Nature* **344**, 513-516 (1990).
- Swart, R., de Boois, H. & Vellinga, P. in *The Full Range of Responses to Anticipated Climatic Change* Ch. 9, 137-159 (United Nations Environment Program and The Beijer Institute, Stockholm, 1989).
- Smith, K. & Ahuja, D. *Clim. Change* (in the press).
- Noordwijk Declaration on Atmospheric Pollution and Climatic Change (Netherlands Ministry of Environment, The Hague, November 1989).
- Deluchi, M., Sperling, D. & Johnston, R. *Transportation Fuels and the Greenhouse Effect* (University of California, University Energy Research Group, UER-182, 1987).
- Okken, P. & Kram, T. *CH₄/CO₂ emission from fossil fuels global warming potential ESC-WR-89-12* (ECN, Petten, The Netherlands, June 1989).
- Dickinson, R. & Cicerone, R. *Nature* **319**, 109-114 (1986).
- Wuebbles, D. *The Relative Efficiency of a Number of Halocarbons for Destroying Stratospheric Ozone* Report UCID-18924 (Lawrence Livermore National Laboratory, Livermore, 1981).
- Maier-Reimer, E. & Hasselmann, K. *Clim. Dyn.* **2**, 63-90 (1987).
- Edmonds, J. & Wuebbles, D. *A Primer on Greenhouse Gases* (US Department of Energy, NBB-0083, Washington, DC, 1988).
- Lashof, D. *Clim. Change* **14**, 213-242 (1989).
- Thompson, A. & Cicerone, R. *J. Geophys. Res.* **91**, 10853-10864 (1986).
- Lashof, D. & Tirpak, D. *Policy Options for Stabilizing Global Climate* Draft Report to Congress (US Environmental Protection Agency, Washington, DC, 1989).
- Cicerone, R. & Oremland, R. *Global Biogeochemical Cycles* **2**, 299-328 (1988).
- Prather, M. *An Assessment Model for Atmospheric Composition* NASA Conference Publication 3023 (NASA, Washington, DC, 1989).
- Thompson, A. et al. *Atmos. Envir.* **23**, 519-532 (1989).
- Ramanathan, V. et al. *Rev. Geophys.* **25**, 1441-1482 (1987).
- Okken, P. *Energy Policy* (in the press).

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Microatolls and recent sea level change on coral atolls

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MICROATOLLS are colonies of corals, commonly *Porites*, which are dead on top but living around their perimeter, and are found in intertidal environments on coral atolls. They can grow to several metres in diameter. Their upward growth is constrained by sea level through prolonged exposure at the lowest spring tides^{1,2}, and