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An Alternative to the Global Warming Potential for Comparing Climate Impacts of Emissions of Greenhouse Gases

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Globalt oppvarmingspotensial (Global Warming Potential, GWP), som blir brukt i Klimakonvensjonens Kyotoprotokoll, veier klimaeffekter av forskjellige drivhusgassutslipp. GWP har fått mye kritikk for sin utforming, men har likevel blitt foretrukket på grunn av sitt enkle design og bruk, samt sin klarhet i forhold til foreslåtte alternativer. Her blir et nytt mål, som vi kaller Globalt temperaturendringspotensial (Global Temperature Change Potential, GTP), foreslått. Målet er basert på en enkel analytisk klimamodell som representerer temperaturendring på et gitt tidspunkt som et resultat av enten enkeltutslipp (puls) av en gass eller en vedvarende utslippsendring relativ til samme utslippsendring av karbondioksid. GTP for et enkeltutslipp (puls) illustrerer at GWP ikke beskriver godt den relative temperaturresponsen; men, GWP viser seg å være nær GTP for en vedvarende utslippsendring i tidsperioder på 100 år eller mer. Det nye målet beholder GWPs fordeler med henhold til klarhet, og de relativt få inndata som kreves for beregningen. Imidlertid er den mer relevant siden den går lenger ut i årsak-virkning kjeden av effekter av drivhusgassutslipp. GTP for vedvarende utslipp ser ut til å være robust for en rekke usikkerheter og forenklinger, og kan være et godt alternativ til GWP.

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Abstract: The Global Warming Potential (GWP) is used within the Kyoto Protocol to the United Nations Framework Convention on Climate Change as a metric for weighting the climatic impact of emissions of different greenhouse gases. The GWP has been subject to many criticisms because of its formulation, but nevertheless it has retained some favour because of the simplicity of its design and application, and its transparency compared to proposed alternatives. Here a new metric, which we call the Global Temperature Change Potential (GTP), is proposed which is based on a simple analytical climate model that represents the temperature change at a given time due to either a pulse emission of a gas or a sustained emission change relative to a similar emission change of carbon dioxide. The GTP for a pulse emission illustrates that the GWP does not represent well the relative temperature response; however, the GWP is shown to be very close to the GTP for a sustained emission change for time horizons of 100 years or more. The new metric retains the advantage of the GWP in terms of transparency, and the relatively small number of input parameters required for calculation. However, it has an enhanced relevance, as it is further down the cause-effect chain of the impacts of greenhouse gases emissions. The GTP for a sustained emission appears to be robust to a number of uncertainties and simplifications in its derivation and may be an attractive alternative to the GWP.

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1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has, since its first scientific assessment in 1990, used the Global Warming Potential (GWP) as a method for comparing the potential climate impact of emissions of different greenhouse gases (IPCC 1990; IPCC 2001). The GWP is the time-integrated radiative forcing due to a pulse emission of a given gas, over some given time period (or horizon) relative to a pulse emission of carbon dioxide (see Appendix). The GWP has been adopted as an instrument in the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC). Emission targets are set in terms of equivalent emissions of carbon dioxide, where the carbon dioxide equivalence of emissions of other greenhouse gases (methane, nitrous oxide, the hydrofluorocarbons, the perfluorocarbons and sulphur hexafluoride) is determined using the GWP with a 100 year time horizon (henceforth GWP(100)).

Since its introduction the GWP has been subject to scrutiny and criticism (e.g. Wigley (1998); Fuglestvedt *et al.* (2000); O`Neill (2000); Smith and Wigley (2000a); Smith and Wigley (2000b); Manne and Richels (2001)). One criticism relates to the fact that, despite its name, the global *warming* potential does not actually represent the impact of gas emissions on temperature. The GWP uses the time integrated radiative forcing and this cannot be used as a unique indicator of the effect of pulse emissions on temperature, because of large differences in the time constants of the various greenhouse gases. Although a strong greenhouse gas with a short lifetime could have the same GWP as a weaker greenhouse gas with a longer lifetime, identical (in mass terms) pulse emissions of the two gases could cause a quite different temporal behaviour of temperature change. Economists have also criticised the GWP concept for not being based on an analysis of damages caused by the emissions (e.g. Kandlikar (1995); Schmalensee (1993); Hammitt *et al.* (1996)). Although within this paper we restrict the discussion to an improved physically-based metric, the new metric could feed into the development of damage-based indices.

However, despite these criticisms and the suggestion of many alternatives, the GWP seems to have retained its attractiveness and widespread use, mainly because of the simplicity of its definition, the small number of required input parameters and the relative ease of calculation, compared to some of the alternatives. Additionally, the "transparency" and ease of application appear to be important aspects of acceptability amongst policymakers (Fuglestvedt *et al.* 2003; Skodvin and Fuglestvedt 1997).

Negotiations over the so-called second reporting period of the UNFCCC (i.e. the period beyond 2012 that is not covered by the Kyoto Protocol) will begin soon, as will preparations for the Fourth Assessment Report of the IPCC (due out in 2007). This raises the question as to whether a metric can be designed that addresses some of the problems with the GWP, while at the same time maintains its transparency and ease of use. This paper aims to propose one such metric as a contribution to the growing debate (e.g. O'Neill (2000; 2003); Godal (2003); Smith (2003)) over whether, and how, the GWP could be superseded for use within international climate agreements and in other applications of climate change metrics.

The impact of climate emissions can be regarded, in a simplified manner, as the chain: emission changes → concentration changes → radiative forcing → climate impacts → societal and ecosystem impacts → economic "damage" (O'Neill (2000); Smith and Wigley (2000a); Fuglestvedt *et al.* (2003)). It has been recognised that, in general the relevance of the impacts become greater as we move down this chain, and hence a metric designed to compare more relevant impacts would be desirable. However, it has also been recognised that the uncertainty generally becomes greater as we move down this chain.

This paper proposes an alternative to the GWP that moves one step further down the chain from radiative forcing to represent the global-mean surface temperature change. It does so by

using a simple model of the climate system, in the spirit of designing a transparent metric which may be more widely accepted. However, the framework we present is clearly suitable for extension beyond this by using, for example, output from a sophisticated climate model, and could incorporate other impacts, such as sea-level rise, as an end point. Even if the metric is not acceptable as a replacement for GWPs, the method does seem to have value as a pedagogic tool for testing alternative metrics and understanding the behaviour of various climate change agents and their effects on the climate system. We will call this new metric the *Global Temperature Change Potential* (GTP).

It is somewhat surprising that such a metric has not been presented before. The basic framework is well known (e.g. Hasselmann *et al.* (1997); Sausen and Schumann (2000); Smith (2003)) and has been extensively used even as a way of assessing GWPs. But it has not, to our knowledge, been proposed directly in a relatively simple analytic form as a candidate for superseding GWPs.

2 The Global Temperature Change Potential

The simplest representation of the global-mean surface temperature change, ΔT, to a global-mean radiative forcing, ΔF, is (e.g. Hartmann (1996)):

$$C\frac{d\Delta T(t)}{dt} = \Delta F(t) - \frac{\Delta T(t)}{\lambda} \tag{1}$$

where t is time, C is the heat capacity of the system and λ is a climate sensitivity parameter which indicates the change in equilibrium surface temperature per unit radiative forcing. In this paper it will be assumed that λ is a constant that is independent of the particular mechanism causing the radiative forcing; however, the absolute value of λ is poorly known (e.g. IPCC (2001) and we will explore the dependence of the GTP on this uncertainty. There is much current research in attempting to assess the extent to which λ is truly independent of the radiative forcing mechanism (Hansen *et al.* 1997; Joshi *et al*. 2003) but it appears to be generally robust for the relatively well-mixed greenhouse gases being considered in the Kyoto Protocol. In any case, mechanism-dependent values of λ could easily be incorporated within the framework of the GTP.

The general solution of (1) is

$$\Delta T(t) = \frac{1}{C}\int_o^t \Delta F(t')\exp(\frac{t'-t}{\lambda C})dt' \tag{2}$$

where the exponential can be viewed as an impulse response (or Green) function to a δ forcing at time t'. λC is a time constant for the climate system and will be given the symbol τ.

Such a simple model, as represented by (1), can be used to obtain an approximate solution of the response to a forcing by regarding the heat capacity C to represent the mixed-layer of the ocean; it will be assessed relative to a slightly more sophisticated box-diffusion model in Section 3.6.

If ΔF(t) has a sufficiently simple form, (2) can easily be integrated to yield an analytical form for the calculation of ΔT(t). We will consider first what we refer to as the *Absolute Global Temperature Change Potential*, $AGTP_P$, where the subscript P indicates the response to a *pulse* emission. The units of the $AGTP_P$ are K kg^{-1}.

For the majority of greenhouse gases, the radiative forcing following an emission at time t=0 will have the form $A\exp(-t/\alpha)$ where α is the time constant for removal of the gas from the atmosphere and A is the radiative forcing for a 1 kg change in concentration of that gas. We will (following the IPCC procedure for calculating GWPs) assume that A is independent of that gas's concentration and that it is not dependent on the changes in concentration of other greenhouse gases, either because it is in sufficiently low concentrations or because a linearisation is made about present day concentrations. It will also be assumed that α is a constant although, in reality, it may depend on the concentration of the gas itself and other gases. The issue of non-linearity is addressed elsewhere (e.g. IPCC (1995); Fuglestvedt *et al.* (2003)) and is not the focus of this work.

In this case, using (2) the $AGTP_P(t)$ for gas x is

$$AGTP_P^x(t) = \frac{A_x}{C(\tau^{-1} - \alpha_x^{-1})}[\exp(-\frac{t}{\alpha_x}) - \exp(-\frac{t}{\tau})] \tag{3}$$

provided $\tau \neq \alpha_x$. The $\tau = \alpha_x$ case is simple to derive but will not be needed here.

For carbon dioxide, the concentration response to a pulse emission is more complex than the simple $\exp(-t/\alpha)$ form. In many applications this response, $R(t)$, derived from more complete carbon cycle models, has been approximated by

$$R(t) = a_o + \sum_i a_i \exp(-\frac{t}{\alpha_i}), \tag{4}$$

where typically 3 or 4 terms are included in the summation. In this work, we use the 4 term representation derived from the Bern carbon cycle model (Joos *et al.* 1996) for the case of a constant future mixing ratio; the same response function, in a different mathematical form was used in IPCC (1996; 2001) - see the Appendix for the coefficients and further details. Equation (4) is certainly suitable for the illustrative purposes of this paper.

Incorporating the radiative forcing due to the pulse, $A_C R(t)$, into (2) yields the $AGTP_P$ for carbon dioxide

$$AGTP_P^C(t) = \frac{A_C}{C}\{\tau a_o[1 - \exp(-\frac{t}{\tau})] + \sum_i \frac{a_i}{(\tau^{-1} - \alpha_i^{-1})}[\exp(-\frac{t}{\alpha_i}) - \exp(-\frac{t}{\tau})]\}. \tag{5}$$

It has been the convention within IPCC to quote GWPs relative to CO_2, although this choice is by no means an obvious one (e.g. Wuebbles *et al.* (1995)). Following this convention, the relative pulse GTP for gas x is then

$$GTP_P^x(t) = \frac{AGTP_P^x(t)}{AGTP_P^C(t)}. \quad (6)$$

Although the GTP_P follows the general philosophy of the GWP, a major distinction is that the final result is the ratio of the temperature changes at a particular time, *t*, rather than, as is the case for the GWP, the ratio of the integrated changes over the period leading up to *t* (see Appendix). Hence a pulse emission of 1 kg of gas x will give an identical temperature change in year t as $GTP_P^x(t)$ kilograms of carbon dioxide, at least to the extent that (1) is a reasonable representation of the climate system. As discussed earlier, the GWP does not guarantee any such equivalence.

The concept can be extended to consider the impact of *sustained* changes in emissions of a gas, a quantity that may arguably have greater policy relevance if a country were to make changes in a given industrial or agricultural process that had a long-term impact on emissions; at the very least the difference between the pulse and sustained forms is instructive. We denote this as $AGTP_S$ where the subscript S indicates a sustained emission change. The units of $AGTP_S$ are taken to be K (kg year^{-1})$^{-1}$.

For non-CO_2 greenhouse gases, the concentration change $\Delta\chi$ resulting from a change in emissions ΔS can be represented by

$$\frac{d\Delta\chi(t)}{dt} = \Delta S(t) - \frac{\Delta\chi(t)}{\alpha}. \quad (7)$$

If ΔS is independent of time it is straightforward to show that

$$\Delta\chi(t) = \alpha\Delta S[1 - \exp(-\frac{t}{\alpha})], \quad (8)$$

and then, by representing the forcing as $A\Delta\chi(t)$ and assuming that ΔS is unity (in kg year^{-1}), this can be incorporated into (2) to yield the $AGTP_S$ for gas x

$$AGTP_S^x(t) = \frac{\alpha_x A_x}{C}\{\tau[1 - \exp(-\frac{t}{\tau})] - \frac{1}{(\tau^{-1} - \alpha_x^{-1})}[\exp(-\frac{t}{\alpha_x}) - \exp(-\frac{t}{\tau})]\}, \quad (9)$$

again assuming $\tau \neq \alpha_x$.

The $AGTP_S$ for CO_2 is more complicated because of the nature of its response function (Eq. (4)); a simplified representation can be given by the analogue to (2) for the case of modelling the time-dependent response to changes in CO_2 emissions. Using (4) to represent the response to a pulse emission

$$\Delta\chi^C(t) = \int_o^t \Delta S^C(t')\left[a_o + \sum_i a_i \exp(\frac{t'-t}{\alpha_i})\right]dt'. \quad (10)$$

This can be incorporated into (2), again assuming ΔS^C is unity, to yield the $AGTP_s$ for carbon dioxide

$$AGTP_S^C(t) = \frac{A_C}{C}\{a_o t\tau - a_o\tau^2[1-\exp(-\frac{t}{\tau})] + \sum_i \alpha_i a_i[(\tau(1-\exp(-\frac{t}{\tau})) - \frac{1}{\tau^{-1}-\alpha_i^{-1}}(\exp(-\frac{t}{\alpha_i}) - \exp(-\frac{t}{\tau}))]\} \quad (11)$$

The relative GTP_S^x is then

$$GTP_S^x(t) = \frac{AGTP_S^x(t)}{AGTP_S^C(t)}. \quad (12)$$

Although somewhat more complicated than the equivalent GWP expressions, equations (3), (5), (9) and (11) are nevertheless transparent in their derivation, require relatively few parameters to calculate (note that while the heat capacity C cancels in (6) and (12), it is still required for the calculation of τ) and are suitable for use by policymakers and other parties with little or no further scientific input.

Some care must be taken with the units when calculating the absolute values as, for example, radiative forcings are often quoted per ppbv rather than per unit mass, and because of the choice of years as the basic time unit. The Appendix elaborates on the necessary constants required to derive consistent values.

3 Illustrative calculations

3.1 The behaviour of GTP_P and the near-equivalence of GWP and GTP_S at long time horizons

For the initial calculations, it is assumed that the heat capacity C is that appropriate to a global ocean mixed layer of 100 metres depth (i.e. 4.2 x 10^8 J K^{-1} m^{-2}) and λ is 0.8 K $(Wm^{-2})^{-1}$, appropriate to an equilibrium surface warming of 3 K for a doubling of CO_2. This parameter choice yields a value of τ of 10.7 years.

Table 1 shows the absolute AGWP, $AGTP_P$ and $AGTP_S$ for carbon dioxide. It also shows the values of the GWP, GTP_P and GTP_S for 5 other gases with a wide range of properties: HFC152a is chosen as a very short-lived gas in quite widespread use; methane is the most important greenhouse gas (in terms of total radiative forcing since pre-industrial times) after carbon dioxide included within the Kyoto Protocol; HFC134a is the dominant hydrofluorocarbon in terms of its total contribution to radiative forcing; N_2O is a relatively long-lived gas, again important in terms of its contribution to total radiative forcing; and CF_4 is a representative of the very long-lived greenhouse gases. For all these gases, lifetimes and the radiative forcing per ppbv are taken from IPCC (2001), to ensure that the GWPs essentially agree with values given in that report, although there are grounds for revising some of these values (see e.g. Sihra *et al.* (2001)); the adopted values, and an explanation for

a slight deviation from IPCC (2001) GWPs, are given in the Appendix. The AGWP, $AGTP_P$ and $AGTP_S$ for methane have been multiplied by 1.3 to account for the indirect forcing from tropospheric ozone and stratospheric water vapour changes, again following IPCC (2001). Figure 1a shows the radiative forcing due to the pulse emission for a selection of the gases considered here, and Figure 1b shows the respective temperature response to these pulse emissions using the $AGTP_P$ expression. Note that to reduce the number of lines on these plots, HFC-134a and N_2O are not included. However, given that HFC134a has a similar lifetime to that of methane (Table A1 in the Appendix), the HFC134a curve is almost identical to the methane curve ignoring the multiplication by 50 (which is the ratio of the specific radiative forcings per unit mass of HFC134a to methane, including the methane indirect effects).

Table 1 and Figure 1 show the result that has been pointed out elsewhere (e.g. Smith and Wigley (2000a); Fuglestvedt *et al.* (2003)) that the GWP does not describe the relative temperature impact of the pulse, for short-lived gases for times long (compared to the gas lifetime) after the pulse emission. Thus, pulses of HFC152a, CH_4 and HFC134a have almost a negligible effect on temperature after 100 years; their concentrations have decayed to near zero and the climate system (or at least the simple climate model) has almost forgotten about the pulse. By contrast, the GWP for HFC134a at 500 years still has the relatively large value of 400. For N_2O, its relative importance at 20 and 100 years is almost identical for the GWP and GTP_P, although after 500 years its decay has left it with a small impact on temperature (the GTP_P is 13), whilst its GWP remains substantial at 160. For the very long-lived CF_4 the two measures are qualitatively quite similar for all three time horizons.

TABLE 1: Absolute GWP (in 10^{-14} $Wm^{-2}kg^{-1}year$), GTP_P (in 10^{-16} K kg^{-1}) and GTP_S (in 10^{-14} K (kg $year^{-1})^{-1}$) for carbon dioxide and relative values of these parameters for 5 other greenhouse gases at time horizons of 20, 100 and 500 years. The values for methane include the indirect forcing. The GTP values are calculated with a climate sensitivity of 0.8 K$(Wm^{-2})^{-1}$ and a mixed layer with a depth of 100 metres.

	GWP			GTP_P			GTP_S		
	20	100	500	20	100	500	20	100	500
Absolute CO_2	2.66	9.05	29.1	8.34	5.46	3.47	1.24	6.67	23.0
HFC152a	400	120	37	170	0.15	0	570	130	40
CH_4	62	22	7	52	0.35	0	69	24	7
HFC134a	3290	1260	390	2840	34	0	3590	1370	400
N_2O	270	290	150	290	270	13	260	290	160
CF_4	3850	5650	8730	4150	7490	11700	3610	5480	8690

Turning now to the GTP_S, Figure 2 shows the radiative forcing and temperature response due to the sustained emission changes; since the concentration (and hence the forcing) comes to an equilibrium in response to the sustained emissions for times long compared to the gas lifetime, the forcing and temperature response are proportional to each other (via $\Delta T=\lambda\Delta F$), and the two plots have very similar forms except at early times.

Table 1 shows that the GTP_S is very similar to the GWP for all 5 gases in this study, a similarity that increases with time horizon. At 100 years, the time horizon chosen in the Kyoto Protocol, the two measures agree to within 10%. At 500 years, the agreement is around 2%. Even at 20 years, the agreement is better than about 10%, except for the short-lived HFC152a.

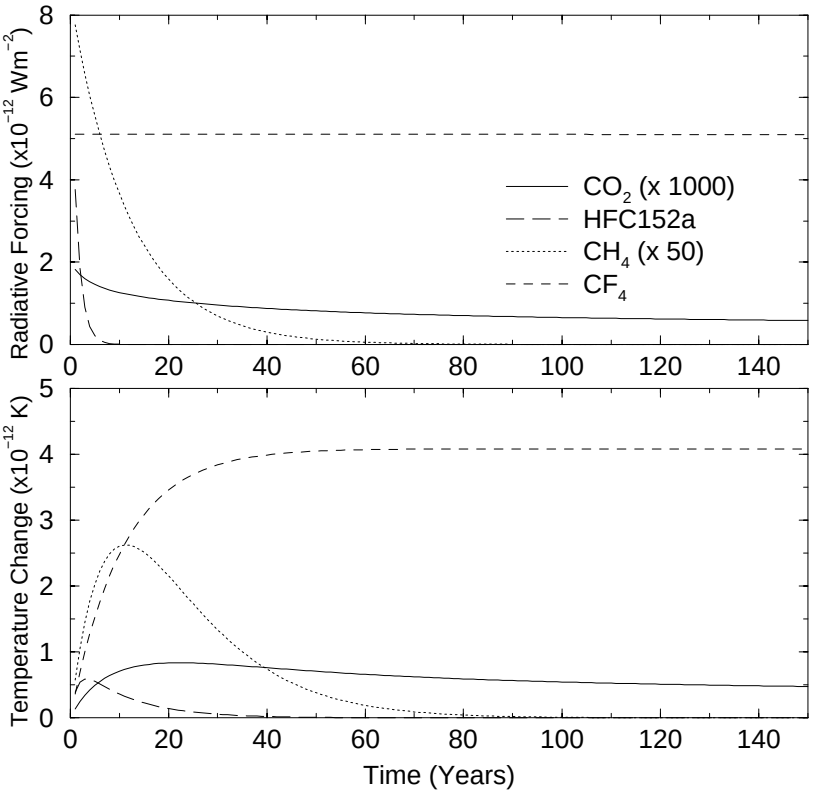

Figure 1 (a): Radiative forcing due to a 1 kg pulse emission of greenhouse gases with a range of lifetimes (see Table A1). The AGWP is the integral under these curves to a given time horizon. (b) Temperature response of simple climate model (Equation (1)) to the radiative forcing shown in (a).

This result can be explained by considering the asymptotic limits of the various expressions. At long time horizons, (9) takes the form $A_x\alpha_x\lambda(1\text{-}\exp(-t/\alpha_x))$ which reduces to $A_x\alpha_x\lambda$ if the time horizon is much greater than the gas lifetime. Hence it has an identical form to (A1). Similarly, (11) takes the form $A_c\lambda(a_o t + \sum_i \alpha_i a_i)$ similar to the long lifetime limit of (A2). Essentially the AGWP gives the integral of a decaying pulse, whilst the $AGTP_S$ represents the exponential approach to an asymptotic temperature change; these two cases have the same mathematical forms which, when ratioed with the absolute AGWP and $AGTP_S$ for CO_2, yield similar values for the GWP and GTP_S.

This near-equivalence between the ratio of the integrated radiative forcing of a pulse emission of two gases and the corresponding ratio of the temperature change due to a sustained emission change on temperature was discussed, in terms of a steady state temperature change and infinite time horizon GWPs, in one of the earliest usages of a GWP-like metric (Fisher *et al.* 1990). This equivalence has been noted occasionally since then (e.g. O'Neill (2000), Fuglestvedt *et al.* (2003)) but has received surprisingly little attention, for example, by IPCC.

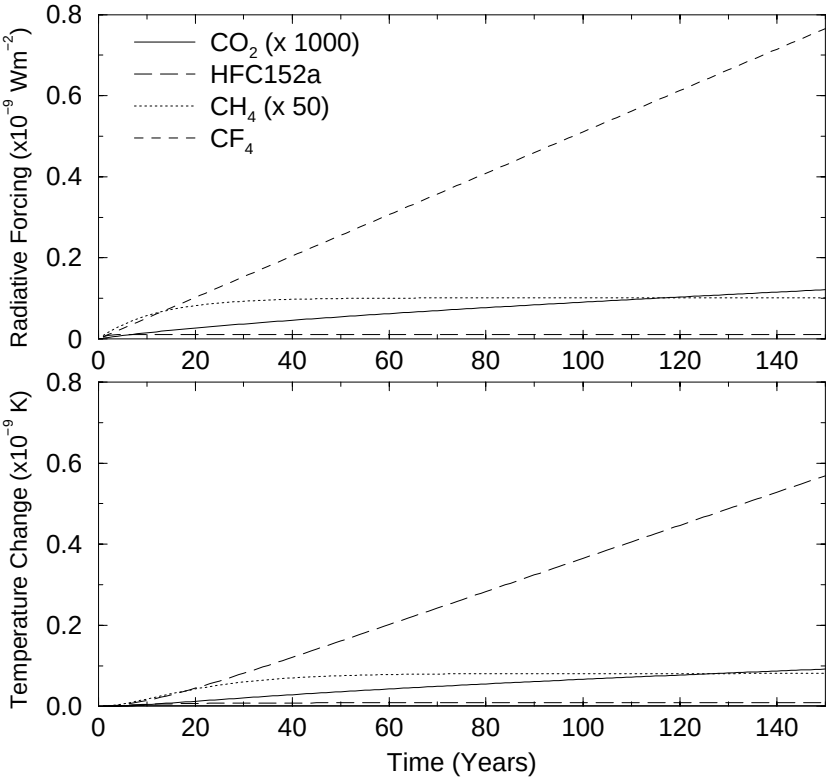

Figure 2: (a) Radiative forcing due to sustained emission increase of 1kg year^{-1} of greenhouse gases with a range of lifetimes (see Table A1) (b) Temperature response of a simple climate model (Equation (1)) to the forcings shown in (a).

3.2 Illustration 2: Comparison of the GTP for gases with an identical GWP

One problem with the GWP is that two gases could have identical values for GWP(100), but different values of A_x and α_x, and so will have a quite different impact on the temporal evolution of the temperature change in response to a pulse emission. This is illustrated by considering two fictitious gases, with the same GWP(100) as methane. The fictitious gases are labelled "CH_4 short", with a lifetime of 4 years and a specific radiative forcing of 1.11×10^{-3} Wm^{-2} $ppbv^{-1}$, and "CH_4 long", with corresponding values of 20 years and 2.23×10^{-4} Wm^{-2} $ppbv^{-1}$. These can be compared with the IPCC-recommended values for methane of 12 years and 3.7×10^{-4} Wm^{-2} $ppbv^{-1}$. In all three cases the indirect forcing is included by multiplying by a factor of 1.3 and yields a GWP(100) of 22. (The GWP(500) are also essentially identical for the three gases, and the GWP(20) ranges from 76 for "CH_4 short" and 48 for "CH_4 long".)

Table 2 illustrates the results for t=100 years. As can be seen, the temperature change in response to a pulse emission, as represented by the GTP_P, differs significantly between the three gases. As expected a gas with a lower specific radiative forcing but a longer lifetime has a greater effect than a gas with a larger specific forcing and short lifetime; Table 2 shows that the impact can be considerable (more than 2 orders of magnitude). However, as can be anticipated from the results in Section 3.1, the difference between the three gases is very small for the GTP_S, illustrating again the robustness of the GWP if it is reinterpreted as an approximate measure of temperature response at a given time resulting from sustained emissions.

At other time horizons the GTP_S and GWP remain more similar to each other than the GTP_P for the three gases. At 500 years, the GTP_S and GWP are identical, but the GTP_P is zero; at 20 years the GTP_S and GWP are within 25% of each other, with the GTP_P differing by over 40%. At 20 years, the GTP_P of "CH_4 long" remains 50% larger than "CH_4 short". Thus the lack of temperature change equivalence for GWP-weighted emissions of gases with identical values of GWP(100) is present over a large span of time horizons.

TABLE 2: Comparison of GWP, GTP_P and GTP_S at a 100-year time horizon for methane and two hypothetical methane-like gases with an identical 100-year GWP but different radiative forcings and lifetimes.

	GWP(100)	$GTP_P(100)$	$GTP_S(100)$
CH_4	22	0.35	24
"CH_4-short"	22	0.01	24
"CH_4-long"	22	2.2	25

3.3 Illustration 3: Impact of varying the climate sensitivity parameter

The climate sensitivity parameter λ is one of the most uncertain features of the climate system (IPCC 2001). It is included implicitly in the expressions for GTP_P and GTP_S via the time constant τ in (3), (5), (9) and (11) and can be varied to illustrate the impact of the uncertainty on the potentials. We varied λ across the IPCC (2001) range from 0.4 to 1.2 $K(Wm^{-2})^{-1}$ (corresponding to double-CO_2 equilibrium surface warmings of about 1.5 and 4.5K respectively). Table 3 illustrates the results; recall that the values for a λ of 0.8 $K(Wm^{-2})^{-1}$ are included in Table 1.

TABLE 3: Comparison of GWP, GTP_P and GTP_S at a 100-year time horizon for two different values of the climate sensitivity parameter of 0.4 and 1.2 K $(Wm^{-2})^{-1}$ (values for λ = 0.8 $K(Wm^{-2})^{-1}$ are given in Table 1).

	GWP(100)	$GTP_P(100)$		$GTP_S(100)$	
		λ=0.4	λ=1.2	λ=0.4	λ=1.2
HFC152a	120	0	2.0	120	135
CH_4	22	0.11	1.2	23	25
CF_4	5650	7650	7300	5560	5400

An increased λ yields an increased time constant τ for the climate system. This impacts on the $AGTP_P$ for shorter-lived (<20 years) greenhouse gases more, as the exponential decay of the temperature response to the pulse is dramatically affected by changes in τ; by contrast, the $AGTP_P$ for longer-lived gases scales approximately with λ; it can be seen that the $GTP_P(100)$ increases by an order of magnitude or more for HFC152a and CH_4 as λ is increased. However, the GTP_S is strikingly independent of λ, because the numerator and denominator are, to first order, affected in a similar way by changes in λ.

3.4 Illustration 4: Use of GTP_P for constraining temperature change at a given time

Manne and Richels (2001) have presented an index that examines the equivalence of emissions when contributing to a temperature change at a given time, H, in the future. Part of the motivation for this is to consider the case of trying to constrain the temperature change to a certain level at some future time. It addresses the question: how should the emphasis between reductions in short-lived and long-lived gases change as that H is approached?

Manne and Richels (2001) used an integrated model including components describing the energy sector and the economy to calculate a price (relative to an emission of CO_2) an emitter would be willing to pay to emit an additional ton of gas. The model incorporates the marginal cost of abating emissions of greenhouse gases.

This section uses the GTP_P to pose a similar question. It has the advantage over the Manne and Richels (2001) approach in terms of transparency, but by restricting the index to physical science, does not take into account the economic efficiency of the reductions. Manne and Richels (2001) showed that the control of short-lived gases grows in importance as H is approached. They contrast this with the GWP(100) which, of course, puts equal weight on gases throughout the period. However, there is no limitation on using a time-varying GWP where the time horizon is the difference between H and the time of emission and we therefore include the time-varying GWP in this illustration. Table 1 illustrates that the GWP will be approximately the same as the GTP_S, so the GTP_S is excluded from this comparison for clarity. We restrict attention to CH_4 and N_2O, as these were the two gases discussed by Manne and Richels (2001).

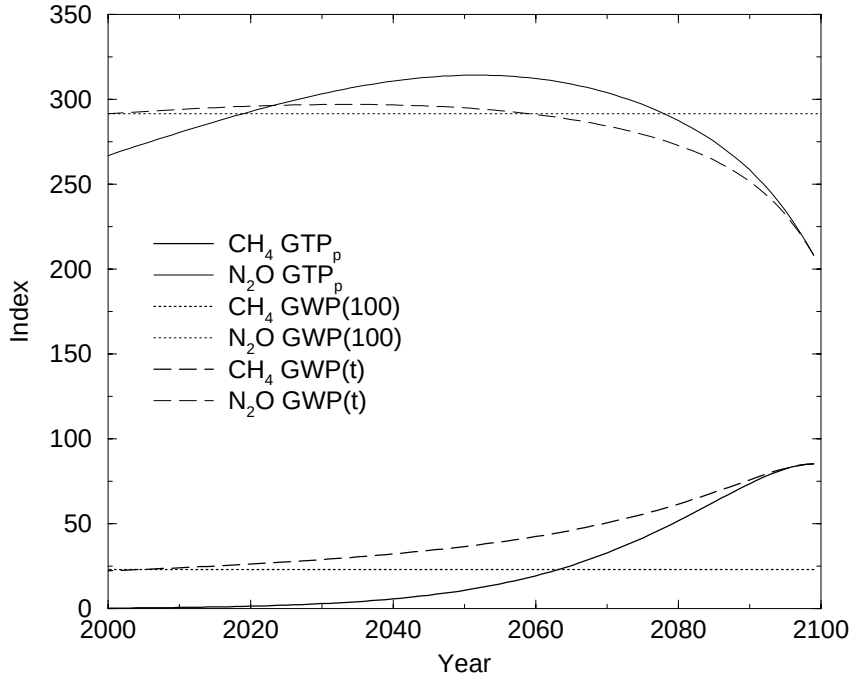

Figure 3: GTP_P plotted as a function of time assuming a need to restrict temperature change at some given time in the future (the year 2100 is shown here) for CH_4 and N_2O. The values show the relative importance of emissions of a gas as that time is approached. The 100-year GWP for each gas is also shown for reference as is the GWP for a time horizon given by the difference between 2100 and the time of emission.

Figure 3 shows the GTP_P and GWP(t) for the case of trying to constrain temperature changes in the year 2100. Hence the 2090 value is the 10-year GTP_P and GWP(t), the 2080 value is the 20-year GTP_P and GWP(t) etc. The value of the GTP_P in a given year indicates that a 1 kg emission of a gas in that year will cause the same temperature change in 2100 as GTP_P kilograms of carbon dioxide emitted in that same year. As expected, Fig. 3 shows that reductions of the relatively short-lived CH_4 early in the period has little impact in 2100, but its importance grows rapidly (and exceeds the importance indicated by GWP(100)) as 2100 is approached, in qualitative agreement with Manne and Richels (2001). The GTP_P for the much

longer-lived N_2O not only varies relatively little during the period (as found by Manne and Richels (2001)), but the value remains quite close to the GWP(100) and GWP(t) throughout. Note that for CH_4 the GWP(t) (and hence the GTP_S) has a higher value than the GTP_P early in the period. To some extent this is misleading as it is not emissions early in the period that have any impact on the temperature change in 2100; indeed Fig. 3 shows that the GWP(100) is closer to the average of the GTP_P than is the GWP(t), and so remains useful as a crude indicator of relative importance. Nevertheless, the GTP_P is a better guide of the impact of emissions in a given year on temperature at some later year.

This application of GTP_P can be considered to be an example of "backward discounting". In the design of GWP-style indices (Fuglestvedt *et al.* 2003; Kandlikar 1995; Lashof and Ahuja 1990), discounting is sometimes applied in an economical context to lessen the importance of times far into the future that are considered less important for the present than the nearer future. In this illustration, if temperature changes at a given time in the future are considered, then emissions of short-lived gases at a much earlier time are effectively physically discounted by the climate system. The GWP(100), on the other hand, puts equal weight on radiative forcings whenever they occur.

3.5 Illustration 5: Very short-lived species

The GWP has not generally been applied to the climate effect of very short-lived species (order of weeks or less), such as those of very short-lived greenhouse gases, sulphur dioxide, tropospheric ozone precursors or aircraft-induced contrails. The reasons for this omission do not seem to have been clearly spelt out (perhaps because it has been believed that the short lifetime would lead to a small GWP) and this could be a barrier to the inclusion of other species in future protocols of the UNFCCC. The GTP_S formulation does allow an obvious extension to allow their inclusion. The GTP_P for such gases would be vanishingly small for any time horizon beyond a year or so.

For a short-lived species, the forcing is almost immediately in equilibrium with the emission change so that (9) becomes

$$AGTP_S^{short}(t) = \lambda \alpha_x A_x [1 - \exp(-\frac{t}{\tau})].$$

As an example, we take $\alpha_x A_x$ due to the direct effect of sulphate aerosol to be $-5\text{x}10^{-12}$ $\text{Wm}^{-2}(\text{kgS yr}^{-1})^{-1}$ (derived from values in IPCC (2001), assuming 80 TgSyr^{-1} of anthropogenic emissions have cause a forcing of -0.4 Wm^{-2}, and that the forcing is linear in emissions). This then yields GTP_S at 20, 100 and 500 years of -240, -52 and -15 respectively, indicating the extent to which the (direct) cooling of a constant emission of sulphur are more effective in changing global-mean temperature than the same emission of CO_2.

3.6 Illustration 6: Comparison with a box-diffusion model

Clearly the model embodied in (1) is a gross simplification of the climate system. One of the simplifications is that the thermal inertia of the climate system is represented by that of the ocean mixed layer so that the climate system has a single time constant. Transfer of heat into the deep ocean, by diffusive and convective processes, slows the climate system response but also adds to the memory of the system's response to a pulse. For a limited exploration of the ability of (1) to calculate values of GTP_P and GTP_S, a simple box-diffusion model is used, with 40 layers representing a 900 m deep ocean below a 100 m mixed layer, with a diffusion co-efficient of $1\text{x}10^{-4}$ m^2s^{-1}, following Hansen et al. (1981). Further simulations performed

using a 60 m mixed layer and a diffusion co-efficient of $2x10^{-4}$ m^2s^{-1} (both following Table 9.A1 (page 577) of IPCC (2001)) yielded qualitatively the same conclusions and so are not shown.

Table 4 shows the comparison for the GTP_P. For the shorter time horizon of 20 years, the analytical and numerical models agree well. At 100 years, it can be seen that for the shorter-lived greenhouse gases there is a substantial difference between the two GTP_P values, by an order of magnitude or more – this is because the deep ocean prolongs the relative temperature response for the short-lived gases. The ability of the box diffusion model to properly represent the response to such a pulse is also open to question and more sophisticated models are required to fully assess the GTP_P. Nevertheless, the numerical-model GTP_P is closer to the analytical GTP_P than it is to the GWP(100) (Table 1), and hence the analytical GTP_P more closely represents the temperature response at a given time.

TABLE 4: Comparison of GTP_P calculated using the analytical expressions (Equations 3 and 5) and using a box diffusion model (parameters are described in the text).

	20 year		100 year	
	analytical	diffusion model	analytical	diffusion model
HFC152a	170	170	0.15	32
CH_4	52	50	0.35	6.9
HFC134a	2840	2750	34	400
N_2O	290	290	270	280
CF_4	4150	4200	7490	6900

One possibility for improving the analytical GTP_P is to represent the temperature response in (2) by a sum of exponentials with different time constants representing different components of the climate system (as used, for example, by Hasselmann *et al.* (1997)). Exploratory calculations were performed with a two-component model developed for a UNFCCC assessment (www.cru.uea.ac.uk/unfccc_assessment), which was based on the transient response of a general-circulation model (GCM) to a steadily increasing forcing. Such an approach yielded a value in better agreement with the diffusion model GTP_P at 100 years for HFC152a, although at the expense of the value at 20 years. Nevertheless, this indicates that it may be possible to achieve a better representation by fitting exponentials to the GCM response to a pulse-like forcing.

Table 5 shows that for the GTP_S, the analytical expression and the numerical model yield good agreement to better than 10% at both time horizons for all gases. This is encouraging for the analytical model and indicates that the GTP_S is likely to be a reasonably robust tool as a metric despite the simplifications in its formulation.

TABLE 5: Comparison of GTP_S calculated using the analytical expressions (Equations 9 and 11) and using a box diffusion model (parameters are described in the text).

	20 year		100 year	
	analytical	diffusion model	analytical	diffusion model
HFC152a	570	540	130	140
CH_4	69	68	24	26
HFC134a	3590	3540	1370	1470
N_2O	260	260	290	290
CF_4	3610	3650	5480	5370

4 Conclusions

In the preparations for both the next IPCC assessment and the negotiations for the next reporting period of the UNFCCC, it is important that the climate change community reassesses the metrics available to policymakers for comparing the climatic impacts of different emissions.

In this paper, as a contribution to this reassessment, two related alternatives to the GWP have been presented, which represent the impacts of emissions on global-mean surface temperature change. The GTP_P compares the temperature effect of pulse emissions, while the GTP_S compares the effect of sustained emission changes. Both new metrics retain some of the attractions of the GWP, such as a transparent formulation, the reliance on relatively few parameters and the possibility of use by policymakers with little further input from scientists. They have a clear advantage over the GWP in that they represent an actual (if crude) climate impact, rather than the more abstract concept of integrated radiative forcing due to a pulse emission.

The GTP_P shows clearly that pulses of short-lived gases can only have a modest impact on temperature change at 100 years, if their lifetime is short compared to the typical response time of the climate system, a fact that might not be inferred from the values of the GWP(100). This is further illustrated by comparing three gases which have an identical GWP(100) but different specific radiative forcing and lifetimes; a pulse emission of a weaker greenhouse gas with a longer lifetime can have a far greater impact on surface temperature than a stronger short-lived gas on a 100 year time scale. One problem with the formulation of the GTP_P is that there are indications that a simple (mixed-layer only) representation of the climate system produces smaller GTP_P values for the shorter-lived gases at 100 years than inferred numerically from a (still simple) box-diffusion model that incorporates more timescales for the response of the climate system. Further research with more sophisticated models, including GCMs, would be necessary to assess the likely true system response to a pulse forcing. Despite this, the simple GTP_P formulation represents better the relative temperature impact of different gases than might be inferred by using the GWP which puts equal emphasis on radiative forcing no matter when this occurs. The GTP_P can be used as a way of providing equivalence of emissions in a given year, if a target is to restrict temperature change in a particular year (e.g. 2100) in the future.

The GTP_S may be a more policy-relevant metric as it represents the relative climate impact of sustained emission changes. One interesting result is that the GTP_S and GWP produce very similar values, a result that was pointed out in a somewhat different context by Fisher *et al.* (1990). This result indicates that the GWP may have a greater utility than has generally been recognised and represents more than just the integrated radiative forcing in response to a pulse emission. Nevertheless, the GTP_S more explicitly represents the temperature response to a sustained emission change for all time horizons and would be preferable to a reinterpreted GWP, if a temperature change metric is required. The GTP_S could then be used in a similar way to the GWP, as a basis for providing equivalence between sustained emission changes of CO_2 and other greenhouse gases for the period leading up to a given time (e.g. 100 years) in the future.

Unlike the GTP_P, the GTP_S reproduces results from a box-diffusion model to better than 10% at both 20 year and 100 year timescales and is also relatively insensitive to uncertainties in the climate sensitivity parameter; this uncertainty, to first order, affects the gas under consideration and the reference gas in a similar way. Thus the GTP_S appears to be robust to a number of uncertainties in the tests performed here and this may commend its adoption as a replacement to the GWP.

If the GTP_S was to find favour as a metric, its similarity with the GWP can be considered as an advantage, as the policy consequences of changing the metric would be slight (assuming, of course, that a time horizon of 100 years is retained for the GTP_S which is by no means obvious). One aspect and possible drawback of the GTP_S (and the GWP when reinterpreted as an approximate GTP_S) is that emission changes must be maintained beyond any reporting period; otherwise a GTP_S-based equivalent emission change would not guarantee (approximate) equivalence in terms of induced temperature change if the chosen time horizon is beyond the reporting period.

The GTP_P and GTP_S formulations presented here could no doubt be extended further – for example, multiple timescales of climate response could be represented by using a sum of exponentials approach. It is possible that values could be derived for emission changes intermediate between pulse and sustained, which might be useful in some applications. The formulation could also be extended to represent other parameters, such as sea-level rise, the rate of change of temperature or even economic damage. One aspect of the GTP developed here is that it concentrates on equivalence of temperature change at a particular time, rather than the path of temperature change leading up that time. A further possible extension of the metric would be towards one that used integrated temperature change up to a given time horizon, which would account, to some extent, for the path.

One significant simplification in this study is the representation of the carbon budget. It may be that in any "legislative" application of the GTP, a more sophisticated carbon budget model could be used to provide the AGTP for the reference gas and that model could also have a built-in dependence on a chosen background scenario of CO_2 change.

Appendix

This appendix gives some basic information on parameters used in this work, to allow the calculation of the values here. For consistency, all values are those used for GWP calculations are essentially identical to those in IPCC (2001).

The absolute global warming potential for non-CO_2 greenhouse gases is given by

$$AGWP^x(t) = \int_0^t A_x \exp(-t'/\alpha_x)dt' = A_x\alpha_x[1-\exp(-\frac{t}{\alpha_x})]. \quad \text{(A1)}$$

For carbon dioxide, using (4) then

$$\begin{aligned} AGWP^C(t) &= \int_o^t A_c[a_o + \sum_i a_i \exp(-\frac{t'}{\alpha_i})]dt' \\ &= A_c[a_o t + \sum_i a_i\alpha_i(1-\exp(-\frac{t}{\alpha_i}))] \end{aligned} \quad \text{(A2)}$$

For (A2) and (4), the coefficients are a_o=0.1756, a_1=0.1375, a_2=0.1858, a_3=0.2423 and a_4=0.2589. α_1=421.093, α_2=70.5965, α_3=21.4216, α_4=3.4154 (all α values are in years). These coefficients were provided by F. Joos (personal communication) using the model of Joos et al. (1996) and are a fit to the same response function as used by IPCC (2001). However, note that IPCC used a fit with a different mathematical form (see WMO (1999)) which was not amenable to the analytical integrations performed in this paper. The difference in the two fits results in a *slight* difference in the values for the $AGWP^C$; for example, at 100 years, the value used here is 1.5% higher than the IPCC (2001) value, and consequently some of the values of GWP also slightly differ (and are slightly lower) to the IPCC (2001) values. Table A1 lists the values of A_x and α_x used here.

For (3), (5), (9), (11), (A1) and (A2), some care is required with the units. It is convention, in IPCC reports and elsewhere, to quote the specific radiative forcings in $Wm^{-2}ppbv^{-1}$, whereas the expressions use a mass form in $Wm^{-2}kg^{-1}$; values for both forms are shown in Table A1. To convert the per ppbv values to per kg, they must be multiplied by $(M_A/M_x)(10^9/T_M)$ where M_A is the mean molecular weight of air (28.96 kg $kmol^{-1}$), M_x is the molecular weight of molecule x, and T_M is the total mass of the atmosphere, about $5.15x10^{18}$ kg.

In addition, if the time constants τ and α are taken to be in years, then it is necessary to multiply (3), (5), (9) and (11) by the number of seconds in a year, about $3.16x10^7$ seconds.

TABLE A1: Values of radiative forcing, A_x, (in $Wm^{-2}kg^{-1}$ and $Wm^{-2}ppbv^{-1}$) and gas lifetime, α_x, (in years) from IPCC (2001) for the gases used in this paper. The radiative forcing for methane given in this table has to be multiplied by 1.3 to account for indirect forcings in the calculations presented here.

Gas	Radiative forcing ($Wm^{-2}kg^{-1}$)	Radiative Forcing ($Wm^{-2}ppbv^{-1}$)	Lifetime (years)
CO_2	$1.98x10^{-15}$	$1.548x10^{-5}$	see text
HFC152a (CH_3CHF_2)	$7.66x10^{-12}$	0.09	1.4
CH_4	$1.3x10^{-13}$	$3.7x10^{-4}$	12
HFC134a (CH_2FCF_3)	$8.27x10^{-12}$	0.15	13.8
N_2O	$3.96x10^{-13}$	$3.1x10^{-3}$	114
CF_4	$5.11x10^{-12}$	0.08	50000

References

Fisher, D.A., C.H. Hales, W.-C. Wang, M.K.W. Ko, and N.D. Sze 1990 Model Calculation on the Relative Effects of CFCs and their Replacements on Global Warming. *Nature*, **344,** 513-516

Fuglestvedt, J.S., T. Berntsen, O. Godal, and T. Skodvin 2000 Climatic implications of GWP-based reductions in greenhouse gas emissions. *Geophys.Res.Lett.*, **27,** 409-412

Fuglestvedt, J.S., T.K. Berntsen, O. Godal, R. Sausen, K.P. Shine, and T. Skodvin 2003 Metrics of Climate Change: assessing radiative forcing and emission indices. *Climatic Change*, **,** (to appear)

Godal, O. 2003 The IPCC's Assessment of Multidisciplinary Issues: The Case of Greenhouse Gas Indices. *Climatic Change*, (to appear)

Hammitt, J.K., A.K. Jain, J.L. Adams, and D.J. Wuebbles 1996 A Welfare-based Index for Assessing Environmental Effects of Greenhouse-gas Emissions. *Nature*, **381**

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell 1981 Climate Impact of Increasing Atmospheric Carbon-Dioxide. *Science*, **213,** 957-966

Hansen, J., M. Sato, and R. Ruedy 1997 Radiative forcing and climate response. *J. Geophys. Res.-Atmos.*, **102,** 6831-6864

Hartmann, D.L. 1996 *Global Physical Climatology*, Academic

Hasselmann, K., S. Hasselmann, R. Giering, V. Ocana, and H. van Storch 1997 Sensitivity study of optimal CO_2 emission paths using a structural integrated assessment model (SIAM). *Climatic Change*, **37,** 345-386

IPCC 1990 *Climate Change: The Intergovernmental Panel on Climate Change Scientific Assessment*, Cambridge University Press, Cambridge UK

IPCC 1995 *Climate Change 1994. The Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK

IPCC 1996 *Climate Change 1995. The Science of Climate Change. The Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge UK

IPCC 2001 *Climate Change 2001: The Scientific Basis. Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge UK

Joos, F., M. Bruno, R. Fink, T.F. Stocker, U. Siegenthaler, C. Le Quéré, and J.L. Sarmiento 1996 An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. *Tellus*, **48B,** 397-417

Joshi, M.M., K.P. Shine, M. Ponater, N. Stuber, R. Sausen, and L. Li 2003 A comparison of climate response to different radiative forcings in three general circulation models: towards an improved metric of climate change. *Climate Dynamics*, (to appear)

Kandlikar, M. 1995 The relative role of trace gas emissions in greenhouse gas abatement policies. *Energy Policy*, **23**

Lashof, D.A., and D.R. Ahuja 1990 Relative contributions of greenhouse gas emissions to global warming. *Nature*, **344,** 529-531

Manne, A.S., and R.G. Richels 2001 An alternative approach to establishing trade-offs among greenhouse gases. *Nature*, **410,** 675-677

O'Neill, B.C. 2000 The Jury is Still Out on Global Warming Potentials. *Climatic Change*, **44,** 427-443

O'Neill, B.C. 2003 Economics, natural science, and the costs of the global warming potential. *Climatic Change*, (to appear)

Sausen, R., and U. Schumann 2000 Estimates of the climate response to aircraft CO_2 and NO_x emission scenarios. *Climatic Change*, **44,** 27-58

Schmalensee, R. 1993 Comparing Greenhouse Gases for Policy Purposes. *The Energy Journal*, **14**

Sihra, K., M.D. Hurley, K.P. Shine, and T.J. Wallington 2001 Updated radiative forcing estimates of sixty-five halocarbons and non-methane hydrocarbons. *J. Geophys. Res.*, **106,** 20493-20505

Skodvin, T., and J.S. Fuglestvedt 1997 A comprehensive approach to climate change: political and scientific considerations. *Ambio*, **26,** 351-358

Smith, S.J. 2003 The evaluation of greenhouse gas indices. *Climatic Change*, **,** (to appear)

Smith, S.J., and T.M.L. Wigley 2000a Global warming potentials: 1. Climatic implications of emissions reductions. *Climatic Change*, **44,** 445-457

Smith, S.J., and T.M.L. Wigley 2000b Global warming potentials: 2. Accuracy. *Clim. Change*, **44,** 459-469

Wigley, T.M.L. 1998 The Kyoto Protocol: CO_2, CH_4 and climate implications. *Geophys.Res.Lett.*, **25,** 2285-2288

WMO 1999 *Scientific Assessment of Ozone Depletion: 1998: Global Ozone Research and Monitoring Project Report No 44*, World Meteorological Organization, Geneva, Switz.

Wuebbles, D.J., A.K. Jain, K.O. Patten, and K.E. Grant 1995 Sensitivity of direct global warming potentials to key uncertainties. *Climatic Change*, **29,** 265-297