A guide to global warming potentials (GWPs)

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In order to quantitatively compare the green-house effect of different greenhouse gases a global warming potential (GWP) index has been used which is based on the ratio of the radiative forcing of an equal emission of two different gases, integrated either over all time or up to an arbitrarily determined time horizon. The GWP index is analogous to the ozone depleting potential (ODP) index. However, the GWP index is subject to major conceptual difficulties arising from the fact that the atmospheric lifespan for part of the emitted CO_2 is, for all practical purposes, infinite. In addition, there are major uncertainties in the atmospheric lifespans and indirect heating effects of the important green-house gases, which are reviewed here. An alternative GWP index is proposed which explicitly takes into account the duration of capital investments in the energy sector and is less sensitive to uncertainties in atmospheric lifespans and radiative heating than the usual GWP index for time horizons longer than the lifespan of the capital investment. The effect of the GWP index proposed here, compared with previous indices, is to shift attention away from short lived gases such as methane and toward CO_2.

Human activities have led to increases in the concentration of a number of gases which are effective in absorbing and reemitting radiation in the infrared part of the electromagnetic spectrum, leading to a strengthening of the so-called greenhouse effect. The primary gases responsible for this strengthening are carbon dioxide (CO_2), methane (CH_4), tropospheric ozone (O_3), the chlorofluorocarbons (CFCs)

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and nitrous oxide (N_2O). Many of the proposed replacements for CFCs, such as the HCFCs and HFCs, are also greenhouse gases. Other gases, such as carbon monoxide (CO) and the nitrogen oxides (NO_x), as well as hydrocarbons (HCs), are not themselves greenhouse gases but influence the concentration of one or more greenhouse gases and thus indirectly affect the strength of the greenhouse effect.

Certain costs will be entailed in reducing the emissions of any one of these gases (whether economic or other kinds of costs). In developing an overall strategy to reduce emissions of greenhouse gases, it is important to be able to quantitatively compare the contribution to the greenhouse effect of a given quantity of each of the gases. The relative unit contribution of each gas to the greenhouse effect can then be compared with the unit cost of emission reduction in instances where there is a trade off between reducing emissions of one gas more and another gas less, or where measures to reduce emissions of one gas might lead to an increase in emissions of another gas.

Unfortunately, the task of quantitatively comparing the greenhouse effectiveness of different gases is fraught with numerous difficulties, both conceptual and analytic. These difficulties arise from the fact that the heat trapping ability of a given gas depends on a number of parameters which change through time, that indirect chemical effects are involved and, most importantly, that the average lifespan in the atmosphere of each gas is different. Thus, if equal quantities of each gas are emitted into the atmosphere at a given time (or conversely, equal emissions are avoided), the relative amounts of the gases remaining in the atmosphere continuously change through time.

Several authors have attempted to overcome the problem of differing lifespans by introducing an index based on the ratio of radiative forcing by different gases integrated over a specific time interval.[1] The expectation is that such indices will be used by policy makers during the negotiation of

overall limitations of greenhouse gases, either to permit trading between gases or to allow a given state to choose the specific combination of greenhouse gas emission reductions that it wishes in achieving a given reduction in total greenhouse heating.[2] The purpose of this paper is to argue that the conceptual difficulties and scientific uncertainties in computing GWPs are so large, and will remain so large, that such indices have no practical value in the applications suggested above. An alternative conceptual framework to calculating GWPs is proposed which is robust to scientific uncertainties and which can be applied to the more limited problem of evaluating the net effect of different fossil fuel using technologies when alternative technologies emit more than one greenhouse gas but in different proportions.

The problem

Given that the relative greenhouse effect of equal emissions of different gases changes over time, one way to quantitatively compare two or more gases is to compare the *integrated* heating effect over all time. If $C_i(t)$ is the concentration of gas i at time t following the emission of a unit amount at time $t = 0$, $f_i(t)$ is the heat trapping ability at the same time per unit of concentration, and $C_c(t)$ and $f_c(t)$ the corresponding quantities for CO_2, then the GWP of gas i relative to CO_2 could be given by

$$GWP = \frac{\int_0^\infty f_i(t)C_i(t)\mathrm{d}t}{\int_0^\infty f_c(t)C_c(t)\mathrm{d}t} \qquad (1)$$

A similar approach is used in calculating the ozone depleting potential (ODP) of different ozone depleting gases: one compares the ozone depletion per unit of concentration of two gases, times the concentration remaining after a pulse input, integrated over all time as the concentrations of the gases continously decrease. For a linear response to CFC emissions, this is mathematically equivalent to considering a continuous and equal rate of emission of two different gases, and comparing the steady state ozone depletion resulting from the two gases.

There is no conceptual problem in making this comparison (whether for ODPs or GWPs) as long as both gases have a finite atmospheric lifetime or, conversely, as long as both gases asymptote to a steady state concentration given a continuous and constant rate of emission. This condition is satisfied for all gases of interest *except* CO_2. Unlike all other gases emitted in the atmosphere by humans, CO_2 does not have a chemical or photochemical sink

within the atmosphere itself. Removal of CO_2 is therefore dependent on exchanges with other carbon reservoirs. Following the emission of a hypothetical pulse of CO_2 into the atmosphere, about 10% will be removed within two years through gaseous diffusion into the mixed layer of the ocean. Subsequent removal is dependent on downward mixing into the deeper ocean. Ultimately, about 85% of the initial pulse can be removed by mixing into the ocean, but only over a time period of several hundred to a thousand years.[3] Another 10% of the initial pulse will be removed by dissolution of marine carbonate sediments, but over a period of several thousand years.[4] The remaining 5% or so is removed over a period of 100 000 years through silicate rock weathering.[5]

Three-dimensional models of ocean chemistry, circulation and deep mixing have been used to determine the rate of decrease in concentration C of a pulse of CO_2, neglecting the geological timescale processes of carbonate sediment dissolution and silicate rock weathering. The concentration of remaining CO_2 following a unit pulse emission can be conveniently approximated by:[6]

$$C_c(t)=\Sigma_{i=0}^4 A_i \exp \left(-\frac{t}{\tau_i} \right) \qquad (2)$$

where the values of A_i and τ_i are given in Table 1. Since $\tau_0=\infty$ this can be written as

$$C_c(t)=A_0+\Sigma_{i=1}^4 A_i \exp \left(-\frac{t}{\tau_i} \right) \qquad (2)$$

As $t\to\infty$, a fraction A_0 of the initial impulse remains in the atmosphere, all other terms in Equation (3) decaying to zero. As previously noted, this CO_2 will eventually be removed by carbonate dissolution and silicate rock weathering, but the rate of removal is so slow that it is zero for all practical purposes. Thus, for any constant non-negligible anthropogenic emission rate, the CO_2 concentration does not asymptote

Table 1. Values of the constants A_i and τ_i in Equation (2), as given in Maier-Reimer and Hasselmann.

i	A_i	τ_i
0	0.131	∞
1	0.201	362.9
2	0.321	73.6
3	0.249	17.3
4	0.098	1.9

Source: E. Maier-Reimer and K. Hasselmann, 'Transport and storage of CO_2 in the ocean – an inorganic ocean circulation carbon cycle', *Climate Dynamics*, Vol 2, 1987, pp 63–90.

to a steady state value, but increases indefinitely. Hence, the lower integral in Equation (1) is infinite.

This problem has been resolved in two ways. One is to set $\tau_0 < \infty$, which is equivalent to assuming that the asymptotic airborne fraction A_0 decreases through time. Lashof and Ajuha, for example, set $A_0 = 1000$ years.[7] However, at the century timescale of human interest, A_0 will actually *increase* with time because of the increase in the oceanic buffer factor, so that the ability of the ocean to absorb CO_2 inputs to the atmosphere decreases. Only at the timescale of several oceanic overturnings, of the order of several thousand years, will A_0 decrease, as a result of dissolution of carbonate sediments. Resolving the problem of infinite integrals by letting A_0 decay to zero with the relatively short time constant of a thousand years serves to underestimate the long-term importance of CO_2 emissions relative to emissions of other greenhouse gases.

An alternative solution to this problem is to retain $\tau_0 = \infty$ but to integrate the radiative forcing arising from an impulse input only up to a time horizon T. Thus,

$$GWP = \frac{\int_0^T f_i\,(t) C_i\,(t)\,\mathrm{d}t}{\int_0^T f_c\,(t)\,C_c\,(t)\,\mathrm{d}t} \qquad (4)$$

This approach has been adopted by the Intergovernmental Panel on Climatic Change (IPCC) and in subsequent work by Lashof and coworkers published by the Advisory Group on Greenhouse Gases (AGGG).[8] The GWP so defined depends on the choice of time horizon: for gases having a shorter atmospheric residence time than the average for CO_2, GWP decreases as longer time horizons are considered.

The foregoing outlines the conceptual problem in determining GWPs for different gases. In the approaches used so far, the conceptual problem reduces to deciding on a choice of time horizon. Short time horizons are appropriate if one is more concerned with potential climatic changes during the next few decades or if one is concerned with the rate of climatic change, where the rapid build-up of short lived greenhouse gases would tend to provoke initial rapid rates of warming. Longer time horizons are more appropriate if one is more concerned about long-term, chronic effects of climatic warming (such as sea level rise). There are, however, a whole series of uncertainties dealing with the hard science – in particular, determining the direct and indirect radiative heating effects of different gases (the f_i values above) and the time constants for removal from the atmosphere of CO_2 and other gases (the τ values

Table 2. Radiative heating effect per molecule and per unit mass of various greenhouse gases relative to CO_2.

Trace gas	Heating relative to CO_2 per molecule	Per unit mass
CO_2	1	1
CH_4	26	72
N_2O	206	206
CFC-11	12 400	3970
CFC-12	15 800	5750
HCFC-22	10 700	5440
CF_3Br	16 000	4730

above). These uncertainties are briefly outlined below.

Uncertainties in calculation

Radiative effects

The globally and annually averaged trapping of infrared radiation at the tropopause (the base of the stratosphere) provides a first order estimate of the overall warming effect of a given greenhouse gas. This trapping involves two components: a decrease in upward radiation from the troposphere (which underlies the stratosphere) and an increase in downward radiation from the stratosphere. The net effect on infrared radiation depends on:

● absorption and emission coefficients as a function of gas amount, pressure, temperature, and wavelength, which can be determined to high accuracy from laboratory spectroscopic measurements;

● the degree of overlap in the absorption of the gas in question with absorption by other gases, and hence on the concentrations of all other gases;

● the atmospheric temperature profile and cloudiness.

The absorption coefficients of many gases do not vary linearly with gas concentration: the radiative heating of a unit of a given gas thus depends on the preexisting concentration of the gas and thus changes through time. It also depends on the concentrations of other gases which absorb in the same spectral regions. For these reasons, the heat trapping ability f_i depends on the scenarios of future concentrations of most or all of the greenhouse gases. All calculations of GWP to date have assumed time invariant f_i values, appropriate to present day conditions.

Table 2 compares the average radiative heating per molecule of various gases relative to CO_2, as

determined by the IPCC except for CH_4, which is based on Lelieveld and Crutzen.[9] The values given in Table 2 assume the gases to be uniformly mixed in the atmosphere. This is a valid assumption for the gases shown in Table 2, but not for O_3, whose concentration varies substantially in all three dimensions. The effectiveness of a given tropospheric gas in reducing upward infrared radiation at the tropopause is greater the colder it is relative to the surface; removal of an ozone molecule in the upper troposphere (which is coldest relative to the surface) causes a much greater decrease in the greenhouse effect than removal of an ozone molecule near the surface. In the case of stratospheric ozone, an ozone decrease in the lower stratosphere is more effective in reducing downward radiation at the tropopause than a decrease in the middle or upper stratosphere. Offsetting this decrease to varying degrees is an increase in downward solar radiation at the tropopause. Hence, the net effect of ozone losses depends critically on the vertical distribution of changes, and can be one of heating or cooling.[10]

Atmospheric lifetime

CO_2. Observations from polar ice cores indicate that the atmospheric CO_2 concentration was close to constant for several hundred years prior to the industrial revolution.[11] Since 1800, the atmospheric CO_2 concentration has increased by 25% and there is no doubt that this increase is due to anthropogenic activities. However, the observed increase – the so-called *airborne fraction* – is only about 50% of the cumulative emissions since 1800. The remaining 50% has already been absorbed by some combination of the oceans and terrestrial biosphere. Unfortunately, we are not able to determine the relative importance of these two sinks. Some evidence indicates that the oceans could not have absorbed more than 1/3 of the non-airborne CO_2 and that the northern temperate latitude biosphere is a major carbon sink.[12] This, however, is contradicted by isotopic ^{13}C data, which indicate that the northern high latitude oceans are a larger sink than the northern biosphere.[13]

Determination of the current CO_2 sinks, and how these sinks are likely to change with increasing CO_2 emissions, is crucial to the calculation of GWPs. If the primary sink is the terrestrial biosphere then continuing forest destruction, nutrient limitations or temperature induced increases of respiration could dramatically increase the lifetime of CO_2 in the atmosphere.[14] If the primary sink is the oceans, then climatic change-induced changes in ocean circulation or biological productivity could significantly alter the

atmospheric CO_2 lifetime. Sarmiento and Toggweiler, and Baes and Killough concluded that decreased oceanic overturning would reduce atmospheric CO_2, while Baes, and Broecker and Takahashi suggest the opposite.[15] Uncertainty in the removal rates of CO_2 from the atmosphere is a major source of uncertainty in the calculation of GWPs over a time horizon of the next few decades.

CH_4. The primary sink of methane is reaction with atmospheric OH, with soils serving as an additional small sink.[16] The average lifetime of a methane molecule is 8–12 years, based on the global average OH concentration, which is computed from the distribution and concentration trend for methyl chloroform.[17] However, the exact value is sensitive to the atmospheric OH distribution. It is assumed that CH_3CCl_3 is destroyed only by reaction with OH, but recent work suggests that some CH_3CCl_3 is taken up by the ocean.[18] Such additional loss could mean that the inferred OH concentration is 5–20% too large, and hence that the lifetime of molecules lost solely by reaction with OH is 5–20% longer than currently estimated. In addition, a recent revision of the CH_4–OH rate constant suggests a further 25% increase in the estimated lifetime of CH_4.[19]

The OH concentration itself depends in complex ways on emissions of CH_4, thus introducing a feedback between CH_4 concentration and its GWP. Uncertainties in the CH_4–OH coupling introduce a further uncertainty in the CH_4 GWP of about 20–30% over a 50 year time horizon.[20] Other chemical effects on the CH_4 GWP are discussed below.

N_2O. The major sink of N_2O is photochemical destruction in the stratosphere, and its estimated lifetime has recently been revised from 150 years to 110 years.[21] The main sources appear to be the oceans, denitrification in aerobic soils, and combustion and biomass burning. However, we cannot at present balance the N_2O budget, which introduces uncertainties in determining its present atmospheric lifetime. As with CO_2, it is possible that changes in ocean circulation or biological productivity as climate changes could significantly alter its atmospheric lifetime.

Halocarbons. Although the most ozone damaging chemicals will be strongly controlled over the coming years, many of the proposed substitutes are important greenhouse gases. Most of these are hydrochlorofluorocarbons (HCFCs), and are destroyed principally by reaction with tropospheric OH.[22] Their lifetime will therefore change in re-

sponse to changing OH concentration. Additionally, the role of the oceans in absorbing HCFCs is not known.

Effects of atmospheric chemistry

As discussed above, atmospheric chemistry can influence the GWP of a given gas by altering its atmospheric lifetime, primarily through changing OH concentrations. Atmospheric chemistry can also alter the concentration or occurrence of greenhouse gases other than the one being emitted. Such indirect effects should be added to the direct heating effect of a given gas in assessing its GWP. The major indirect effects are discussed below.

CO_2. An increase of CO_2, unlike that of other greenhouse gases, tends to cool the stratosphere. To the extent that this favours the formation of polar stratospheric clouds, this will worsen stratospheric ozone depletion. Such ozone depletion will have a cooling effect, although further effects through negative impacts of increased UV radiation on terrestrial and oceanic photosynthesis could lead to increased CO_2 fluxes to the atmosphere. The radiative impact of both effects is likely to be small compared to uncertainties concerning the atmospheric lifetime of CO_2, although the implications for stratospheric ozone depletion are serious as CO_2 induced stratospheric cooling would reinforce stratospheric cooling due to ozone depletion itself.

CH_4. Methane can indirectly affect the trapping of infrared radiation in the following ways:

● Oxidation of methane in the stratosphere produces stratospheric water vapour, which is not subject to the rapid removal of the lower atmosphere (where the mean lifespan is eight days), thereby increasing greenhouse heating by as much as 1/3 of the direct effect of methane according to the IPCC but by only 7% according to Lelieveld and Crutzen.[23]

● The afore mentioned stratospheric water vapour production leads to ozone destruction in the upper stratosphere.

● Methane tends to increase stratospheric ozone in the lower stratosphere by forming HCl from free Cl, thereby removing Cl from the catalytic ozone destruction cycle.[24]

● Methane contributes to the formation of tropospheric ozone under conditions of high NO_x;[25] the net heating effect of all ozone change is estimated to be 40–60% by Rotmans *et al* and 20–40% by Lelieveld and Crutzen, while Owens *et al* estimate the net effect of combined

water vapour and ozone changes to be 76% of the direct effect.[26]

● By altering the OH concentration, methane emissions alter the atmospheric lifespan of other greenhouse gases besides its own; for some scenarios, up to a 50% increase in the lifetime of methane and CFC substitutes is estimated, with heating effects of 20–50% of the direct effect.[27]

● Methane is ultimately oxidized to CO_2.

Both the direct and indirect methane GWPs decrease as the time horizon increases, although the indirect GWP as a percentage of the direct GWP can increase or decrease through time, depending on the gas emission scenario. For constant emissions of all gases, Lelieveld and Crutzen find that the indirect methane GWP adds 38% to the direct GWP at a 20 year time horizon but only 25% at a 100 year time horizon, while for a scenario of increasing gas emissions the indirect effects add 60% and 74% to the direct effects at 20 and 100 year time horizons respectively.[28] The impact of CH_4 (and CO) emissions on OH and tropospheric ozone depends on the background NO_x concentration, which is highly variable.[29] The mean atmospheric lifetime of methane is long (8–12 years) compared to the time to mix throughout the atmosphere (months within hemispheres, one year for mixing between hemispheres), so that the net effect of a given methane emission on OH and ozone is largely independent of where the emission occurs, although computation of the globally averaged effect requires integration over regions of differing background chemistry and radiative fluxes.

In light of these uncertainties, the IPCC update declined to estimate an indirect methane GWP, while pointing out that the indirect GWP could be comparable in magnitude to the direct GWP.[30]

N_2O. N_2O is an important source of reactive nitrogen in the stratosphere; it contributes to ozone destruction both through gaseous phase chemistry and through the formation of polar stratospheric clouds, which are implicated in the Antarctic ozone hole.[31] These effects probably reduce the GWP of N_2O but are also probably small.

CFCs. To the extent that CFC emissions alone are responsible for stratospheric ozone depletion (ie if CO_2 induced stratospheric cooling were negligible or had a negligible effect), the net warming effect of CFC emissions is reduced. A recent analysis for the period 1970–81 indicates that the stratospheric ozone depletion in northern hemisphere mid-

latitudes during this period masked half of the incremental heating due to increase of CO_2 during the same period.[32] Limited data from a single southern hemisphere mid-latitude location also imply a surface cooling due to ozone changes, while indirect evidence suggests that ozone changes at low latitudes have also had a net cooling effect. Since the direct heating effect of CFC increases between 1970 and 1980 was only 40% that due to the CO_2 increase,[33] the net effect of CFCs could be one of cooling. As discussed above, the net effect of ozone changes depends critically on the vertical distribution of changes, as ozone losses above 30 km have a net warming effect due to the fact that the increased penetration of solar radiation more than compensates the reduction in infrared emission to the troposphere. Further complicating the picture is the fact that stratospheric ozone loss allows an increase in penetration of ultraviolet radiation to the troposphere, leading to increased tropospheric ozone and production of OH, thereby tending to reduce the mean atmospheric methane lifespan.[34] There are, therefore, large uncertainties in the determination of the net radiative effect of ozone changes and hence in the net effect of CFCs.

CO. CO emissions, like those of methane, affect tropospheric OH and ozone concentrations and thus indirectly affect greenhouse heating. Three-dimensional model simulations suggest that anthropogenic CO emissions have decreased atmospheric OH at low latitudes and in the southern hemisphere, but have increased atmospheric OH north of 20° N.[35] The mean atmospheric lifetime of CO is about two months, which is comparable to atmospheric mixing times, so that the average global effect of CO emissions depends on where the emissions occur. As with methane, CO is ultimately oxidized to CO_2.

NO$_x$. NO_x emissions contribute to tropospheric ozone formation and hence indirectly add to the greenhouse effect, but also tend to increase atmospheric OH, which will tend to shorten the lifetime of CH_4 and other greenhouse gases, thereby reducing the greenhouse effect. The extent and even occurrence of ozone formation associated with NO_x emissions is highly dependent on the regional atmospheric chemistry, so that, like CO, there is no single GWP for NO_x which can be applied everywhere. Furthermore, NO_x emissions in the upper troposphere (from aircraft) are about 20 times more effective in producing O_3 than are surface emissions, and upper tropospheric ozone is about 1.3 times

Table 3. Atmospheric lifespans and global warming potentials per unit mass as computed by the IPCC update for time horizons of 20, 100 and 500 years.

Gas	Average lifespan (years)	20 years	Time horizon 100 years	500 years
CH_4	10.5	35	11	4
N_2O	132	260	270	170
CFC-11	55	4500	3400	1400
CFC-12	116	7100	7100	4300
HCFC-22	15.8	4200	1600	540

more effective, on a molecule-per-molecule basis, in trapping infrared radiation than surface ozone. Consequently, NO_x emissions from high flying aircraft are calculated to have about 30 times the warming effect of equal emissions from surface sources.[36]

Direct GWPs

Table 3 gives GWPs for CH_4, N_2O, CFC-11, CFC-12 and HCFC-22 as computed by the IPCC update;[37] these GWPs include only direct radiative effects. A revision in the estimated lifespan of CO_2, or climate–carbon cycle feedbacks, could dramatically change all of the GWPs given in Table 3.

Potential applications of GWPs

Given the enormous uncertainties in the calculation of GWPs and their dependence on future scenarios, it is difficult to see how they could be used in any rigorous way for policy analysis. The US administration advocates a basket approach to any greenhouse gas emission reductions, whereby any nation can reduce the mix of greenhouse gases giving an agreed net effect. This requires the ability to quantitatively compare different greenhouse gases. As indicated above, we are far from the point where reliable intercomparisons can be made for a given time horizon. Indeed, it is extremely unlikely that we will be able to predict all of the changes affecting the atmospheric lifetime of CO_2 and other greenhouse gases; such changes as do occur are likely to occur in a non-uniform manner, implying strong non-linearities in the response to successive emission increments. Oceanic circulation, changes in which could significantly affect the mean atmospheric CO_2 lifetime, can change dramatically following subtle changes in precipitation and evaporation fields.[38] In addition, the problem of which time horizon to use remains and is not subject to scientific determination. A further problem with this potential application of GWPs is the great difficulty in quantifying and monitoring the sources and sinks of most gases, as discussed by Victor.[39]

Another potential application of GWPs is in assessing the net effect of measures which reduce emissions of one greenhouse gas but increase emissions of another gas. For example, switching from coal to natural gas for electricity generation *might* lead to an increase of methane emissions (depending on the relative magnitude of methane leakage from natural gas distribution and methane seepage from coal mining) while significantly reducing CO_2 emissions. This potential application suggests an alternative GWP index tied to the lifetime of the particular investment decision under consideration.

An alternative GWP index

The change in concentration $y(t)$ of a given gas following a continuous emission at a rate $x(t)$ is given by the convolution of the emission rate with the impulse response, $C(t)$. That is,

$$y(t) = \int_0^t x(t')C(t - t')dt' \qquad (5)$$

Equation (5) assumes a linear relationship between emission and concentration, so that successive emission pulses have the same incremental effect on concentration. For the case of CH_4, $C(t)$ can be represented by a simple exponential decay, $\exp(-t/\tau)$, so that Equation (5) yields

$$y_{CH4}(t) = \tau x_{CH4} \left(1 - \exp \left(-\frac{t}{\tau} \right) \right)$$

for a constant emission rate x_{CH4}. As $t \to \infty$, the methane concentration approaches the steady state value τx_{CH4}. For the case of CO_2, $C(t)$ can be given by Equation (3), so that the CO_2 concentration change is

$$y_{CO2}(t) = x_{CO2} \left(A_0 t + \Sigma_i \tau_i \left(1 - \exp \left(-\frac{t}{\tau_i} \right) \right) \right)$$

where x_{CO2} is a constant CO_2 emission rate. If the radiative forcing per molecule is constant in time, the GWP as defined by Equation (4) is mathematically equivalent to comparing the radiative heating of two gases at time T after a continuous and equal emission of both gases up to time T. Thus, for CH_4 the GWP as given by Equation (4) is equivalent, for these conditions, to

$$\frac{y_{CH4}(T)}{y_{CO2}(T)} \quad \frac{f_{CH4}}{f_{CO2}}$$

where f_{CH4} and f_{CO2} are the time invariant radiative forcings per unit concentration. In the more general case where the radiative forcing per molecule varies with time, the GWP is given by

$$GWP(t) = \frac{\int_0^T f_i(t)C_i(T-t')dt'}{\int_0^T f_c(t)C_c(T-t')dt'} \qquad (6)$$

where $f_i(t)$ and $f_c(t)$ are the time dependent radiative forcings for gas i and CO_2, and $x_i(t) = x_c(t) = x_0$ and thus cancel from the numerator and denominator of the above expression.

Casting the GWP in the form given by Equation (6) represents an important conceptual shift from that of Equation (4). Rather than viewing the GWP as the ratio of the integrated radiative heating due to a single pulse emission of both gases at time $t = 0$, it can be viewed as being approximately equal to the ratio of instantaneous radiative forcings at the end of a given time period, assuming equal and continuous emissions during the entire time interval of interest.

In the case of investment decisions involving emissions of two or more gases over a finite period of time, the time horizon T should be chosen equal to the lifespan of the end-use technology. If one is interested in the relative greenhouse impact of switching from oil to natural gas for automobiles, home heating, or electricity generation, taking into account the greenhouse forcing of CH_4, then $T = 10$, 20 and 40 years respectively are reasonable choices.

If one is concerned with the greenhouse implications of a given investment decision beyond the lifetime T of the decision, then it is appropriate to assume that the emission rate $x(t) = 0$ for $t > T$. That is, *in assessing the relative greenhouse impact of different investment options, one should assume that emissions of all the associated greenhouse gases occur only for as long as the lifetime of the investment decision, even if one is interested in longer time horizons.* If it is decided to replace an old fossil fuel using end-use technology at the end of its economically useful life with a new fossil fuel using technology, that represents a separate investment decision, the impact of which should not be incorporated in analysis of the greenhouse implications of the first investment decision. Furthermore, it is possible that a fossil fuel technology installed now might be replaced with a non-fossil fuel technology at the end of its life.

Based on the above discussion, the GWP for times $t \geq T$ is given by

$$GWP(t) = \frac{\int_0^T f_i(t)C_i(t - t')dt'}{\int_0^T f_c(t)C_c(t - t')dt'}, \quad t \geq T \qquad (7)$$

of which Equation (6) is a special case.

Table 4. Global warming potentials per unit mass for CH$_4$ and HCFC-22 for different time horizons and investment lifetimes as computed using Equation (7).

Time horizon years												
20		**40**			**100**				**500**			
Investment lifetime (years)												
10	20	10	20	40	10	20	40	100	10	20	40	500
CH$_4$ 26.7	42.7	6.0	9.3	28.3	1.1	1.1	1.2	15.3	1.0	1.0	1.0	6.1
HCFC-22 3093	4036	1104	1509	2949	36	51	110	1628	0.0	0.0	0.0	580

For purposes of illustrating the difference in GWP for time horizons t beyond the lifetime T of an investment decision, assume that $f_i(t)$ and $f_c(t)$ are constant. We shall consider the direct GWP of methane and HCFC-22 using the relative radiative heatings and lifetimes given in Tables 2 and 3 respectively, and taking into account the CO$_2$ produced from oxidation of methane. The GWP for methane, assuming that emissions occur only during the lifetime T of an investment decision, is given by

$$GWP(t) = \frac{f_{CH4}\int_0^T C_{CH4}(t - t')x_0 dt' + f_c\int_0^t C_c(t - t')x_c(t')dt'}{f_c\int_0^T C_c(t - t')x_0 dt'} \quad (8)$$

where the CO$_2$ source $x_c(t)$ due to methane oxidation is given by

$$x_c(t) = \begin{cases} x_0\left(1 - \exp\left(-\dfrac{t}{\tau}\right)\right) & t \le T \\[2ex] x_0 \exp\left(-\dfrac{t}{\tau}\right)\left(\exp\left(\dfrac{T}{\tau}\right) - 1\right) & t > T \end{cases} \quad (9)$$

Table 4 gives the GWP, as computed by Equation (8), for time horizons t of 10, 20, 40, 100 and 500 years. The IPCC/AGGG method implicitly assumes an investment lifetime equal to the time horizon, while for the new method, results are given assuming investment lifetimes T of 10, 20 and 40 years.

For time horizons equal to the lifetime of the particular investment decision, the GWP index proposed here is equivalent to that of the IPCC. The GWP values given in Table 4 for this case differ from the IPCC values given in Table 3 because of the use of a different model for absorption of CO$_2$ by the oceans and because of the inclusion here of the CO$_2$ oxidation product in the case of methane. For time horizons beyond the investment lifetime, the GWPs rapidly fall to one in the case of CH$_4$, or zero in the

case of HCFC-22 (indicating in both cases, that only CO$_2$ is important), whereas they remain large using the IPCC/AGGG approach. The GWPs rapidly approach one or zero using the new approach because of the short atmospheric lifespan of CH$_4$ and HCFC-22 relative to CO$_2$ and relative to the time since the cessation of emissions. For example, the average lifespan of CH$_4$ is 10 years, compared to removal time constants of up to 363 years for CO$_2$. A 100 year time horizon is six mean lifespans beyond the last emission of CH$_4$ for a 40 year investment life, so that there is negligible CH$_4$ remaining. Since the cumulative carbon emission is the same for CH$_4$ and CO$_2$ emissions, and all the CH$_4$ is ultimately converted to CO$_2$, the GWP rapidly asymptotes to a value of 1.0.

An interesting property of the GWP index proposed here is that, for gases whose atmospheric lifetime is short compared to that of CO$_2$, it is less sensitive to changes in the relative radiative forcing per molecule or greenhouse gas lifetimes for time horizons longer than the investment lifetime. Given the large uncertainties in these parameters, this robustness is important from a policy point of view.

Practical implications of GWPs

It is argued above that the scientific uncertainties in the calculation of GWPs, coupled with the great difficulties in measuring anthropogenic emissions of most gases, preclude the use of GWPs as part of an international agreement involving overall greenhouse forcing limits or trading between gases. The only foreseeable application of GWP is in determining the net effect of fuel switching in order to screen potential greenhouse gas emission reduction options. In this case, the great uncertainty associated with GWPs for time horizons comparable to the investment lifetime can be accounted for by allowing only those fuel switching options which are calculated to reduce total greenhouse forcing by a large fraction. However, when one screens fuel switching options in terms of cost-effectiveness as part of an

integrated greenhouse gas emission reduction strategy, one finds that the net greenhouse reduction of many options which pass the economic test is so large that even the most extreme GWP values do not cause the fuel switching option to be rejected.

The effective CO_2 emission factor for a mix of greenhouse gases is given by

$$F_{eff} = E(F_{CO2} + \Sigma F_i GWP_i) \qquad (10)$$

where E is the fossil fuel consumption (GJ) at the point of use, F_{CO2} is the CO_2 emission factor (kg/ GJ), and F_i and GWP_i are the emission factors (kg/GJ) and GWPs for the other emitted gases. The CO_2 emission factors for coal, oil, and natural gas are 88–95 kg/GJ, 68–73 kg/GJ and 49.5 kg/GJ respectively.[40] In comparing different fuels, account also must be taken of the emissions of all gases associated with the extraction, processing, and transportation of the fuel to the point of use. This requires multiplying the above CO_2 emission factors by average markup factors of 1.04, 1.13 and 1.18 for coal, oil and natural gas respectively.[41] Methane emission factors range from 0.019 kg/GJ for typical lignites to 0.554 kg/GJ for typical bituminous coals (based on Barnes and Edmonds,[42] assuming heating values of 7000 Btu/lb for lignite and 12000 Btu/lb for bituminous coal), while each percentage leakage of natural gas corresponds to an emission factor of 0.182 kg/GJ (based on the higher heating value for methane of 55 MJ/kg and assuming natural gas to be 100% methane). Examples of fuel switching with large effective CO_2 emission reductions are given below.

Coal to natural gas for electricity generation

If natural gas combined cycle (46–48% efficiency) or cogeneration (65–95% marginal efficiency) replaces conventional coal-fired electricity generation (33% efficiency), CO_2 emission per kilowatt hour of electricity is reduced by a factor of two to four. Because almost two to three times more coal primary energy is used than natural gas primary energy in this comparison, methane emissions will also be reduced if the methane emission factor for natural gas is no more than two to three times larger than for coal. Natural gas emission factors in Western countries are undoubtedly smaller than for bituminous coal, which is the coal most often used for electricity generation.

Electric resistance to high efficiency natural gas for heating

Switching from electric resistance heating to high

efficiency (92%) natural gas heating reduces CO_2 emissions by almost a factor of four if the electricity is coal fired. This reduction is so large, and the reduction in primary energy use so large, that a significant net greenhouse emission reduction occurs even for natural gas leakage rates as large as 1–2%.

Mid-efficiency oil to high efficiency natural gas for heating

Switching from a mid-efficiency (78%) oil furnace to a high efficiency natural gas furnace will reduce CO_2 emissions by about 40%. This is a large enough reduction to give a significant net benefit after allowing for limited (no more than 1%) natural gas leakage and an extreme (twice the direct) GWP for methane.

Electric chillers to advanced natural gas absorption chillers

An alternative to electric chillers (coefficient of performance (COP) = 3–4) is an advanced natural gas absorption chiller (COP = 2–2.5). Although the electric chiller has a higher COP, greater primary energy is required per unit of cooling if the electricity is derived from a conventional coal fired power plant. The CO_2 emission reduction for this switch ranges from 64% to 78%. If natural gas absorption chillers displace electric chillers powered by electricity from cogeneration, on the other hand, there may be no CO_2 emission reduction. However, absorption chillers do not require CFCs or chlorine containing CFC substitutes; although the GWP for these gases might very well be negative (if the effect of ozone loss is included), options which do not require chlorine containing substitutes are likely to be increasingly favoured to provide greater protection to the ozone layer (many proposed CFC substitutes have a significant ODP on a 10–20 year time horizon, with small ODPs only on much longer time horizons).

It should be noted that even in cases where fuel switching for heating and cooling would increase methane emissions, it is still possible to achieve simultaneous reductions in CO_2 and methane if fuel switching is combined with other measures such as thermal envelope improvements and reduction of internal cooling loads through adoption of more efficient lighting and machines. Such 'bundling' of measures is attractive purely as a CO_2 emission reduction measure because savings in downsizing of heating and cooling equipment when they are due for replacement can offset part of the cost of envelope or lighting improvements. Thus, in most cases involving fuel switching it is possible to achieve

simultaneous reductions in both CO_2 and methane, thus rendering the GWP index irrelevant to the decision of whether or not to switch.

Conclusions

The computation of global warming potentials (GWPs) is subject to large uncertainties as well as conceptual difficulties, in contrast to the relatively simple case of ozone depleting potentials (ODPs) which were used in formulating international agreements to protect the ozone layer. It is difficult to see how GWPs could be used in any practical international treaty or in trading between greenhouse gases. On the other hand, it is important to be able to quantitatively compare the trade offs associated with investment decisions which simultaneously increase emissions of one greenhouse gas but decrease emissions of another. In this case, however, an alternative GWP tied to the lifespan of the investment decision is more appropriate and is less sensitive to uncertainties in atmospheric chemistry, radiative forcing and atmospheric gas lifespans. The effect of the alternative GWP index is to shift attention more strongly toward CO_2. In retrospect, this is not surprising, given the uniqueness of CO_2 among greenhouse gases arising from the absence of a chemical or photochemical sink in the atmosphere, and the much longer timescales associated with its final removal from the atmosphere.

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