Comparing the climate effect of emissions of short- and long-lived climate agents

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Multi-gas climate agreements require a metric by which emissions of gases with different lifetimes and radiative properties can be placed on a common scale. The Kyoto Protocol to the United Nations Framework Convention on Climate Change uses the global warming potential (GWP) as such a metric. The GWP has attracted particular criticism as being inappropriate in the context of climate policy which seeks to restrict warming below a given target, because it gives equal weight to emissions irrespective of the target and the proximity to the target. The use of an alternative metric, the time-dependent global temperature change potential (GTP), is examined for its suitability and the prospects for it including very short-lived species. It retains the transparency and relative ease of use, which are attractive features of the GWP, but explicitly includes a dependence on the target of climate policy. The weighting of emissions using the GTP is found to be significantly dependent on the scenarios of future emissions and the sensitivity of the climate system. This may indicate that the use of any GTP-based weighting in future policymaking would necessitate regular revisions, as the global-mean temperature moves towards a specified target.

Keywords: climate change; global warming potential; greenhouse gases; black carbon; climate metrics; Kyoto Protocol

1. Introduction

There is a multitude of contributory causes to climate change (e.g. IPCC 2001). In particular, human activity leads to emissions of many gases and particles which directly act to cause climate change and/or are precursors for the formation of gases and particles which also cause climate change. These gases and particles differ widely in their atmospheric residence times and spatial distribution, and in their potency to perturb the Earth’s energy budget.

The objective of the 1992 United Nations Framework Convention on Climate Change (UNFCCC; http:// unfccc.int) is the ‘stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous
anthropogenic interference with the climate system’, and requires policies to ‘be
cost-effective so as to ensure global benefits at the lowest possible cost’ and that
‘policies and measures should...be comprehensive...[and]...cover all relevant
sources, sinks and reservoirs’. The UNFCCC was made operational by the 1997
Kyoto Protocol, which sets limits on emissions of six different greenhouse gases,
or group of gases. It is a multi-gas agreement which moves some way towards the
UNFCCC’s aim of being comprehensive and cost effective.

Such agreements require a metric by which the climate effects of different
emissions are placed on a common scale. The Kyoto Protocol uses the global
warming potential (GWP) with a 100-year time horizon (GWP(100)) (see §2),
which has been a key product of the Intergovernmental Panel on Climate Change
(e.g. IPCC 2001). It provides a simple method by which emissions of a particular
gas can be converted to CO₂-equivalent emissions.

The advantages and problems of the GWP have been vigorously debated (e.g.
O’Neill 2000; Smith & Wigley 2000; Manne & Richels 2001; Fuglestvedt et al.
2003). However, perhaps owing to the transparency of its formulation, and the
absence of an obvious acceptable alternative, the GWP has become widely
accepted by the user community. One further possible factor in the acceptance of
the GWP is that the Kyoto Protocol does not have a specified long-term target.
While it sets limits on CO₂-equivalent emissions, there is no specific aim in terms
of climate change, for example, constraining the global mean radiative forcing or
warming to stay below some given value.

2. Design of climate metrics

Many issues related to the impact of climate change are made explicit in the
design of metrics which attempt to place some kind of equivalence on different
emissions (e.g. Fuglestvedt et al. 2003). Which parameter is made equivalent? It
could be radiative forcing, temperature change, sea level rise, change in extreme
weather events, economic or ecosystem damage, etc. It could be the absolute
levels of these parameters or their rate of change. Should pulse or sustained
emissions be considered? Over what time period is the effect considered, and is
the metric an integral of a quantity (e.g. radiative forcing) over this period or the
value at the end of this period? Is some kind of ‘discounting’ applied, so that
changes in the near future are given more weight than changes in the distant
future? The decisions made on these and other questions can affect whether it is
perceived desirable to cut emissions of short- or long-lived gases first.

There is a debate on the nature of the metric itself. It could, like the GWP,
just take into account the physics of the climate system. Or it could include
economic information by seeking cost-effectiveness. One way is to seek to
minimize the costs of emission controls when the target of climate policy is
specified. Another is to seek to minimize the sum of the costs of emission controls
and damage (i.e. a cost-benefit analysis).

Two emerging issues encourage further discussion. First, there have been some
moves to clarify the target of climate policy. For example, in 2005, the European
Union stated that ‘the global annual mean surface temperature increase should
not exceed 2°C above pre-industrial levels’ (www.europa.eu/bulletin/en/200503/
i1010.htm). Is the GWP an appropriate metric in the context of such a target?
Second, there has been an increasing discussion of the desirability and practicalities of reducing emissions of very short-lived species (e.g. soot aerosols with a lifetime of about a week) which are not included within the Kyoto Protocol (e.g. Hansen et al. 2000; Collins et al. 2002; Andreae et al. 2005; Berntsen et al. 2005; Bond & Sun 2005; Shine et al. 2005a). The inclusion of these species in climate agreements requires additional considerations, not least because they have other impacts (e.g. on air quality and acidification).

The aim of this paper is to present a usage of an alternative to the GWP, which is consistent with a cost-effective approach to staying below a chosen target and may be better suited to address the effect of short-lived species.

3. The global warming potential

The absolute GWP (AGWP) is the time-integrated radiative forcing due to a pulse emission of a unit mass of gas. The GWP is normally quoted as a dimensionless value by dividing the AGWP by the AGWP of CO$_2$. A user choice is the ‘time horizon’, $H$, for the integration. There is no obvious choice for this; the Kyoto Protocol uses $H=100$ years, perhaps as a compromise between overemphasizing neither the shorter-lived gases nor the very long-lived gases.

For a gas $x$, if $A_x$ is the specific radiative forcing (in W m$^{-2}$ kg$^{-1}$) and $\alpha_x$ is the adjustment time then

$$\text{AGWP}_x(H) = \int_0^H A_x \exp\left(-\frac{t}{\alpha_x}\right) dt = A_x \alpha_x \left[1 - \exp\left(-\frac{H}{\alpha_x}\right)\right].$$

(3.1)

The adjustment time differs from the lifetime of a gas, as it accounts for the effects of feedbacks resulting from a pulse emission (IPCC 2001). The AGWP for CO$_2$ is more complicated, because its atmospheric lifetime cannot be represented by a simple exponential decay (e.g. IPCC 2001).

There are a number of issues associated with the use of GWPs. First, it is well established that the emissions of gases with the same GWP may have quite different climate impacts (e.g. Fuglestvedt et al. 2000; Smith & Wigley 2000). A gas with a high $A_x$ but short $\alpha_x$ will have a different impact on temperature than a gas with the same GWP but with low $A_x$ and long $\alpha_x$ (e.g. Shine et al. 2005b).

Secondly, although GWPs can be computed for very short-lived species, these have not been adopted within policymaking for a range of reasons (e.g. IPCC 2001; Berntsen et al. 2005; Shine et al. 2005a). One is that uncertainties in chemical transport models preclude the computation of robust values of, for example, the change in ozone as a result of NO$_x$ emissions. Another concern is that for short-lived species the same mass emissions from different locations can have markedly different climate effects.

Finally, one particular criticism of the GWP, which we address here, is its use in the context of a climate policy aimed at restricting global-mean warming below a given target. Michaelis (1992) was perhaps the first to illustrate the use of such a target-based regime. Starting from an economics view point, Michaelis formulated a purely physical metric based on a radiative forcing target, and showed that the metric value of shorter-lived species is initially low and grows as the time of the target is approached; this is a feature not captured by the time-invariant
GWP(100). With the GWP(100), a pulse emission of a short-lived gas occurring long before the target is reached, and thus contributing little to the warming close to the target, is given equal weight to an emission at a time closer to the target. It would be possible to use a time horizon for the GWP that depends on the closeness to some given target time, but it is not clear how such a metric would relate to any specific target.

Manne & Richels (2001; henceforth MR01) noted that the use of GWP(100) assumes that the trade-off between emissions of different gases is both constant over time and independent of the goal of climate policy. They proposed an alternative approach, which priced the value of emissions in terms of economical as well as physical considerations. The models applied by MR01, and more recently by van Vuuren et al. (2006), include simple physical models of the climate system, embedded in a more sophisticated framework which includes representations of the energy sector and the economy, in an attempt to compute the most cost-efficient mitigation strategy.

MR01 demonstrated that if the aim of climate policy is to restrict a warming to below 2°C, then the ‘value’ of methane emissions, relative to CO2, grows rapidly throughout the twenty-first century. If the target was, instead, 3°C, then the value of methane is lower and grows more slowly; by the end of the twenty-first century its value is less than a third of that for the 2°C case.

van Vuuren et al. (2006) compared results from 21 Energy Modelling Forum (EMF) models (including that of MR01) which include economic considerations in calculating the trade-offs between different greenhouse gases in climate change mitigation strategies. They showed that, in agreement with MR01, models that use GWP(100) produce distinctly different mitigation strategies to those that use time-dependent weights, based on a target.

Here, we seek to establish the extent to which a model based on a purely physical representation of the climate system can reproduce the main features of the EMF results. We do this for two reasons. The first is pedagogical, as it is important to understand the behaviour of the EMF models. The second relates to the nature of acceptability of metrics by the policymakers. Our analysis uses a simple analytical model which shares the transparency and relative ease of use of the GWP, features which appear to have helped GWPs become accepted by policymakers. This contrasts with the EMF models, with their many sub-models and assumptions. Note that we are not criticising the use of these models per se, as they play a very important role in increasing understanding and informing the climate change debate. The key difference between our proposed metric and the MR01/EMF approach is that, for the latter, the time at which the target is reached is determined endogenously by the model based on input parameters such as discount rate and future mitigation costs; here, the time of reaching the target is an exogenously defined parameter.

4. The global temperature change potential

Shine et al. (2005b) presented a possible alternative to the GWP, the global temperature change potential (GTP). One argument in favour of its use is that by comparing temperature changes, it is further down the cause-effect chain from emissions to impacts than the GWP, and hence more relevant. A simple
analytical model of the climate system was used to compute the temperature change at some given time due to either a pulse or sustained emission of a gas. Here, we focus on the pulse form, the GTPP.

The absolute GTPP (AGTPP), gives the temperature change (in K kg$^{-1}$) at time $t = H$, due to a pulse emission at time $t = 0$, for gas $x$

$$\text{AGTPP}_x^P(H) = \frac{A_x}{C(\tau^{-1} - \alpha_x^{-1})} \left[ \exp\left(-\frac{H}{\alpha_x}\right) - \exp\left(-\frac{H}{\tau}\right) \right]. \quad (4.1)$$

Compared with the GWP, extra parameters are required, owing to the inclusion of the simple climate model—the time-scale of the climate response, $\tau$, and the heat capacity of the climate system, $C$ (or equivalently, $C$ and the climate sensitivity parameter, $\lambda$; the three parameters are related since $\tau = C\lambda$). As with the GWP, a more complex relationship is required for CO2. More details, and values of parameters used here, are given in Shine et al. (2005b). The GTPP is given by the AGTPP for gas $x$ divided by the AGTPP for CO2.

The GWP and GTPP emphasize different characteristics of the climate system, as the GWP is integrative, while the GTPP is an endpoint metric. The choice of GTPP at an arbitrary time in the future could be quite inappropriate, particularly, if $H$ is much greater than $\alpha_x$. However, here we apply it in the spirit of the analysis of MR01 to generate a metric which, unlike the GWP(100), ‘is a function of the target and proximity to the target’.

5. Time-dependent GTP in the context of specific climate targets

We assume that the aim of climate policy is specified by two parameters. $T_{\text{tar}}$ is the target itself (e.g. global mean warming of 2°C above pre-industrial values), $t_{\text{tar}}$ is the time at which $T_{\text{tar}}$ is expected to be reached. Clearly, $t_{\text{tar}}$ will depend on the assumed scenario of future emissions and we explore the dependence on this assumption. For illustrative purposes, we make the naive assumption that $t_{\text{tar}}$ is simply the time at which the scenario reaches $T_{\text{tar}}$ rather than, for example, computing a gradual transition to a stabilization at $T_{\text{tar}}$ as is done by MR01. Even though this approach is simple, it is a substantial improvement compared with the time-invariant GWP(100) and provides a guide to the main temporal features of GTP weighting. We have chosen to use a temperature target, as this is further down the cause-effect chain; as noted above, if instead a radiative forcing target was defined, a similar (and simpler) metric could be derived.

We calculate the time-dependent GTPP for an emission pulse in starting year $t_{\text{init}}$, with $H = t_{\text{tar}} - t_{\text{init}}$, and then for each year $t$ between $t_{\text{init}}$ and $t_{\text{tar}}$. To emphasize the time dependence in this usage of the GTPP, we denote it GTPP$(t)$ henceforth. The metric is only valid if a total (CO2-equivalent) emission pathway leading to stabilization is pre-defined by specific calculations of the required emission reductions; the GTPP$(t)$ then provides weights for the CO2-equivalence of the non-CO2 gases along this pathway. One difficulty concerns the period beyond (and indeed approaching) $t_{\text{tar}}$. Choices made concerning the mix of gases at these times will clearly impact on temperatures beyond $t_{\text{tar}}$ and may make it easier or harder to keep temperatures at or below $T_{\text{tar}}$. We will not discuss in any detail the use of metrics beyond the time of stabilization.
We start by considering methane and nitrous oxide, with adjustment times of 12 and 114 years, respectively. Methane includes its indirect effects, following IPCC (2001). The default value of $\lambda$ is 0.8 K (W m$^{-2}$K$^{-1}$ (roughly equivalent to a 3 K warming for a doubling of CO$_2$) and $\tau$ is 10.7 years.

Figure 1 allows a direct comparison with MR01. Here $T_{\text{tar}}$ is the change relative to 2000. For the MR01 reference case $t_{\text{tar}} \approx 2080$ for $T_{\text{tar}} = 2^\circ$C, and $t_{\text{tar}} \approx 2120$ for $T_{\text{tar}} = 3^\circ$C. Figure 1 also shows the GWP(100). The results for methane are qualitatively similar to those of MR01, although the values here are about a factor of two to three higher at times approaching $t_{\text{tar}}$. This could be due to different assumptions in the representation of the climate system, the impact of MR01’s economic models, and/or the way the target is determined. Because emissions of short-lived species can have only a small impact on temperatures in the far future, the GTP$_P(t)$ starts small in 2000, but grows rapidly as $t_{\text{tar}}$ is approached. The results also illustrate how misleading the GWP(100) is in this context, as it gives equal weight to methane emissions throughout the period. Note that the $T_{\text{tar}} = 2$ and $3^\circ$C curves are identical, but displaced by 40 years, owing to the difference in $t_{\text{tar}}$.

The values for nitrous oxide are also qualitatively similar to MR01; however, MR01 find that their price ratio for nitrous oxide is about a factor of two higher than the GWP. In our case, the GTP$_P(t)$ has a similar value to the GWP, but the relative variation over the century is larger than obtained by MR01. We have used a consistent set of parameters for the calculation of both the GWP and GTP$_P(t)$, but we do not know if this is the case in MR01. The time variations of

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*(a) Comparison with Manne and Richels*

Figure 1. Global temperature change potential (GTP$_P(t)$) for methane and nitrous oxide for each year from 2000 to the time at which the temperature change target ($T_{\text{tar}}$ relative to 2000) is reached, for the Manne & Richels (2001) reference scenarios. The 100-year global warming potential is also shown for the two gases. The climate sensitivity parameter is 0.8 K (W m$^{-2}$)$^{-1}$. 

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...the AGTP(t) of nitrous oxide and CO₂ are broadly similar, although the multiple time-scales in the removal of CO₂ mean that its AGTP(t) has subtle variations compared with nitrous oxide, particularly close to \( t_{\text{tar}} \).

The simple physical model reproduces the qualitative behaviour of MR01’s results, which encourages further investigation of this methodology.

\( (b) \) Dependence on emission scenario

The dependence of the GTPP(\( t \)) on \( T_{\text{tar}} \) and \( t_{\text{tar}} \) is shown in figure 2; henceforth \( t_{\text{init}} \) is taken to be 2010 and \( T_{\text{tar}} \) is the change relative to pre-industrial values. Here \( t_{\text{tar}} \) is dependent on the chosen emissions scenario for a given \( \lambda \). We use two IPCC emissions scenarios, A1FI (which broadly represents business-as-usual) and B2 (which assumes a transition to a lower carbon economy). The temperature changes, which are required to compute \( t_{\text{tar}} \) for a given \( T_{\text{tar}} \), have been calculated using an upwelling-diffusion climate model (Schlesinger et al. 1992; Fuglestvedt et al. 2000). For \( T_{\text{tar}} = 2 \degree C \), \( t_{\text{tar}} \) is 2045 for A1FI and 2056 for B2. For \( T_{\text{tar}} = 3 \degree C \), the corresponding \( t_{\text{tar}} \) are 2062 and 2097. Figure 2 shows a strong dependence on scenario, particularly for methane. For A1FI and \( T_{\text{tar}} = 2 \degree C \), current methane emissions have a higher weight than indicated by GWP(100). By contrast, for B2 with \( T_{\text{tar}} = 3 \degree C \), methane does not reach the GWP(100) value until beyond 2060. Interestingly, the weight associated with nitrous oxide emissions is relatively independent of both target and scenario until about 2030, presumably due to the similarity in nitrous oxide and CO₂ adjustment times.

\( (c) \) Dependence on climate sensitivity

Figure 3 addresses the GTPP(\( t \)) dependence on the uncertainty in \( \lambda \). The value is varied between 0.4 and 1.2 K(W m\(^{-2}\))\(^{-1}\), the approximate range given in IPCC (2001), for the A1FI \( T_{\text{tar}} = 2 \degree C \) case. The main impact of changing \( \lambda \) is to

![Figure 2. As figure 1, but with a start year of 2010, using \( T_{\text{tar}} \) (relative to pre-industrial) derived from temperature changes generated using the IPCC A1FI and B2 emissions scenarios.](http://rsta.royalsocietypublishing.org/Downloaded from http://rsta.royalsocietypublishing.org/ on July 11, 2017)
markedly alter $t_{\text{tar}}$, from 2067 in the $\lambda = 0.4 \text{(W m}^{-2})^{-1}$ case to 2035 in the $\lambda = 1.2 \text{(W m}^{-2})^{-1}$ case. The GTPP$(t)$ is also affected by the impact of $\lambda$ on $\tau$ in equation (4.1); unlike in earlier figures, the two GTPP$(t)$ curves for each gas are not simply time-shifted versions of each other. Figure 3 makes it clear that even with good knowledge of the emission scenario, uncertainty in climate sensitivity has a large impact on estimates of the appropriate metric value for methane at the present time; the 2010 value varies by an order of magnitude between the two values of $\lambda$ (although this dependence is reduced to a factor of 5 using the energy balance model (EBM) described in §5d). The impact on the GTPP$(t)$ for nitrous oxide is less severe.

(d) Dependence on climate model

The AGTPP in equation (4.1) uses the simplest possible climate model (where the planet’s heat capacity is contained in a global 100 m mixed-layer ocean). The impact of this simplification is tested to some extent by using the response to a pulse emission of gas derived from an upwelling-diffusion EBM (Shine et al. 2005b). This EBM consists of a mixed layer and a 40-level deep ocean and calculates surface temperatures over land and ocean in each hemisphere separately. The EBM is also a simplified representation of the climate system, but it includes the effect of the long-term thermal inertia of the ocean that is excluded from the analytical model; it would also be possible to use the pulse-response derived from more sophisticated climate models. Figure 4 shows that despite the simplification, the analytical model is reasonable. The difference between the two models increases with increasing $t_{\text{tar}}$ and also increases with decreasing lifetime of the gas; the higher thermal inertia in the EBM means a methane pulse emitted in 2010 still has some impact in 2100, unlike in the

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analytical model. Nevertheless, given the uncertainties in future scenarios and climate sensitivity shown in §5a–c, it is concluded that the analytical model is adequate, at least, for illustrative purposes.

(e) Behaviour for a very short-lived climate agent—black carbon

The final example concerns a very short-lived climate agent, black carbon (BC or soot). There are many caveats to developing climate metrics for BC, not least because the relationship between radiative forcing and temperature response is not straightforward (e.g. Hansen et al. 1997; Cook & Highwood 2004). Many of the difficulties are spelt out in Bond & Sun (2005), but in the spirit of their analysis, we apply their BC parameters ($A = 3.5 \times 10^{-9} \text{ W m}^{-2} \text{kg}^{-1}$ and $\alpha = 0.015$ years) to the GTP$_P(t)$. Several authors (e.g. Hansen et al. 2000; Jacobson 2002) have proposed that controlling BC emissions may be attractive in the short-term, not only for climate change, but also for air quality. The very short lifetime of BC is offset by its specific forcing being around one million times larger than that of CO$_2$. Bond & Sun (2005) compute a GWP(100) for BC of 680. For very short-lived species, equation (5.1) simplifies to

$$\text{AGTP}_P(H) = \frac{A_x \alpha_x}{C} \exp \left( -\frac{H}{\tau} \right). \quad (5.1)$$

Figure 5 shows the GTP$_P(t)$ for various scenarios and climate sensitivities—note the use of a logarithmic axis, as the value of the GTP$_P(t)$ now stretches over three orders of magnitude, exceeding 20 000 close to $t_{\text{tar}}$. However, even far from $t_{\text{tar}}$ it can remain significant—for example for $\lambda = 0.8 \text{ K(W m}^{-2})^{-1}$ the value in 2010 still exceeds 100, emphasizing the climate potency of black carbon. Figure 5
also shows the inadequacy of GWP(100) in representing the role of BC. As indicated above, the very low GTPP\(t\) values in the early years of the B2 scenario are likely to be an artefact of the simple analytical model’s smaller thermal inertia.

6. Conclusions

We have explored the use of a recently proposed climate metric, the GTP\(_P\), in the context of a climate policy that seeks to limit global-mean warming at some point in the future. The framework is similar to that used in some integrated climate-economics models, but the metric used here is (i) analytical in formulation, (ii) requires relatively few input parameters, and (iii) considers only the physics of the climate system. This facilitates the investigation of the sensitivity of the metric to a number of uncertainties. The behaviour of our model is similar to that of MR01 and other EMF models, but we are not able to diagnose whether differences are due to the way the climate system is represented or to the effect of the economic sub-models. It is important that the behaviour of the EMF climate sub-models is better understood, and the framework presented here is one way that this could be achieved.

The GTP\(_P\) is strongly affected by currently unavoidable uncertainties in both the climate system and future emission scenarios. Thus any application of such a metric would itself have to be time dependent; as we learn more about the climate system and the speed with which we move towards a given target, values may need to be revised. A climate policy based on this metric would first set
limits on total CO₂-equivalent emissions consistent with an overall long-term target, for each mitigation period through a series of negotiation rounds. The revised metric values, together with the actual mitigation costs for the different species, would determine the composition of the total emission reductions.

It is noted that the GTP₁(ₜ) concept may have difficulties at times close to and beyond the time of stabilization. If, for example, it is decided to emit CO₂ rather than short-lived species, this may help in meeting the target at a particular time, but lead to difficulties in maintaining stabilization, owing to the longer time-scale response to the CO₂ emissions. Beyond the stabilization time, it is not clear what kind of substitution among emissions of different gases is appropriate, to maintain stabilization. Decisions will depend on the time-horizons considered and economic factors such as mitigation costs and future discount rates. This difficulty is likely to be common to any purely physical metric.

Regardless of these difficulties, this dynamic usage of the GTP₁ has clear advantages over the GWP. It is a function of both time and climate policy, thereby providing a metric that serves a cost-effective policy. It addresses directly a more tangible impact of emissions on climate (surface temperature change, rather than integrated radiative forcing). It retains the transparency of the GWP, which may have some attractions for its application in a policy context. While it neither addresses issues of non-climate impacts of emissions nor the climate benefits of emission reduction, it could be a useful tool in such analyses. The shape of the temporal development of the GTP₁(ₜ) could provide valuable information to policymakers when considering the development of new strategies and technologies.

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