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Stable climate metrics for emissions of short and long-lived species—combining steps and pulses

William J Collins[1,4], David J Frame[2], Jan S Fuglestvedt[3] and Keith P Shine[1]

[1] Department of Meteorology, University of Reading, Reading, United Kingdom
[2] New Zealand Climate Change Research Institute, Victoria University of Wellington, Wellington, New Zealand
[3] Center for International Climate and Environmental Research (CICERO), Oslo, Norway
[4] Author to whom any correspondence should be addressed.

E-mail: w.collins@reading.ac.uk

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Abstract

Multi-gas climate agreements rely on a methodology (widely referred to as 'metrics') to place emissions of different gases on a CO_2-equivalent scale. There has been an ongoing debate on the extent to which existing metrics serve current climate policy. Endpoint metrics (such as global temperature change potential GTP) are the most closely related to policy goals based on temperature limits (such as Article 2 of the Paris Agreement). However, for short-lived climate forcers (SLCFs), endpoint metrics vary strongly with time horizon making them difficult to apply in practical situations. We show how combining endpoint metrics for a step change in SLCF emissions with a pulse emission of CO_2 leads to an endpoint metric that only varies slowly over time horizons of interest. We therefore suggest that these combined step-pulse metrics (denoted combined global warming potential CGWP and combined global temperature change potential CGTP) can be a useful way to include short and long-lived species in the same basket in policy applications—this assumes a single basket approach is preferred by policy makers. The advantage of a combined step-pulse metric for SLCFs is that for species with a lifetime less than 20 years a single time horizon of around 75 years can cover the range of timescales appropriate to the Paris Agreement. These metrics build on recent work using the traditional global warming potential (GWP) metric in a new way, called GWP*. We show how the GWP* relates to CGWP and CGTP and that it systematically underestimates the temperature effects of SLCFs by up to 20%. These step-pulse metrics are all more appropriate than the conventional GWP for comparing the relative contributions of different species to future temperature targets and for SLCFs they are much less dependent on time horizon than GTP.

1. Introduction

Climate metrics are often criticised for over- or under-stating the importance of different species on climate, particularly for short-lived climate forcers (SLCFs) e.g. (Pierrehumbert 2014). The IPCC 4th Assessment Report (AR4) (Forster *et al* 2007) noted the many shortcomings in the Global Warming Potential GWP (100), but recommended its use (at least for long-lived greenhouse gases LLGHGs) as a multi-gas strategy is preferable to a CO_2-only mitigation strategy. The IPCC 5th Assessment Report (AR5) presents global warming potentials (GWP) and global temperature change potentials (GTP) for 20-year and 100 year time horizons leading to a range of values (for methane these ranged from 4 to 84) with no recommendation as to which should be used (Myhre *et al* 2013). Hence, for methane, policymakers have at least a scalar factor of 20 in the value of the metric they can choose; the situation is similar for all other SLCFs. This range is due both to the choice of the types of metric, chosen impact parameter (forcing, temperature, etc), end-point (GTP) or integrated (GWP), and to the choice of time horizon. Endpoint metrics compare the relative impacts at a particular time horizon after the emission of a species; integrated metrics compare the relative impacts integrated from the time of emission up to the chosen time horizon.

The UNFCCC's Ad Hoc Working Group on the Paris Agreement is proposing (https://unfccc.int/documents/184956) that National Inventory Reports for the Paris climate agreement will use the GWP(100) from AR5 to report aggregate emissions and removals of greenhouse gases (GHGs), although other metrics such as the GTP may be used additionally. However the IPCC Expert Meeting on Short-Lived Climate Forcers (IPCC 2018) concluded that SLCF inventories should not be converted to CO_2 equivalents using GWP(100), but rather reported separately until further assessment on the use of metrics was provided by IPCC AR6. The range in possible choices of metric value causes significant problems when making policy decisions. It has been argued that the metric value that is recommended in the UNFCCC guidance (GWP (100)) is inappropriate for the goals of the Paris Agreement (Allen *et al* 2016, Allen *et al* 2018, Fuglestvedt *et al* 2018) , although it has been suggested (Schleussner *et al* 2019) that overstating the impacts of non-CO_2 forcers (for instance by use of GWP(100)) will encourage even stronger CO_2 mitigation to compensate.

The Paris Agreement specifies two clear scientific goals: to limit temperature increases (Article 2), and to achieve balance between sources and sinks of greenhouse gases (Article 4); Fuglestvedt *et al* (2018) discuss various interpretations of the balance concept in the agreement. One interpretation of 'balance' could be evaluated in terms of the GHG emissions that stabilize radiative forcing (RF) at some level. Both goals are related to the impact at some later time (whether the end of the century or at the time of maximum temperature rise). For such targets endpoint metrics such as the GTP are more appropriate than integrated metrics (Shine *et al* 2005, Shine *et al* 2007). These endpoints can be fixed to a particular date such that the time horizon decreases as the date is approached (Shine *et al* 2007). Conversely, metrics that integrate from present to a future date (GWP or integrated GTP) give an equal weighting to climate impacts that occur now as to climate impacts that will occur when a target is about to be met or exceeded (Pierrehumbert 2014); therefore they do not directly address the Paris goals. Indeed many studies have shown that an integrated climate metric such as GWP is not useful for comparing long-term temperature effects (Allen *et al* 2016, Allen *et al* 2018, Fuglestvedt *et al* 2018). Thus the metrics most closely aligned with the Paris Agreement are endpoint metrics (either temperature or radiative forcing), although the time horizon of the specific endpoint is not clear. It could be the time of peak warming, or if temperatures are expected to overshoot a target, then some future time by which temperature would be required to come back below the target.

Integrated metrics would be more appropriate in economic analyses (Kandlikar 1995, Kandlikar 1996) which often look to minimise an integrated damage measure; however there is no internationally agreed damage measure due to the structural uncertainty in their underlying functional form (Weitzman 2012). Endpoint sea-level rise metrics do have mathematically similar constructions to integrated radiative forcing or integrated temperature metrics (Sterner *et al* 2014). These would be appropriate if there were a specified sea-level rise threshold below which we agreed to attempt to stay.

In this paper we use the concepts of relating the impacts of a step change in SLCF emissions with a pulse emission of CO_2 that was first introduced in Smith *et al* (2012). Allen *et al* (2016) took this considerably further, devising a metric (subsequently labelled GWP* in Allen *et al* (2018)) based on a scaling of GWP that approximated the relative temperature impacts of a step change in SLCF emission with a pulse emission of CO_2. Allen *et al* (2018) deliberately chose to retain the use of the familiar GWP (and the reported values of the GWP) in framing the GWP*, to maintain a level of continuity with existing policy and make it easy to apply. However, they recognised that by doing this, the step/pulse equivalence would only be approximate. Here we develop further the ideas of Allen *et al* (2016, 2018) to demonstrate that a more formal approach (less constrained by consideration for continuity and application) to providing step/pulse equivalence leads to a metric that captures the equivalence more accurately. It retains an important policy benefit of the GWP*, which is the relative lack of sensitivity to the time horizon, but still retains an explicit time dependence.

2. Metric design

The two most common metrics GWP and GTP differ both in the impacts they represent (radiative forcing or temperature) and in whether they are integrated or endpoint based. Following Myhre *et al* (2013) these metrics are defined as the absolute impact measure for a pulse emission of species X divided by that for CO_2, i.e. $\mathrm{GWP}_X = \mathrm{AGWP}_X/\mathrm{AGWP}_{CO_2}$, and $\mathrm{GTP}_X = \mathrm{AGTP}_X/\mathrm{AGTP}_{CO_2}$, where these absolute metrics are defined as $\mathrm{AGWP}_X(H) = \int_0^H \Delta F_X(t)dt$, and $\mathrm{AGTP}_X(H) = \Delta T_X(H)$, where $\Delta F_X(t)$ and $\Delta T_X(t)$ are the radiative forcing and temperature changes at time t following a unit pulse emission of species X, and H the chosen time horizon. An integrated version of the AGTP can be also constructed $\mathrm{iAGTP}_X(H) = \int_0^H \Delta T_X(t)dt$ (Gillett and Matthews 2010, Peters *et al* 2011, Azar and Johansson 2012, Olivié and Peters 2013). For completeness here we also define an endpoint version of the AGWP which we call $\mathrm{AGFP}_X(H) = \Delta F_X(H)$ where AGFP is

Table 1. Climate metrics for methane (using CO_2 as a reference) for 20, 50 and 100 year time horizons. The radiative efficiencies for CH_4 and CO_2 are 4.40×10^{-4} W m^{-2} ppb^{-1} and 1.30×10^{-5} W m^{-2} ppb^{-1} respectively (based on Etminan *et al* (2016)), CO_2 response function is from Joos *et al* (2013) and temperature response function from Geoffroy *et al* (2013). The methane perturbation lifetime is 12.4 years. The ozone and stratospheric water vapour contributions are from Myhre *et al* (2013) Additional carbon cycle responses to temperature (Gasser *et al* 2017) are excluded here.

Time horizon (years)	20	50	75	100
GFP	48	5	0.8	0.1
GWP	99	57	42	34
GTP	67	14	8	7
iGTP	107	52	46	37

the absolute global forcing potential. See appendix A.1, available online at stacks.iop.org/ERL/15/024018/mmedia, for derivations of these formulae. As before, the relative metrics can be derived by dividing by the corresponding absolute values for CO_2 (see table 1 for values for methane). For simplicity we do not incorporate carbon cycle-temperature responses for the non-CO_2 species (equivalent to 'no cc fb' in Myhre *et al* (2013)).

The indirect effects of methane on ozone and stratospheric water vapour are included following Myhre *et al* (2013) as 1.82×10^{-4} and 0.54×10^{-4} W m^{-2} ppb$(CH_4)^{-1}$ respectively. They are added to the Etminan *et al* (2016) CH_4 radiative efficiency, rather than scaling it by 1.65 as in Myhre *et al* (2013). The indirect effects of N_2O on methane follow Myhre *et al* (2013). No effects of N_2O or halocarbons on stratospheric ozone destruction are included. Table 1 and appendix A.1 shows that the iGTP and GWP are very similar, indicating that the main difference between the metrics is whether one wishes to compare an *integrated* impact or an *endpoint* impact, rather than whether a radiative forcing or temperature impact is preferred. The endpoint metrics (GFP and GTP) vary much more strongly with time horizon than the integrated metrics, and differ significantly because the thermal inertia of the climate system means that the temperature response is felt for longer than the forcing itself. Thus although physically they correspond more closely with the Paris targets, for short-lived species they vary so strongly with time horizon as to be difficult to implement in policy applications where this time horizon decreases as date is approached (Shine *et al* 2007).

One way out of the above impasse was proposed by Smith *et al* (2012). Instead of trying to equate impacts of pulses, i.e. 1 kg emission of X with 1 kg emission of CO_2, they suggested it was more useful to compare rates of emission (in kg yr^{-1}) of short-lived species with cumulative emissions (in kg) of CO_2. This concept was introduced into metrics in Allen *et al* (2016) where they used a single number ($GWP_X(100)\times100$) to equate permanent step changes in SLCF emissions to a one-off pulse emission of CO_2. Collins *et al* (2018) calculated the impact of methane mitigation on allowable carbon budgets. Using a simple climate model coupled to a carbon cycle model, they showed that for a fixed temperature target, a step reduction in methane emissions of 1 Gt(CH_4) yr^{-1} was approximately equivalent to an increase in allowed cumulative CO_2 emissions of 2900–3300 Gt(CO_2). In this paper we expand on the central step-pulse distinction in Allen *et al* (2016) to show how combined step/pulse metrics can be derived from first principles; and we extend this logic to include an explicit time dependence.

Although metrics have generally been defined in terms of a pulse emission of 1 kg of a species, they can equivalently be defined in terms of a step change in emission of 1 kg per year as described in Fuglestvedt *et al* (2003) and Shine *et al* (2005). We will use the 'P' or 'S' superscripts to denote metrics based on pulse or step emissions. These metrics have physically equivalent outputs (so that $AGTP^P$ and $AGTP^S$ both describe the change in endpoint temperature and $AGFP^P$ and $AGFP^S$ both describe the change in endpoint forcing), it is only the form of the input (i.e. whether a pulse or step change is considered) that changes. So for a given goal (such as a temperature threshold) the $AGTP^P$ applied to pulse emission change or the $AGTP^S$ applied to a step emissions change are both equally valid choices of metric to assess progress towards the limit. The inputs do not even need to be the same for each species; because they both measure progress towards the same limit, it is entirely physically consistent to compare the temperature response to a step input in one species with that to a pulse input in another. We can therefore define combined metrics 'combined GWP' ($CGWP_X$) and 'combined GTP' ($CGTP_X$) as the ratio of step responses to X to pulse responses to CO_2: $CGWP_X = AGFP^S_X/AGFP^P_{CO2}$ and $CGTP_X = AGTP^S_X/AGTP^P{}_{CO_2}$. These metrics are no longer dimensionless, but have units of time reflecting the need to compare rates (kg yr^{-1}) with pulses (kg).

In terms of the more usual metrics, an endpoint metric for a step change in emissions is equivalent to an integrated metric for a pulse emission, i.e. $AGFP^S$ is equivalent to $AGWP^P$, and $AGTP^S$ is equivalent to $iAGTP^P$ (see section A.1 for derivations). However, in order to emphasise the preference for endpoint metrics we will not use the integrated metric notation.

3. Results

Figures 1(a), (e) show the radiative forcing and temperature responses as function of time to step changes in emissions ($AGFP^S$ and $AGTP^S$) for four species HFC-32, CH_4, CFC-11 and N_2O chosen to have a range of lifetimes: 5.4, 12.4, 52 and 121 years respectively. For HFC-32 and CH_4 the step responses asymptote quite quickly, whereas for CFC-11 and N_2O they are still increasing after 100 years. The

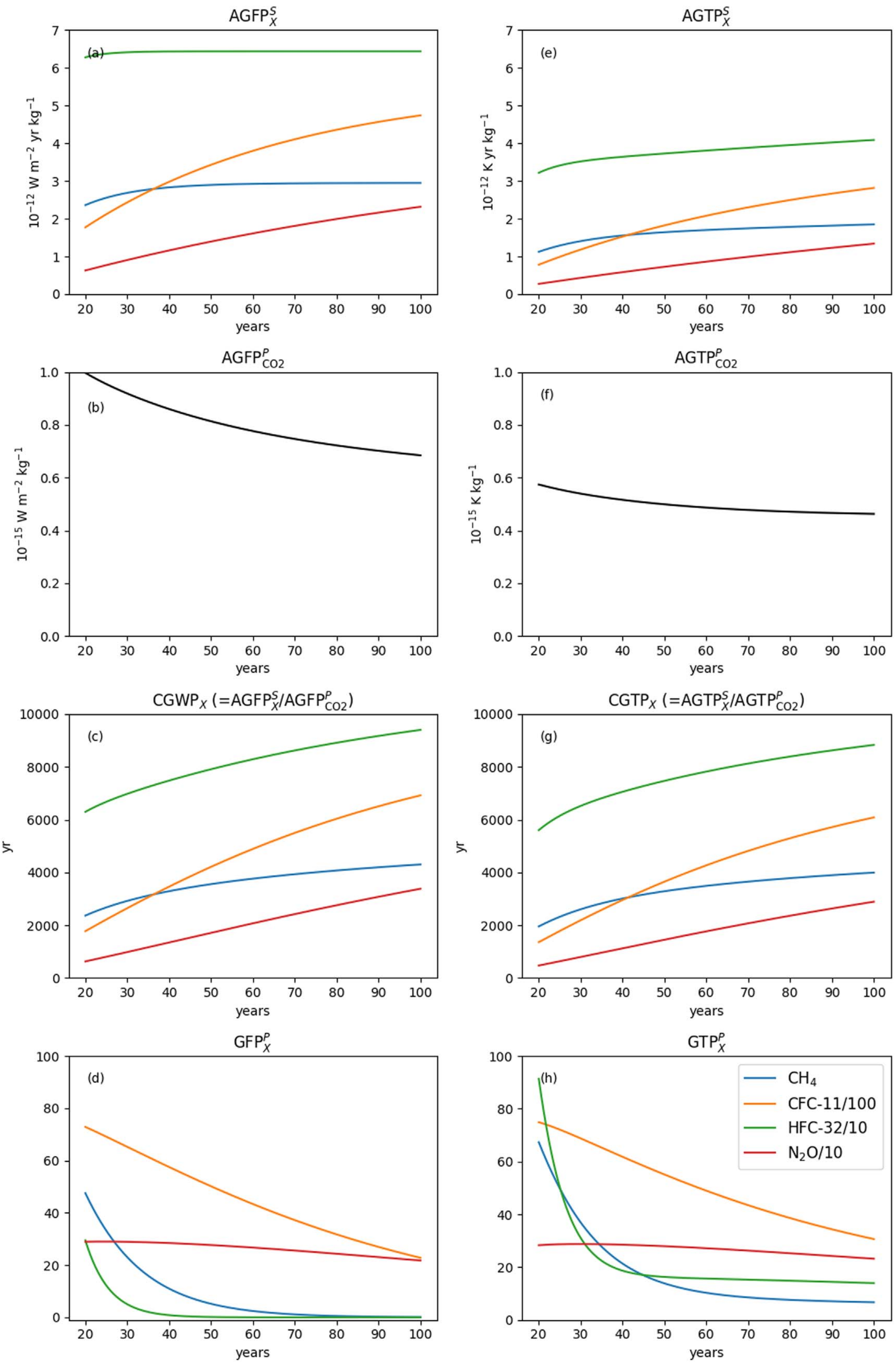

Figure 1. Climate metrics for four gases (HFC-32, CH_4, CFC-11, N_2O) with lifetimes of 5.4, 12.4, 52 and 121 years. Left hand side are radiative forcing based, right hand side are global temperature change based. (a), (e), step change metrics for four gases. (b), (f) pulse metrics for CO_2. (c), (g) ratios of step change metrics for the four gases with pulse metrics for CO_2. (d), (h) pulse/pulse metrics for the four gases. Note AGFP^S is equivalent to AGWP.

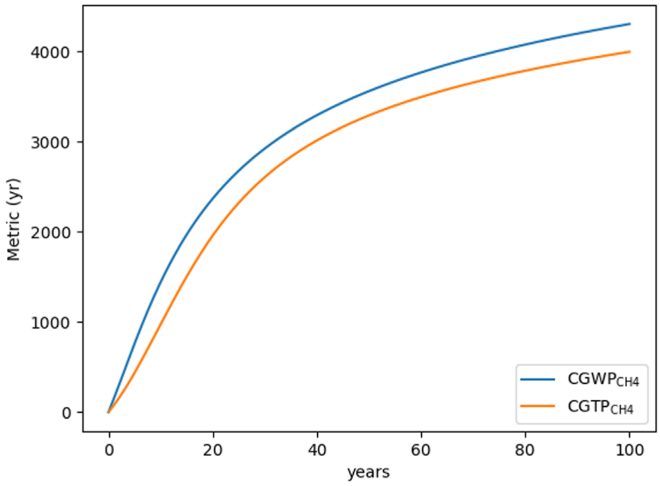

Figure 2. Comparison of the radiative forcing and temperate-change combined metrics ($AGFP^S/AGFP^P$ and $AGTP^S/AGTP^P$) for methane, relative to CO_2.

Table 2. Comparison of pulse metrics with combined metrics for the 4 gases, relative to CO_2. To 2 significant figures.

	Pulse GFP(50)	GFP(75)	GFP(100)	GTP(50)	GTP(75)	GTP(100)
CH_4	5.2	0.8	0.1	14	8	6.7
HFC-32	1.4	0.02	2×10^{-4}	160	150	140
CFC-11	5000	3400	2300	5500	4100	3100
N_2O	280	250	220	280	260	230
	Combined CGWP(50) (yr)	CGWP(75) (yr)	CGWP(100) (yr)	CGTP(50) (yr)	CGTP(75) (yr)	CGTP(100) (yr)
CH_4	3600	4000	4300	3300	3700	4000
HFC-32	79 000	88 000	94 000	74 000	83 000	88 000
CFC-11	420 000	580 000	690 000	370 000	510 000	610 000
N_2O	17 000	26 000	34 000	15 000	22 000	29 000

combined metrics are derived by dividing these responses by those for a pulse of CO_2 (b, f). These $CGWP_X$ and $CGTP_X$ ratios are moderately flat for HFC-32 and CH_4 but rise steadily for CFC-11 and N_2O (figures 1(c), (g)). Conversely, the more usual pulse/pulse metrics of GFP^P and GTP^P (figures 1(d), (h)) decrease significantly with time for HFC-32 and CH_4, but are steadier for N_2O. Metrics that vary strongly with time make them less useful for policy purposes; the choice of 100 years for the GWP as applied in the Kyoto Protocol was in essence an arbitrary (or convenient) one, and not one based on scientific reasoning (Shine 2009). Figure 1 suggests that for shorter-lived species the combined metrics, (i.e. ratio of a step response with the equivalent pulse response for CO_2), vary less with time horizon. For species with a lifetime greater than the timescale of interest (e.g. N_2O) the standard pulse metrics are more useful. For species of intermediate lifetime such as CFC-11 both combined and standard metrics have a time dependence. This is a very similar conclusion to Smith *et al* (2012) but phrased in terms of metrics.

For the combined metrics the difference between the radiative forcing and temperature approaches is not large, the $CGTP_{CH_4}$ is around 7% smaller than the $CGWP_{CH4}$ on the longer time horizons (figure 2). The extra timescales introduced through the temperature response has more effect on the CO_2 pulse than the methane step: in figure 1 the curves in panels (a) and (e) have similar shapes, whereas the curve in (f) plateaus more quickly than (b). Fuglestvedt *et al* (2018) argue that the long-term climate balance goal in the Paris agreement could imply a zero net radiative forcing, for which the CGWP (for short-lived species) and GFP (for long-lived) would be appropriate.

The time variation in the combined metrics for short-lived species is mostly due to the decrease in CO_2 concentration following a pulse. The difference between the 20 year metric and the 100 year metric is still large (roughly a factor of 1.5 for methane compared to the factor of 10 for GTP(20) versus GTP (100)), but the differences between 50 years and 100 years are much smaller (table 2)–factors of 1.2–1.3 for the combined metrics for SLCFs with a lifetime of around 20 years or less rather than the factors up to 2 for the pulse metrics (see also table 1 and appendix A.3). This means that a metric with a 75 year time horizon would be equally applicable for a climate target between (say) 2070 and 2120 within a less than 15% difference. For species with a lifetime of between 20 and 50 years, the time horizon needs to be chosen to reflect the timescale of the climate target. Even for these species the time dependence of the CGTP metric is still less than that for the GTP.

4. Discussion

4.1. Relation to climate goals

The choice of metric depends on the climate goal. In this paper we explicitly focus on the Paris goals, however other choices of climate goals (such as rate of warming or sea-level rise) would require different metrics to CGTP. Integrated climate metrics (GWP or iAGTP) effectively parameterise climate damage as approximately linear with temperature change, i.e. that a small increase in temperature in the next few years is equally damaging as the same increase in temperature at the end of the century. This does not fit into the framework of long-term climate targets (such as the Paris agreement) which are, strictly speaking, implicitly framed as damage only occurring above a threshold temperature, so these integrated climate metrics are not suitable for comparing contributions to achieving the Paris goals. The metrics most closely aligned with the Paris goals are therefore endpoint metrics with a time horizon chosen either around the time of peak warming (if no overshoots are allowed), or at some future time by which we need to have stabilised temperatures. For any temperature-based target CO_2 emissions need to fall to zero, while SLCFs need to stabilise (Tanaka and O'Neill 2018).

When comparing endpoint metrics of pulse emissions of short-lived species with pulse emissions of CO_2, the ratio is very sensitive to the choice of this time horizon making these metrics more difficult to apply in a policy situation. We have shown this sensitivity is very considerably reduced if instead the endpoint metric for a step change in a short-lived species is compared to the endpoint metric for a pulse change in CO_2. For instance, a metric designed to achieve radiative forcing or temperature balance by say late this century ($H \approx 75$ yr) would also be applicable (within a variation of 10%) 25 years either side. This stability has great advantages for policy in that it reduces the error caused by choosing an arbitrary time horizon, and it means that a metric used to determine Nationally Determined Contributions (NDCs) under the Paris Agreement will be approximately applicable for several iterations of the global stocktake cycle.

An issue with the GWP is that a time horizon of 100 years has been adopted without a specific scientific justification as described in section 3. Now that specific climate goals have been stated in the Paris Agreement, we can conclude that the appropriate timescales are between approximately 50 and 100 years (depending on whether the Paris Agreement is taken to relate to peak temperatures or early next century temperatures). With the weaker time sensitivity of the CGTP, we can suggest the CGTP(75) as a single metric that spans the appropriate timescales of interest within a variation of 10%.

4.2. Use of the metrics

4.2.1. Nationally determined contributions

The step change metrics are most easily applied to country-scale aggregated emissions, as these tend to be reported in Gt yr^{-1} and emissions pledges tend to be phrased as permanent step changes relative to the current emissions. For instance, a pledge by a country in their NDC to reduce methane emissions permanently by x Gt yr^{-1} (compared to the current emission rate) by 2030 would be equivalent to a one-off CO_2 reduction of $\sim 3700 \times$ Gt CO_2 (using the CGTP(75) (table 2)). The challenge comes from interpreting the step change CO_2 emission pledges as pulses. Note that pulse emissions are directly related to the cumulative emissions as they add a fixed amount to the total. Determining the cumulative emissions is required following the approximation that the temperature change scales with cumulative carbon emissions (which forms the basis for the widely used transient climate response to cumulative carbon emissions (TCRE) concept (Gregory *et al* (2009))). Therefore, a pledge to mitigate CO_2 emission rates by y Gt yr^{-1} by 2030 does not provide enough information; ideally instead the reduction in cumulative CO_2 emitted in Gt between the start date and 2030 should be reported (and similarly for other LLGHGs). Hence, as is approximately the case with GWP*, SLCF emissions reported as a change in emission rate can be converted to cumulative CO_2 emission equivalents using the combined metric CGTP, and changes in cumulative emissions of LLGHGs can be converted to cumulative CO_2 emission equivalents using pulse GTP, thus putting all emissions on a common scale.

4.2.2. Individual emissions sources

As well as country-scale emissions, the step metrics can also be easily applied to permanent structural emission changes, such as a shift from gas-fired power to renewables. However, they are not readily applicable to individual emission sources that have a finite lifetime. For example, methane emissions of e_{CH4} Tg yr^{-1} from a gas-fired power plant with an operating life of 20 years would cause a cumulative CO_2 equivalent emission of CGTP$\times e_{CH4}$ Tg when turned on, but an approximately equal negative cumulative CO_2 equivalent emission when turned off. The time dependence of CGTP means the negative cumulative CO_2 equivalent emission from decommissioning is slightly smaller than the initial positive CGTP, i.e.

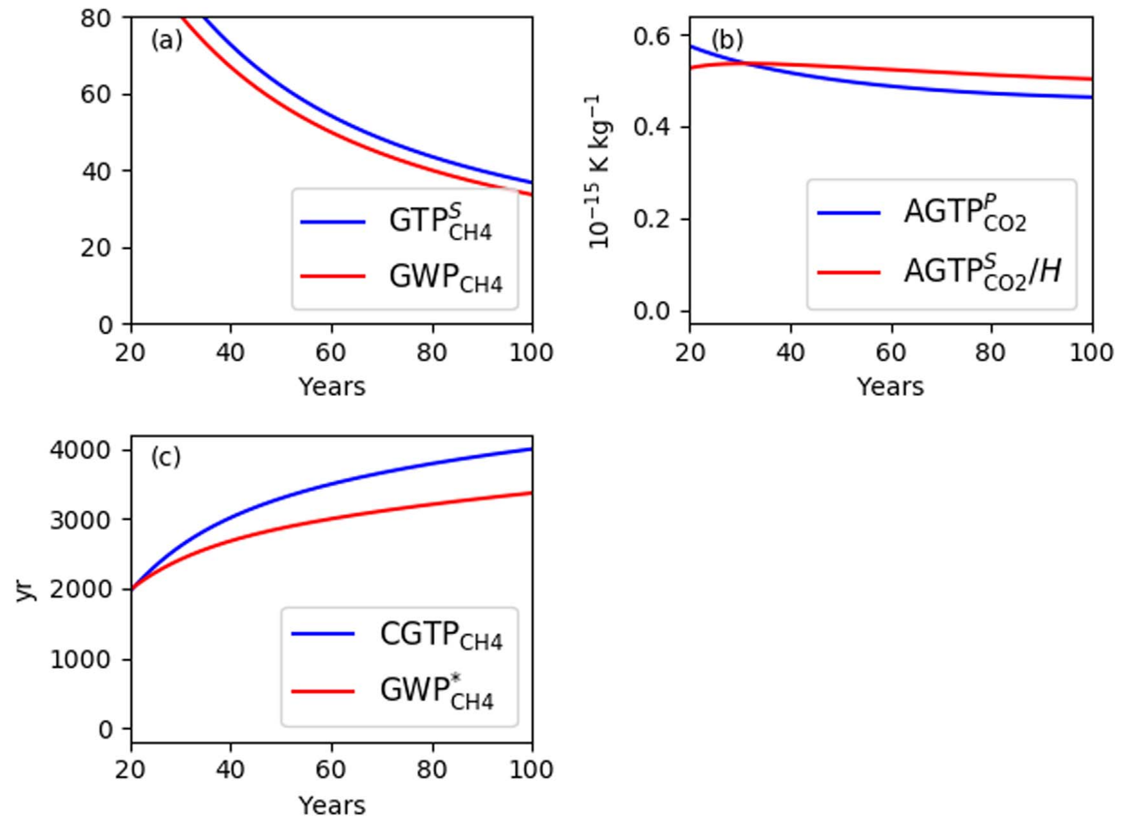

Figure 3. Illustration of the approximations in Allen *et al* (2016). (a) Comparison of GWP and GTP^S for methane, (b) comparison of ΔT with AGTP$^S/H$, (c) comparison of GWP$^*_{CH_4}$ with CGTP$_{CH4}$.

there is a small overall net positive cumulative CO_2 equivalence. This example realistically represents the point that the impact of a relatively short-duration source of methane has only a small effect on long-term temperatures.

4.3. Comparison with GWP*

The CGTP metric compares the endpoint temperatures of a step change in SLCF emissions with a pulse emission of CO_2. Allen *et al* (2016, 2018) show that an approximation to this metric can be derived by simply scaling the GWP by the time horizon H: $GWP^* = AGWP_X/(AGWP_{CO2}/H)$. They use the standard assumption of fixed TCRE (i.e. the temperature change is only dependent on the total CO_2 emitted) to make the approximation that a step change in CO_2 emissions for H years is equivalent to H one-year pulses ($AGTP^S_{CO_2}(H) \approx H \times AGTP^P_{CO_2}(H)$). They also make the approximation that GWP and GTP^S are equal ($AGTP^S_X/AGTP^S_{CO2} = GTP^S \approx GWP$). From this the metric $CGTP_X(H) = AGTP^S_X/AGTP^P_{CO_2}$ approximates to $H \times AGTP^S_X/AGTP^S_{CO_2} \approx H \times GWP_X(H)$. Figure 3 shows the effect of these approximations; panel (a) shows that GWP underestimates GTP^S by 11% at 100 years; panel (b) shows that assumption of constant TCRE leads to an overestimate of $AGTP^P_{CO_2}$ by 8% at 100 years; and panel (c) shows that GWP* therefore underestimates CGTP by up to 20%. An analogue of GWP*, GTP* ($=H^*$GTP^S), would be a closer approximation to CGTP, within 8% for $50 < H < 100$. Note that numerically $GWP^*_{CH_4}(100) \approx CGTP_{CH_4}(60)$ so the 100 year GWP* used in figure 2 of Allen *et al* (2016) gives good agreement with the expected temperature at $t = 60$ years in their panel (b). Therefore relaxing the constraint of trying to keep the GWP and its values for the various gases improves the physical fidelity of the step-pulse metrics from the results of Allen *et al* (2016, 2018). It is important to note that although the GWP* approach and the CGWP and CGTP developed here differ in their precise values, they are structurally and conceptually similar. This should be contrasted with GWP which is structurally inconsistent with the policies being addressed, giving the wrong sign of warming from a SLCF scenario in which emissions were falling (Allen *et al* 2018).

5. Conclusion

We conclude that combined step-pulse metrics (CGWP and CGTP) provide a useful way to compare changes in emission rates of SLCFs (lifetimes less than around 50 years—appendix A3) with cumulative emission changes in LLGHGs so that they may be included within common baskets in climate agreements. These are endpoint climate metrics which are closely tied to long-term climate goals such as the Paris Agreement. Integrated metrics such as GWP have been shown to be structurally unsuitable for such goals (both for SLCFs and LLGHGs). The standard pulse-based endpoint metrics for SLCFs vary strongly with time making them difficult to apply in a policy situation, whereas the combined metrics we propose are reasonably stable to within around 10% over the time horizons of current policy interest (around the end of the 21st century). Thus a single time horizon CGTP(75) can be used as a suitable metric for SLCFs covering the timescales relevant to the goals of the Paris Agreement. It has been suggested (Schleussner *et al* 2019) that because the step-pulse metrics are designed to stablise temperatures they do not encourage further temperature reductions, however such temperature reductions are not part of any formal goal.

Combined step-pulse metrics were first introduced in the GWP* approach (Allen *et al* 2016, 2018, Fuglestvedt *et al* 2018). GWP* was designed to retain the use of values of the standard GWP, for purposes of continuity, but we show that approximations inherent in doing so mean that the GWP* underestimates the contribution of SLCFs to temperature change by up to 20%, compared to a more explicit calculation of the effect of step changes in SLCF emissions relative to a pulse emission of CO_2. We emphasize that the calculation of the combined metrics proposed here need no additional inputs, or assumptions, than are already used to generate the GWP and GTP values in Myhre *et al* (2013); hence tabulated values can be easily constructed. Examples for halogenated species are shown in appendix A.4 table A.1.

For treaties involving multi-species baskets such as the Kyoto Protocol and as used by many countries under their NDCs for the Paris Agreement, climate metrics can be used to convert emissions of all species to a common unit. The application of CGTPs to rates of SLCF emissions and GTPs to total LLGHG emissions allows a conversion to cumulative CO_2 equivalent units which is more relevant to climate polices, such as the Paris Agreement, that are framed in terms of long-term temperature targets. This unit is the fundamental quantity in many climate pathways (Millar *et al* 2017, Forster *et al* 2018) and is approximately related to temperature rise through the TCRE.

There is evidence that these insights can inform national targets and national policies: New Zealand's recent Zero Carbon Act (New Zealand 2019) contains a split-gas target: a decrease for methane, and a net zero target for long-lived gases. This indicates that policymakers are able to respond and adapt to the insights that emerge from considering different metrics, such as those presented here and in in Allen *et al* (2018).

Scientifically, the main insight from this paper and Allen *et al* (2016, 2018) is that the step-pulse approach (such as CGTP or GWP*) represents a vital and significant improvement in the comparison of emissions of SLCFs with long-lived greenhouse gases with regard to long-term temperature goals. Although there is no perfect, universal way of comparing forcing agents across all variables and time horizons, these papers show that the conventional use of GWP is clearly not suitable for comparing the contributions of short and long-lived climate agents towards the Paris temperature goals.

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Data availability statement

Any data that support the findings of this study are included within the article.

ORCID iDs

William J Collins https://orcid.org/0000-0002-7419-0850
David J Frame https://orcid.org/0000-0002-0949-3994
Jan S Fuglestvedt https://orcid.org/0000-0001-6140-8374
Keith P Shine https://orcid.org/0000-0003-2672-9978

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