

# *Stable climate metrics for emissions of short and long-lived species – combining steps and pulses*

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—combining steps and pulses

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Multi-gas climate agreements rely on a methodology (widely referred to as ‘metrics’) to place emissions of different gases on a CO<sub>2</sub>-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<sub>2</sub> 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 understating 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<sub>2</sub>-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), endpoint (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<sub>2</sub> 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, Fuglestedt *et al* 2018), although it has been suggested (Schleussner *et al* 2019) that overstating the impacts of non-CO<sub>2</sub> forcers (for instance by use of GWP(100)) will encourage even stronger CO<sub>2</sub> 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); Fuglestedt *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, Fuglestedt *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 (Stern *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<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub>, i.e.  $GWP_X = AGWP_X / AGWP_{CO_2}$ , and  $GTP_X = AGTP_X / AGTP_{CO_2}$ , where these absolute metrics are defined as  $AGWP_X(H) = \int_0^H \Delta F_X(t) dt$ , and  $AGTP_X(H) = \Delta T_X(H)$ , 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  $iAGTP_X(H) = \int_0^H \Delta T_X(t) dt$  (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  $AGFP_X(H) = \Delta F_X(H)$  where AGFP is

**Table 1.** Climate metrics for methane (using CO<sub>2</sub> as a reference) for 20, 50 and 100 year time horizons. The radiative efficiencies for CH<sub>4</sub> and CO<sub>2</sub> are  $4.40 \times 10^{-4} \text{ W m}^{-2} \text{ ppb}^{-1}$  and  $1.30 \times 10^{-3} \text{ W m}^{-2} \text{ ppb}^{-1}$  respectively (based on Etminan *et al* (2016)), CO<sub>2</sub> 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](https://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<sub>2</sub> (see table 1 for values for methane). For simplicity we do not incorporate carbon cycle-temperature responses for the non-CO<sub>2</sub> 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  $1.82 \times 10^{-4}$  and  $0.54 \times 10^{-4} \text{ W m}^{-2} \text{ ppb}(\text{CH}_4)^{-1}$  respectively. They are added to the Etminan *et al* (2016) CH<sub>4</sub> radiative efficiency, rather than scaling it by 1.65 as in Myhre *et al* (2013). The indirect effects of N<sub>2</sub>O on methane follow Myhre *et al* (2013). No effects of N<sub>2</sub>O 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<sub>2</sub>, they suggested it was more useful to compare rates of emission (in kg yr<sup>-1</sup>) of short-lived species with cumulative emissions (in kg) of CO<sub>2</sub>. This concept was introduced into metrics in Allen *et al* (2016) where they used a single number (GWP<sub>X</sub>(100)×100) to equate permanent step changes in SLCF emissions

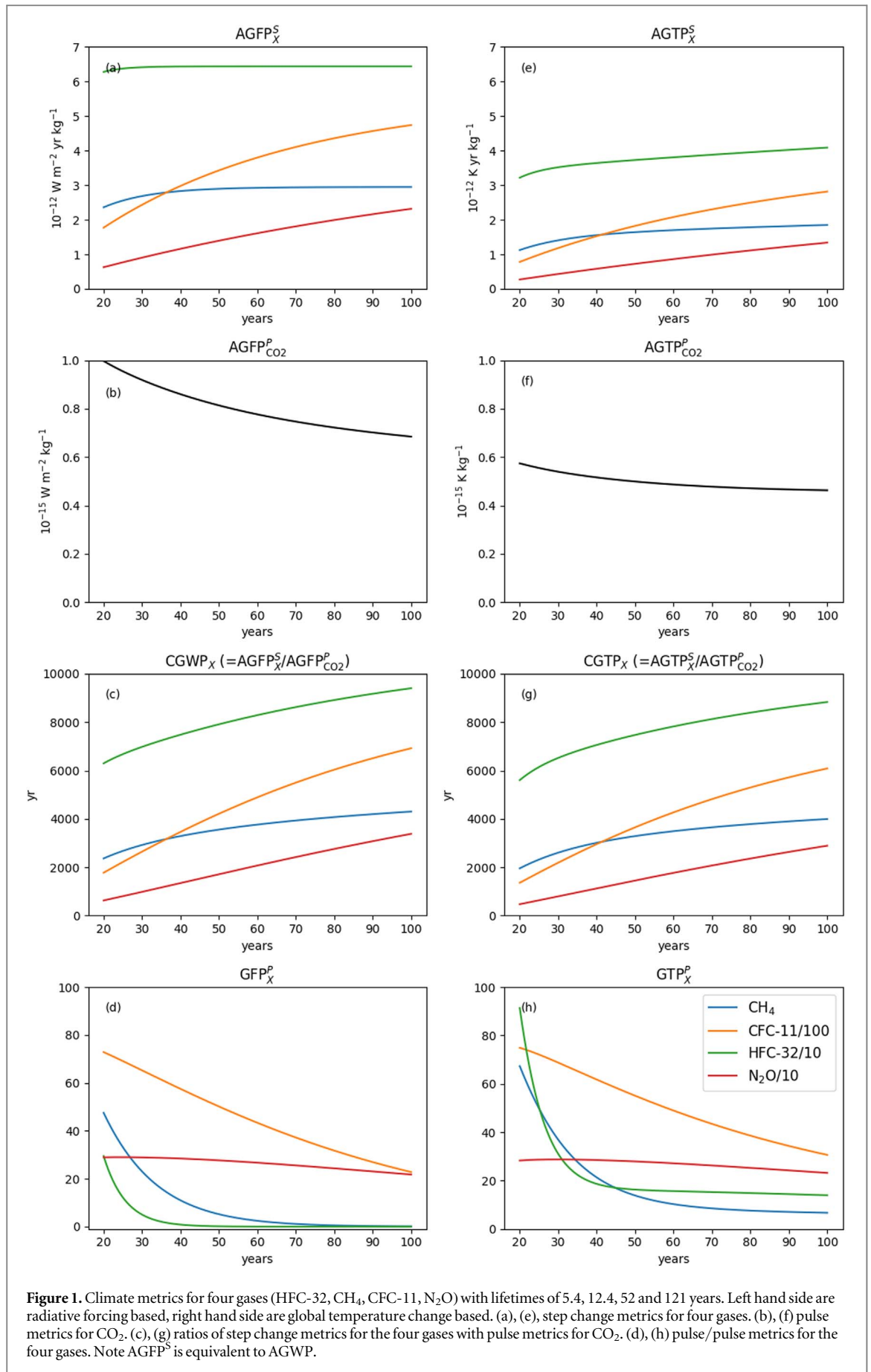
to a one-off pulse emission of CO<sub>2</sub>. Collins *et al* (2018) calculated the impact of methane mitigation on allowable carbon budgets. Using a simple climate model coupled to a carbon cycle model, they showed that for a fixed temperature target, a step reduction in methane emissions of 1 Gt(CH<sub>4</sub>) yr<sup>-1</sup> was approximately equivalent to an increase in allowed cumulative CO<sub>2</sub> emissions of 2900–3300 Gt(CO<sub>2</sub>). 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 Fuglestad *et al* (2003) and Shine *et al* (2005). We will use the ‘<sup>P</sup>’ or ‘<sup>S</sup>’ superscripts to denote metrics based on pulse or step emissions. These metrics have physically equivalent outputs (so that AGTP<sup>P</sup> and AGTP<sup>S</sup> both describe the change in endpoint temperature and AGFP<sup>P</sup> and AGFP<sup>S</sup> 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<sup>P</sup> applied to pulse emission change or the AGTP<sup>S</sup> 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<sub>X</sub>) and ‘combined GTP’ (CGTP<sub>X</sub>) as the ratio of step responses to *X* to pulse responses to CO<sub>2</sub>:  $\text{CGWP}_X = \text{AGFP}_X^S / \text{AGFP}_{\text{CO}_2}^P$  and  $\text{CGTP}_X = \text{AGTP}_X^S / \text{AGTP}_{\text{CO}_2}^P$ . These metrics are no longer dimensionless, but have units of time reflecting the need to compare rates (kg yr<sup>-1</sup>) 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<sup>S</sup> is equivalent to AGWP<sup>P</sup>, and AGTP<sup>S</sup> is equivalent to iAGTP<sup>P</sup> (see section A.1 for derivations). However, in order to emphasise the preference for endpoint metrics we will not use the integrated metric notation.

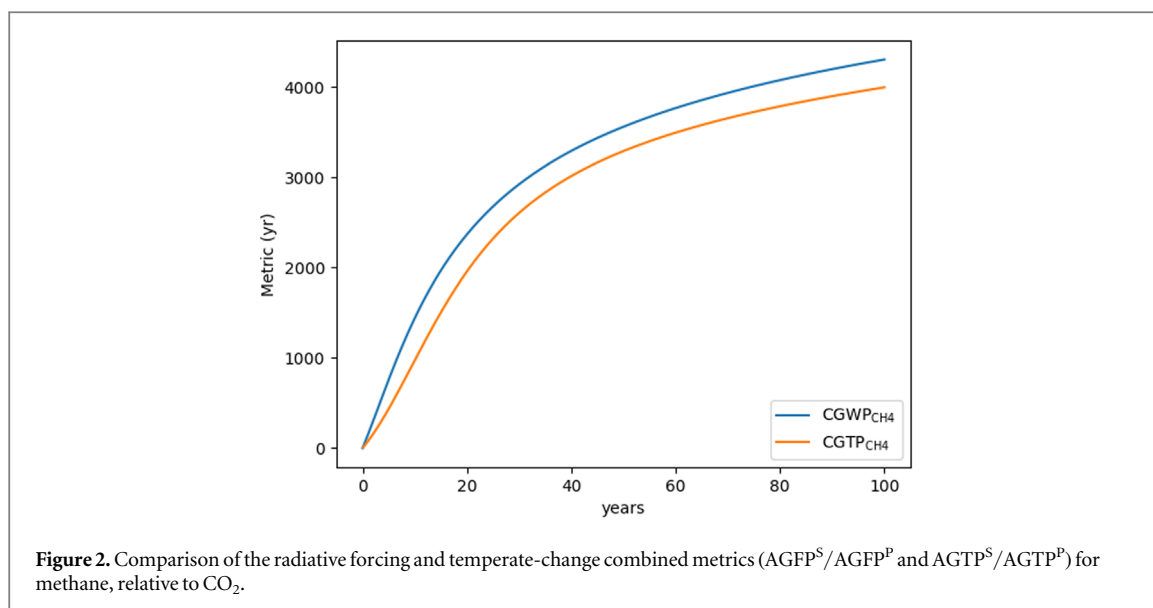
### 3. Results

Figures 1(a), (e) show the radiative forcing and temperature responses as function of time to step changes in emissions (AGFP<sup>S</sup> and AGTP<sup>S</sup>) for four species HFC-32, CH<sub>4</sub>, CFC-11 and N<sub>2</sub>O chosen to have a range of lifetimes: 5.4, 12.4, 52 and 121 years respectively. For HFC-32 and CH<sub>4</sub> the step responses asymptote quite quickly, whereas for CFC-11 and N<sub>2</sub>O they are still increasing after 100 years. The



**Figure 1.** Climate metrics for four gases (HFC-32, CH<sub>4</sub>, CFC-11, N<sub>2</sub>O) 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<sub>2</sub>. (c), (g) ratios of step change metrics for the four gases with pulse metrics for CO<sub>2</sub>. (d), (h) pulse/pulse metrics for the four gases. Note AGFP<sup>S</sup> is equivalent to AGWP.





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

|        | Pulse<br>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             | $2 \times 10^{-4}$ | 160              | 150              | 140               |
| CFC-11 | 5000                         | 3400             | 2300               | 5500             | 4100             | 3100              |
| $N_2O$ | 280                          | 250              | 220                | 280              | 260              | 230               |
|        | Combined<br>CGWP(50)<br>(yr) | CGWP(75)<br>(yr) | CGWP(100)<br>(yr)  | CGTP(50)<br>(yr) | CGTP(75)<br>(yr) | CGTP(100)<br>(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  $CGWP_{CH_4}$  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). Fuglestad *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<sub>2</sub> 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<sub>2</sub>, 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<sub>2</sub>. 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%.

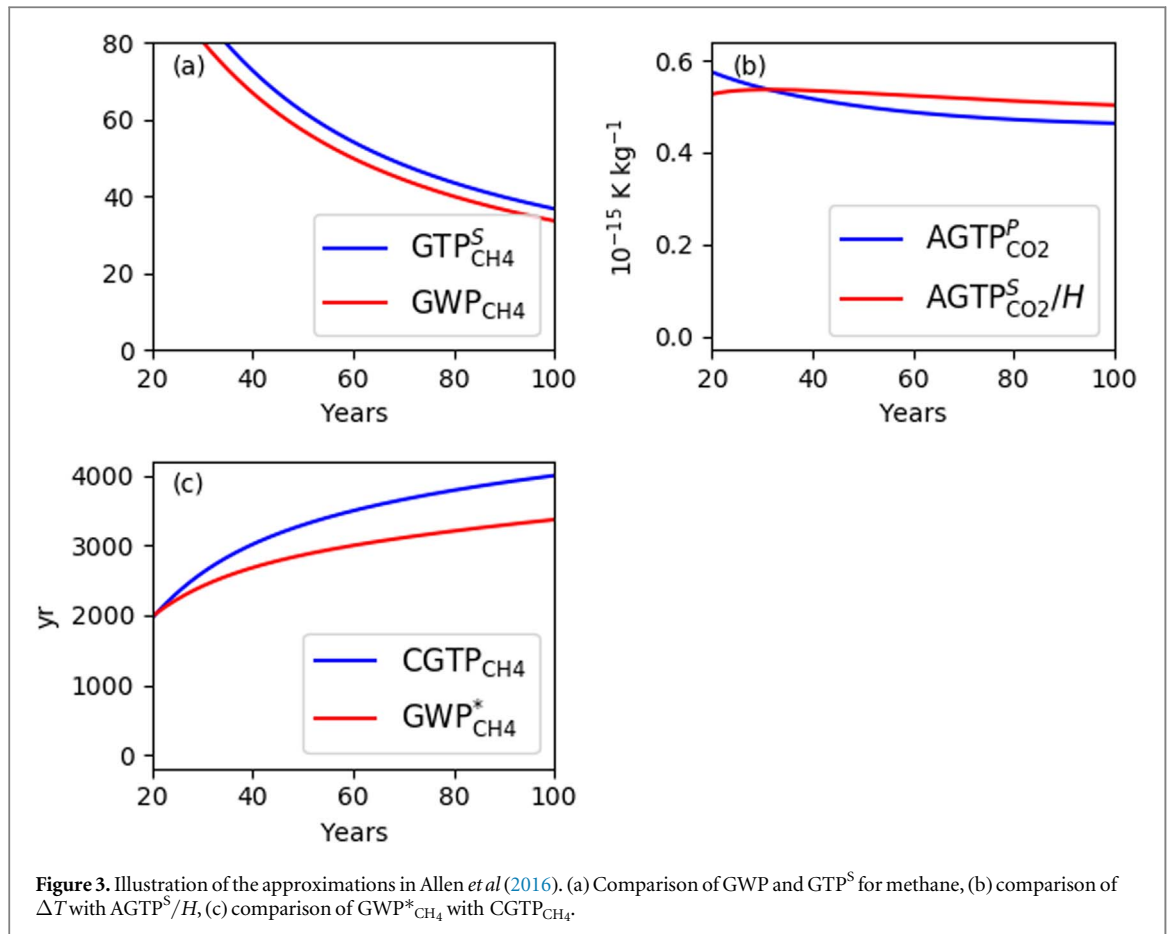
### 4.2. Use of the metrics

#### 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<sup>-1</sup> 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<sup>-1</sup> (compared to the current emission rate) by 2030 would be equivalent to a one-off CO<sub>2</sub> reduction of  $\sim 3700 \times \text{Gt CO}_2$  (using the CGTP(75) (table 2)). The challenge comes from interpreting the step change CO<sub>2</sub> 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<sub>2</sub> emission rates by  $y$  Gt yr<sup>-1</sup> by 2030 does not provide enough information; ideally instead the reduction in cumulative CO<sub>2</sub> 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<sub>2</sub> emission equivalents using the combined metric CGTP, and changes in cumulative emissions of LLGHGs can be converted to cumulative CO<sub>2</sub> 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  $e_{\text{CH}_4}$  Tg yr<sup>-1</sup> from a gas-fired power plant with an operating life of 20 years would cause a cumulative CO<sub>2</sub> equivalent emission of  $\text{CGTP} \times e_{\text{CH}_4}$  Tg when turned on, but an approximately equal negative cumulative CO<sub>2</sub> equivalent emission when turned off. The time dependence of CGTP means the negative cumulative CO<sub>2</sub> equivalent emission from decommissioning is slightly smaller than the initial positive CGTP, i.e.



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  $H$ :  $GWP^* = AGWP_X / (AGWP_{CO_2} / H)$ . 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 ( $AGTP^S_X / AGTP^S_{CO_2} = GTP^S \approx GWP$ ). 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 stabilise 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, Fuglestedt *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<sub>2</sub>. 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<sub>2</sub> equivalent units which is more relevant to climate policies, 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 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.

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