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# Demonstrating GWP\*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants

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## Abstract

The atmospheric lifetime and radiative impacts of different climate pollutants can both differ markedly, so metrics that equate emissions using a single scaling factor, such as the 100-year Global Warming Potential (GWP<sub>100</sub>), can be misleading. An alternative approach is to report emissions as ‘warming-equivalents’ that result in similar warming impacts without requiring a like-for-like weighting per emission. GWP\*, an alternative application of GWPs where the CO<sub>2</sub>-equivalence of short-lived climate pollutant emissions is predominantly determined by changes in their emission rate, provides a straightforward means of generating warming-equivalent emissions. In this letter we illustrate the contrasting climate impacts resulting from emissions of methane, a short-lived greenhouse gas, and CO<sub>2</sub>, and compare GWP<sub>100</sub> and GWP\* CO<sub>2</sub>-equivalents for a number of simple emissions scenarios. We demonstrate that GWP\* provides a useful indication of warming, while conventional application of GWP<sub>100</sub> falls short in many scenarios and particularly when methane emissions are stable or declining, with important implications for how we consider ‘zero emission’ or ‘climate neutral’ targets for sectors emitting different compositions of gases. We then illustrate how GWP\* can provide an improved means of assessing alternative mitigation strategies. GWP\* allows warming-equivalent emissions to be calculated directly from CO<sub>2</sub>-equivalent emissions reported using GWP<sub>100</sub>, consistent with the Paris Rulebook agreed by the UNFCCC, on condition that short-lived and cumulative climate pollutants are aggregated separately, which is essential for transparency. It provides a direct link between emissions and anticipated warming impacts, supporting stocktakes of progress towards a long-term temperature goal and compatible with cumulative emissions budgets.

## 1. Introduction

A range of different climate pollutants contribute to anthropogenic climate change [1]. Emissions of different climate pollutants are often described using a common metric, generally scaled relative to carbon dioxide (CO<sub>2</sub>); hence non-CO<sub>2</sub> emissions are typically communicated (and aggregated) as carbon dioxide equivalent (CO<sub>2</sub>-e) quantities.

The most widely used CO<sub>2</sub> equivalence metric is the Global Warming Potential (GWP), defined as the integrated change in radiative forcing (the

perturbation of the Earth’s atmospheric energy balance, which leads to warming) over a specified time-period following an emission pulse of a given climate pollutant, relative to the same quantity of CO<sub>2</sub>. Emissions of a given climate pollutant ( $E$ ) can thus be converted to a CO<sub>2</sub>-e emission ( $E_{\text{CO}_2\text{-e}}$ ) quantity by multiplying by the appropriate GWP conversion factor, for the specified time-horizon ( $H$ ):

$$E_{\text{CO}_2\text{-e}} = E \times \text{GWP}_H. \quad (1)$$

The 100-year variant of the Global Warming Potential (GWP<sub>100</sub>) has been formally adopted in

international climate policy (currently as established in the Kyoto Protocol, and in the draft text of the Paris Agreement [2]) and standardised Life Cycle Assessment (LCA)/carbon-footprinting approaches [3]). Subsequently,  $GWP_{100}$  has become the *de facto* standard for expressing emissions in the scientific literature and general media, and has essentially become shorthand for the relative climate impacts of a given product or activity. Despite its ubiquity, the relationship between aggregate  $CO_2$ -e emissions calculated using  $GWP_{100}$  and global warming itself is ambiguous.

This has been a significant and long-standing criticism of the GWP (e.g. [4–7]). Fundamentally, many of the shortcomings of the GWP as a universal climate metric arise because it cannot sufficiently differentiate the contrasting impacts of long- and short-lived climate pollutants (SLCPs), and it is this element that we focus on here.

A large fraction of anthropogenic  $CO_2$  emissions will persist in the atmosphere for millennia without active, large-scale efforts to remove them [8, 9]. Consequently, continued emissions add cumulatively to the atmospheric stock, and so within this millennial time period temperatures will increase indefinitely for as long as emissions are maintained, then remain approximately fixed at this level for centuries once emissions cease [10]. For greenhouse gases with relatively short atmospheric lifespans (or, more broadly, SLCPs) such as methane ( $CH_4$ ), however, natural atmospheric removals limit indefinite increases in their atmospheric concentrations for stable emission rates, as an equilibrium can be established where emissions and removals are approximately balanced.  $GWP_{100}$ , or indeed any pulse-based metric treating long- and short-lived climate pollutants in the same way, cannot capture these contrasting dynamics.

Following these behaviours, sustained emissions of an SLCP therefore result in a similar impact to a one-off release of a fixed amount of  $CO_2$ : both lead to a relatively stable long-term increase in radiative forcing. Thus an alternative means of equivalence can be derived, relating a change in the rate of emissions of SLCPs to a fixed quantity of  $CO_2$  ([7, 11–13], and see [14] for a recent elaboration on this equivalence concept). Allen *et al* [15] demonstrated that this can be achieved using GWP conversion factors (and thus based on the same basic atmospheric properties incorporated in the GWP), where a change in the emissions rate of an SLCP ( $\Delta E_{SLCP}$ ) is equivalent to a one-off release or sequestration of  $\Delta E_{SLCP} \times GWP_H \times H$  tonnes of  $CO_2$ . This alternative application of GWPs is termed  $GWP^*$ , and as the means of defining equivalence is better associated with temperature change contribution, can be considered a ‘ $CO_2$  warming equivalent ( $CO_2$ -w.e.)’, in contrast to a per-emission  $CO_2$ -e [16]. (For the rest of this letter we will use  $CO_2$ -w.e. to report equivalents derived using  $GWP^*$ ,  $CO_2$ -e for equivalents from conventional application of  $GWP_{100}$ , and ‘ $CO_2$ -equivalents’ as a generic term to

describe either means of deriving equivalents).  $GWP^*$  was further refined in Allen *et al* [17], showing that specifying a time-period ( $\Delta t$ ) of 20 years over which to assess the change in SLCP emission rates ( $\Delta E_{SLCP}$ ), and scaling the  $CO_2$ -w.e. per year of this period (i.e.  $/\Delta t$ ) provides a good fit for modelled warming, and a means of annualising the reported emissions.

Recent work by Cain *et al* [16] further improved the accuracy of  $GWP^*$ . Sustained SLCP emissions result in stable forcing. Eventually, if maintained indefinitely, this results in no additional warming, but since most SLCP emission sources originated within the past century, there is a slow adjustment even to perfectly constant emissions due to the delayed response to past forcing increases [18]. For  $CO_2$ , this slower temperature adjustment is approximately balanced by medium-term carbon cycle dynamics, particularly ocean  $CO_2$  absorption [19].  $GWP^*$  was consequently redefined to include a smaller component that also treats SLCPs as a ‘stock’ pollutant (similarly to conventional  $GWP_{100}$  usage) to account for this delayed response to past increases in SLCP emissions:

$$E_{CO_2} - \text{w.e.}_{(SLCP)} = \left( r \times \frac{\Delta E_{SLCP}}{\Delta t} \times H + s \times E_{SLCP} \right) \times GWP_H, \quad (2)$$

where  $r$  represents the weighting given to the impacts of changing the rate of SLCP emissions, and  $s$  the weighting given to the impacts of the current emissions rate.

These two weighting factors are scenario dependent (as they will vary based on the historical legacy of emissions, and hence how much of the slow warming component is already experienced), but using the  $GWP_{100}$  and a combination of  $r$  and  $s$  of 0.75 and 0.25 respectively was found to give a good approximation of the historical and projected warming impacts of methane over a range of emission trajectories [16], and we use these parameter values in this letter.

Using the values suggested above, under all scenarios except near-constant emissions the equation is dominated by  $(0.75 \times 100 = 75)$  the rate-based component, with much less weight (0.25) assigned to the stock component. Both components are then multiplied by the  $GWP_{100}$  to provide a  $CO_2$  warming-equivalent quantity of emissions. Alternatively, if  $CO_2$ -equivalent emissions are pre-computed using  $GWP_{100}$ , they can be combined using the part of equation (2) in parentheses: hence  $GWP^*$  is compatible with emissions reporting under the Paris Rule-book agreed at COP24, provided cumulative and SLCPs are reported and aggregated separately in emissions reporting and nationally determined contributions. The rule-book does not explicitly state that gases must be reported individually, although it is near-universal practice in reporting of emissions inventories to specify gases separately in terms of  $CO_2$ -e. Separate reporting and aggregation of cumulative and short-lived

pollutants in all communications between parties and the UNFCCC would substantially enhance the transparency of the UNFCCC process and ensure climatically important information is not lost.

With these suggested parameters, the GWP\* equation can also be simplified further to:

$$E_{\text{CO}_2} - \text{w.e.}_{(\text{SLCP})} = (4 \times E_{\text{SLCP}(t)} - 3.75 \times E_{\text{SLCP}(t-20)}) \times \text{GWP}_{100}, \quad (3)$$

where  $E_{\text{SLCP}(t)}$  is the current SLCP emission rate, and  $E_{\text{SLCP}(t-20)}$  the rate of SLCP emissions 20 years ago, highlighting that GWP\* requires only two values, which are already calculated and reported within the UNFCCC. This version of the equation can be thought of as representing that any ‘new’ methane emissions have a very strong climate impact, 4 times greater than reported by  $\text{GWP}_{100}$ , but after 20 years much of the warming caused is automatically reversed.

Longer-lived climate pollutants (those with a lifespan longer than  $H$ , i.e. 100 years), will also display cumulative behaviours over this timeframe, and so their GWP\*  $\text{CO}_2$ -w.e. follows conventional use of GWP as in (1). Note, however, that this is in the context of formulating near-to-medium term climate policy, and is not meant to suggest that, for example, nitrous oxide ( $\text{N}_2\text{O}$ ) is directly equivalent to  $\text{CO}_2$  either; the impact of our emissions on the carbon cycle means that  $\text{CO}_2$  is unique, and the gas is uniquely long-lived [1, 7]. Whether a given climate pollutant is defined as short- or long-lived depends on the time-scale being considered, and GWP\* could potentially be applied using longer GWP time-horizons than 100 years to also treat longer-lived gases than methane as ‘short-lived’ (i.e. their impacts depend on the ongoing emissions rate, rather than cumulative total emissions, as for  $\text{CO}_2$ ). Further elaboration comparing different timeframes and climate pollutants is shown for related approaches, the combined global warming potential (CGWP) and combined global temperature-change potential (CGTP) in [14]. For this letter we focus exclusively on methane, as the most important SLCP, which must be treated as a non-cumulative pollutant to anticipate the impacts of ambitious emission reduction scenarios even over the next few decades.

Although relatively simple, this new means of deriving  $\text{CO}_2$ -equivalence is a significant reframing of how we report and conceptualise emissions of SLCPs. It is worth illustrating and expanding upon the principles described above, and the nature of GWP\*. In this study we demonstrate a number of methane and  $\text{CO}_2$  emissions scenarios in a simple climate model to display their contrasting dynamics. We show how these emissions scenarios translate to equivalents derived using either  $\text{GWP}_{100}$  or GWP\* noting some of the shortcomings of  $\text{GWP}_{100}$ , and how these are overcome by GWP\*. We then highlight special cases and suggested applications that may provide extra insight or be of particular policy relevance.

## 2. Methods

We used the FaIR (Finite-Amplitude Impulse Response) v1.3 climate-carbon-cycle model to generate changes in atmospheric concentration, radiative forcing and temperature for a number of methane and/or  $\text{CO}_2$  emissions scenarios. FaIR captures the relevant dynamics of different climate pollutants, and has been shown to provide good agreement with other, more computationally intensive, climate modelling approaches [20]. We constrained methane to an average lifespan of 12 years to reflect contemporary conditions, and did not include variations in solar and volcanic forcing to focus on the impacts of our emissions scenarios alone. Radiative forcings are modelled following [21]. Our scenarios are based on perturbations from the standard RCP4.5 pathway from the year 2000. Default RCP4.5 emissions are generated from [20] to produce RCP4.5 concentrations [22] in FaIR. RCP4.5 was used to provide a ‘middle-of-the-road’ scenario, and with relatively stable methane emissions over time (discussed further below). The emissions specified for each scenario were added to these RCP4.5 defaults, and the difference between concentrations, forcings and warming from the modified scenarios and default RCP4.5 show individual contributions of the specified pathways alone.

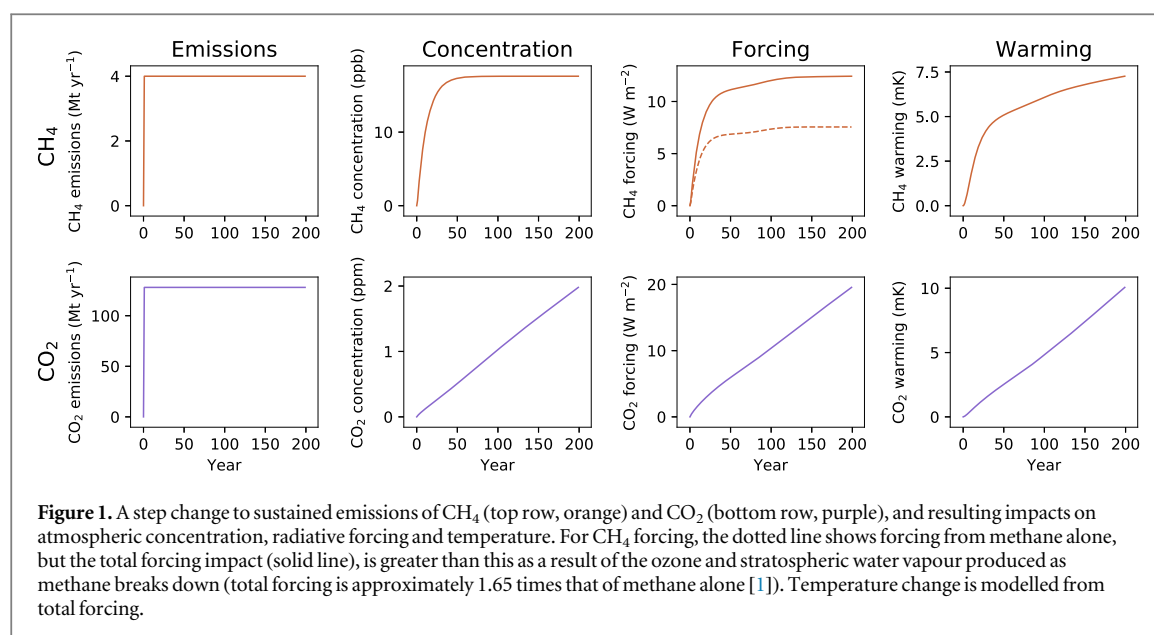
Individual emission scenarios are described alongside their results below, but were broadly variations on a baseline scenario introducing and then sustaining a methane emission of 4 Mt per year. A default annual emission of 4 Mt methane, close to the average UK methane emissions between 1990 and 2016 [23], was selected to represent a significant, policy-relevant methane emission that would not be so large as to greatly perturb the RCP4.5 background conditions. For reference, this is just over 1% of the 353 Mt total anthropogenic methane emissions estimated for 2012 [24].

‘Equivalent’  $\text{CO}_2$  emissions scenarios were derived for  $\text{GWP}_{100}$  and GWP\* using (1) and (2) respectively, both with a  $\text{GWP}_{100}$  conversion factor for methane of 32 from [21]. A fixed GWP value was used, as though in practice this should be updated as greenhouse gas concentrations and hence the unit forcing per emission change in the future, most current climate policy is also based on fixed, present-date GWP values (see also below and supplementary material section 1, available online at [stacks.iop.org/ERL/15/044023/mmedia](https://stacks.iop.org/ERL/15/044023/mmedia) for further discussion on this topic).

## 3. Results and discussion

### 3.1. Atmospheric behaviours of methane and $\text{CO}_2$

To illustrate the principles outlined in the introduction, we start with a simple scenario where an emission is introduced in year 0 and then sustained at the same



rate for 200 years (figure 1). For methane, concentrations increase rapidly but then plateau after a few decades as natural atmospheric removals balance ongoing emissions. Radiative forcing similarly increases rapidly due to the high radiative efficiency of CH<sub>4</sub> (i.e. there is a large change in forcing per change in CH<sub>4</sub> concentration) but then largely stabilises—although there is some increase in forcing between approximately years 50 and 150 as over this period the background methane concentration in RCP4.5 is expected to decline as anthropogenic emission rates are reduced, resulting in a greater radiative efficiency of any remaining methane emissions (i.e. including those modelled here).

This stabilising behaviour is then also reflected in the warming that results from the sustained CH<sub>4</sub> emission: the bulk of the temperature change occurs rapidly, and is significant, but the rate of temperature increase declines after these initial decades. There is, however, still some long-term delayed adjustment to this initial increase. In the very long term (several centuries, but subject to the large uncertainties in the slow temperature equilibration of the Earth) the warming from any biogenic methane emission would also be expected to completely stabilise and generate no additional temperature increases, becoming indistinguishable from long-standing natural methane emission rates to which the climate system has fully adjusted [16], but to anticipate near- to medium-term climate impacts this extended temperature change remains important [18].

For CO<sub>2</sub>, modelling an equivalent (using GWP<sub>100</sub>) emissions scenario, we see that sustained emissions do not result in stabilising concentrations. Instead, concentrations, forcing and subsequently warming continue to increase for as long as the emissions are sustained, with an approximately linear relationship

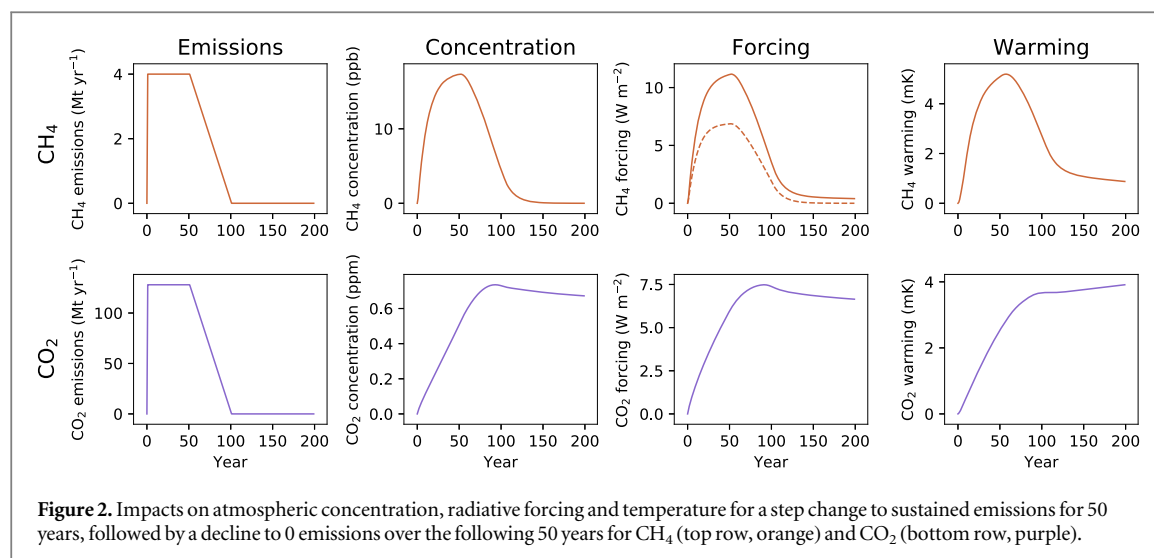
between cumulative CO<sub>2</sub> emissions and resultant warming (as will be expanded upon later).

This simple illustration of the impacts of sustained emissions already highlights how different short- and long-lived GHGs are, and hence why metrics that attempt to treat them in the same way will fall short. These differences are even more pronounced if we consider the impacts of decreasing emission rates.

In figure 2 we demonstrate a scenario which begins in the same way as the previous example, with a step change to sustained emissions, but after 50 years these decline linearly to reach 0 over the following 50 years. For methane, as the emissions rate declines, so too do atmospheric concentrations: from the equilibrium described earlier, we start to reduce emissions while removals continue, and so atmospheric concentrations fall when they are not continuously ‘topped up’ by maintained emissions. These dynamics are then reflected in the change in forcing and ultimately warming, with declining emissions able to reverse a significant proportion of recent warming over relatively short timescales.

For CO<sub>2</sub>, reducing the emission rate merely acts to slow the rate of continued increase in concentration until emissions reach nearly 0, at which point atmospheric concentrations slowly decline as a result of short- and medium-term carbon sinks. It would take millennia for current CO<sub>2</sub> concentrations to return to pre-industrial levels without active intervention [9, 7]. The changes in CO<sub>2</sub> concentration are reflected in the change in forcing over time. Nonlinearities in forcing and warming approximately balance each other out such that the increased temperatures from CO<sub>2</sub> emissions are relatively fixed at this amount once emissions cease [19], maintaining the near-linearity between cumulative CO<sub>2</sub> emissions and warming noted earlier even without ongoing emissions.





**Figure 2.** Impacts on atmospheric concentration, radiative forcing and temperature for a step change to sustained emissions for 50 years, followed by a decline to 0 emissions over the following 50 years for CH<sub>4</sub> (top row, orange) and CO<sub>2</sub> (bottom row, purple).

A ‘zero emissions’ target will therefore have distinct impacts depending on whether the climate pollutant is long- or short-lived, and does not imply an equivalent mitigation effort or climate response.

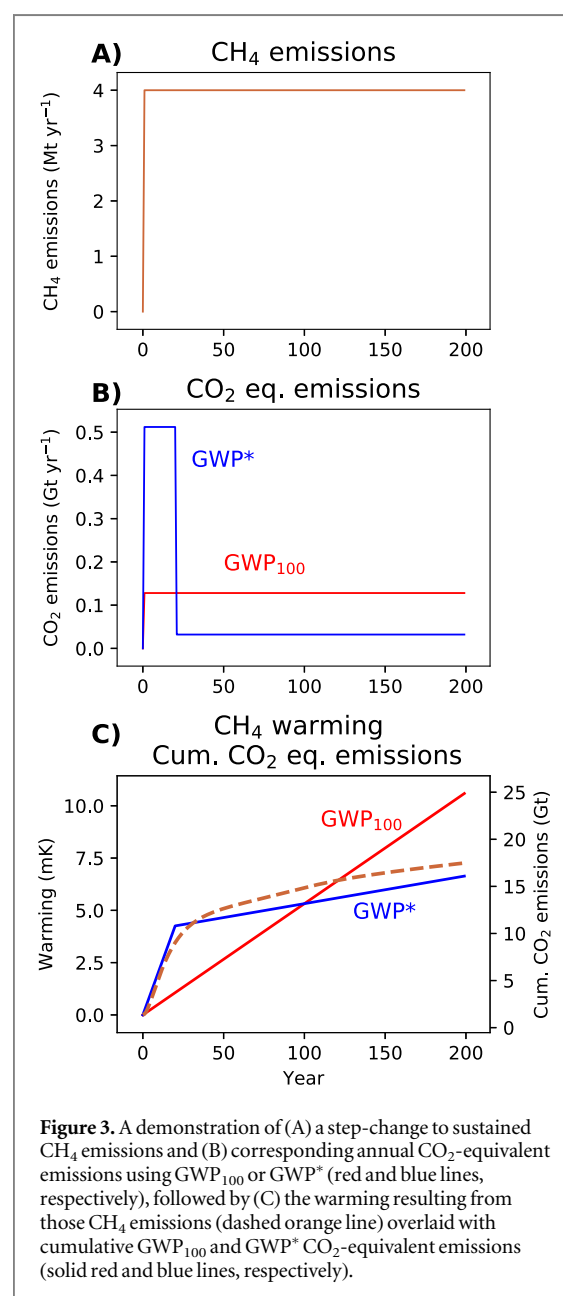
The differing warming legacies once emissions of either gas are removed, as shown in figure 2, also applies to one-off emission pulses. Despite pulse-comparisons being commonplace in metric design (including the GWP) and individual emission offsets, trying to describe the impacts of a pulsed emission of CO<sub>2</sub> with a scaled individual pulsed emission of methane, and vice versa, will inherently fail to provide similar warming pathways, and so transactions based on such exchanges will not result in climatically equivalent responses.

These two scenarios also highlight a broad principle: CO<sub>2</sub>-induced warming depends on cumulative emissions to date, but for SLCPs such as methane, their warming contribution is predominantly a function of recent emission rates [11, 25]. GWP\* can capture this key difference.

### 3.2. CO<sub>2</sub> equivalence of methane emissions

We now show how the corresponding GWP<sub>100</sub> and GWP\* CO<sub>2</sub>-equivalents compare for these two emissions scenarios. Starting with a step-change to sustained methane emissions (figure 3), using conventional application of GWP<sub>100</sub> reports these methane emissions as equivalent to a constant rate of CO<sub>2</sub>-e emissions over time (this is also the same CO<sub>2</sub> emissions scenario as shown in figure 1). Using GWP\* over the first 20 years the methane emissions are represented by very high CO<sub>2</sub>-w.e. emissions, capturing the strong weighting given to the initial change in rate [from 0 emissions], but after this  $\frac{\Delta E_{SLCP}}{\Delta t} = 0$ , and so only the much lower CO<sub>2</sub>-w.e. emissions from the ‘stock’ behaviour of longer-term sustained methane emissions remain.

The main difference between GWP\* and static metrics such as GWP<sub>100</sub> is thus: with static metrics, individual emissions are directly equated by a single



**Figure 3.** A demonstration of (A) a step-change to sustained CH<sub>4</sub> emissions and (B) corresponding annual CO<sub>2</sub>-equivalent emissions using GWP<sub>100</sub> or GWP\* (red and blue lines, respectively), followed by (C) the warming resulting from those CH<sub>4</sub> emissions (dashed orange line) overlaid with cumulative GWP<sub>100</sub> and GWP\* CO<sub>2</sub>-equivalent emissions (solid red and blue lines, respectively).

value that can only represent one particular impact at or over a stated time, and which cannot fully capture the temporal differences between the impacts of different gases; but for GWP\*, 'equivalent' CO<sub>2</sub> can vary in order to describe dynamic responses over any time-frame of interest. As this problem occurs for any static concept of equivalence, it cannot be overcome by using alternative metrics or alternative time-horizons, as illustrated in section 2 of the supplementary material, revealing similar limitations for the 20 year Global Warming Potential (GWP<sub>20</sub>) and the 100-year Global Temperature change Potential (GTP<sub>100</sub>)

As described above, there is an approximately linear relationship between cumulative CO<sub>2</sub> emissions and temperature. If CO<sub>2</sub>-equivalents do indeed describe methane emissions in an equivalent manner to CO<sub>2</sub>, a cumulative CO<sub>2</sub>-equivalent should therefore correspond to the warming generated by the methane emissions they describe. We can illustrate this by plotting our cumulative CO<sub>2</sub>-equivalents alongside temperature, as in figure 3(c). While GWP\* provides a reasonable fit for the methane warming profile (initially rapid temperature increases followed by a longer tail of more gradual warming GWP<sub>100</sub> suggests) a fixed rate of temperature change from methane that does not capture the true dynamics.

Directly relating equivalent emissions to temperature responses was not an intended usage of GWP<sub>100</sub>, and so attempting to link cumulative GWP<sub>100</sub> CO<sub>2</sub>-e to global warming is arguably an inappropriate application of the metric. However, the approach provides useful insight into how the impacts of short- and long-lived gases differ, why static metrics such as the GWP<sub>100</sub> will always miss important dynamics, and reveals further applications that become possible when the equivalent emissions reflect the impacts of cumulative CO<sub>2</sub> emissions.

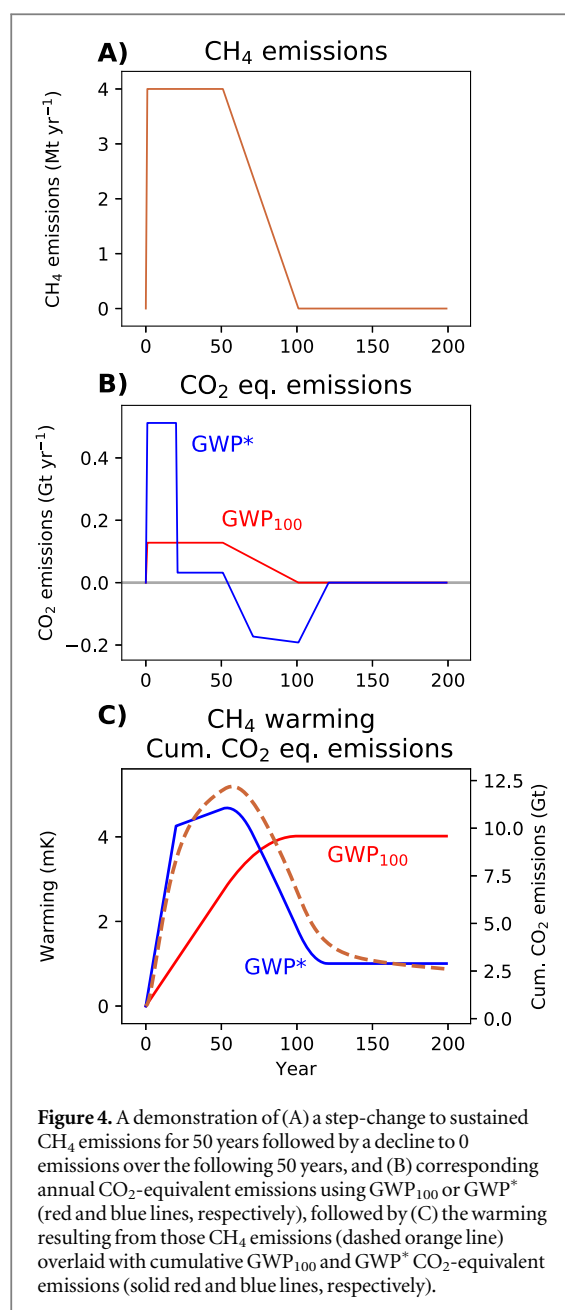
A simple coefficient, the TCRE (Transient Climate Response to cumulative carbon Emissions), can link cumulative CO<sub>2</sub> emissions and temperature as a result of their linear relationship [26, 27]. Not only can cumulative CO<sub>2</sub>-w.e. provide an indication of the shape of the warming profile, therefore, but also suggest a direct correspondence between the scale of emissions and warming. This is represented by the alignment of the two *y* axes in figure 3(c) (and every figure hereafter combining temperatures and cumulative emissions), which are scaled by a TCRE of 0.4 K per Tt CO<sub>2</sub> (1.52 K per Tt C). This TCRE was obtained by identifying the warming response to cumulative CO<sub>2</sub> emissions for RCP4.5 within the same FaIR set-up described above (see supplementary material). By expressing short-lived GHGs as a CO<sub>2</sub>-w.e. consistent with a 'cumulative carbon' framework, GWP\* thus provides a means of directly linking emissions of different gases to their resulting temperature impact through the TCRE.

GWP\*, as a simple metric reliant on assumptions of linearity inherent in the GWP, cannot capture the full complexities of the climate response that alternative approaches may be able to, such as CO<sub>2</sub>-forcing-equivalents [25], the CGTP and CGWP [14], or comprehensive modelling of the climate system. Consequently, the match between cumulative CO<sub>2</sub>-w.e. emissions ( $\times$ TCRE) and warming is not exact (and in this case the underestimation of warming may reflect, among other dynamics, an increase in the radiative efficiency of methane over this period expected as wider global methane concentrations fall under RCP4.5 [28]), while a fixed GWP was used here. There will remain applications where more complex methods are preferred, but the ease of calculating GWP\* will likely prove a significant advantage for many purposes.

Both GWP<sub>100</sub> and GWP\* CO<sub>2</sub>-equivalents and the methane temperature response approximately correspond at 100 years (previously noted in [29, 30] and [31], observing that the sustained Global Temperature change Potential (sGTP)—that is, the temperature change following sustained emissions over a given period—is close to the GWP). This means that, looking back over 100-years of an introduced then sustained emission, GWP<sub>100</sub> could also provide an appropriate indication of the total warming over this period; but otherwise can provide only limited inference. This correspondence is only the case for newly-introduced emissions subsequently sustained at the same rate over this period, and only at approximately 100 years: GWP<sub>100</sub> would understate the total warming impact of sustained emissions before this point, and increasingly overstate the impacts after it. Even within this 100-year period, given that most of the warming occurs in the first few decades of the sustained methane emission, GWP<sub>100</sub> will still overstate the annual contribution to warming at any point after this initial period. For example, if we are in year 30 of this scenario, the bulk of the warming that will result from this sustained methane emission is already experienced (the scale and speed of this warming greatly undervalued by GWP<sub>100</sub>), so from this point onwards GWP<sub>100</sub> would provide an exaggerated estimate of how much additional warming to expect, and hence provide little insight in anticipating future temperatures increases (or associated climate impacts).

Once again, the scenario in which emissions start to decline further emphasises how differently the two gases behave (figure 4). As methane emissions decline, GWP<sub>100</sub> CO<sub>2</sub>-e emissions also decline, but they stay positive (figure 4(b)), which, by comparison with the behaviour of CO<sub>2</sub>, can only indicate a slowing of the resultant warming until emissions reach 0 (as shown in figure 2), at which point the temperature would be expected to remain at this elevated level (figure 4(c)).

Using GWP\*, the annual CO<sub>2</sub>-w.e. emissions profile is more complex (figure 4(b)), as the 20 year reference period tracks across various transitions in the



methane emissions profile, but crucially, in the period of declining methane emissions CO<sub>2</sub>-w.e. emission are negative (i.e. representing a removal of CO<sub>2</sub> from the atmosphere). Figure 4(c) shows how this is essential to capture the temperature impacts of this methane emissions pathway: the automatic reversibility of most methane warming once the emissions are reduced or removed can only be described by a negative CO<sub>2</sub>-equivalent, and so there is no real correspondence between the impact of this methane scenario and cumulative GWP<sub>100</sub> CO<sub>2</sub>-e.

It must be emphasized that during the period of declining methane emissions, using GWP<sub>100</sub> does not even indicate the correct direction of temperature change. The improvement achieved by using GWP\* is therefore not simply a slight refinement to the shape of the warming profile or a better scaling of cumulative emissions to temperature under a given TCRE: it

captures the fundamentally different behaviour of short- and long-lived climate pollutants, which is essential to provide even a broad indication of the impacts of ambitious mitigation strategies [32].

### 3.3. Key principles and special cases of GWP\*

To further highlight some of the important elements described by GWP\*, we now explore a number of shorter-term emission scenarios.

As noted above, GWP<sub>100</sub> can variously over- or under-state the impact of methane emissions depending on the historic trajectory of these emissions, which may not be known. Here we show how application of GWP\*, using the previous 20 years but no further, still gives a useful indication of anticipated temperature change. We also focus on a 50 year period to demonstrate that GWP\* provides a much improved indication of short- and medium-term impacts, and is not relevant only for the longer (200 year) scenarios shown above.

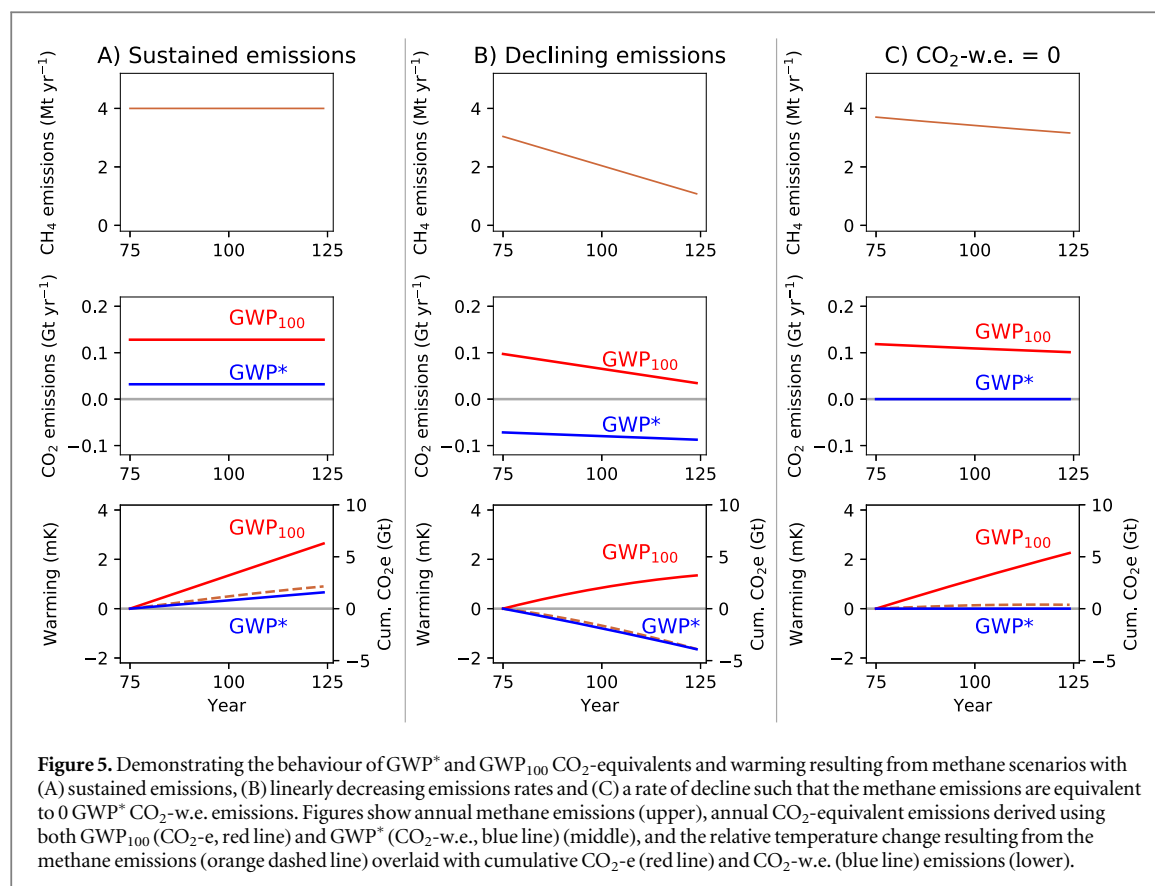
Since most policy scenarios involve some prior methane emissions, we need to include these to show various dynamics that include decreases in emission rate, or incorporate behaviours that emerge in the longer term, and so all of the scenarios shown occur following 50 years of an introduced and then sustained methane emission, building on the examples above. We then change methane emissions to a new demonstrative trajectory, and after 25 years of this change, show the warming response and both CO<sub>2</sub>-equivalent emissions (hence these figures start from 'year 75'). See supplementary material for further description of this approach, including an illustration in figure S4.

#### 3.3.1. Stable and declining methane emissions

We begin by considering scenarios with stable or declining methane emissions (figure 5). For ongoing stable methane emissions (figure 5(a)), the CO<sub>2</sub>-equivalent quantity is a constant annual emission under both GWP<sub>100</sub> and GWP\*, but GWP\* CO<sub>2</sub>-w.e. is much less than GWP<sub>100</sub> CO<sub>2</sub>-e ( $\times 0.25$ , following (2) with the suggested  $s$ ), and cumulative CO<sub>2</sub>-w.e. ( $\times$ TCRE) a much better match for the modelled warming. Consequently, if we sought to offset the continued warming from long-term stable methane emissions by annually sequestering an appropriate amount of CO<sub>2</sub> derived using the GWP<sub>100</sub> (i.e. a 'net-zero emissions' policy using GWP<sub>100</sub>), we would overstate the impacts of this methane and result in cooling, rather than temperature stabilisation [33, 34].

For declining methane emissions rates (figure 5(b)), the key point is as noted above: the falling temperatures under this scenario are equivalent to a removal of atmospheric CO<sub>2</sub>, as described using GWP\* (unless the rate of decline in methane emissions is very gradual, see below). Under conventional use of GWP<sub>100</sub>, it is only possible to equate any ongoing methane emissions at all to a positive CO<sub>2</sub> emission,





**Figure 5.** Demonstrating the behaviour of GWP\* and GWP<sub>100</sub> CO<sub>2</sub>-equivalents and warming resulting from methane scenarios with (A) sustained emissions, (B) linearly decreasing emissions rates and (C) a rate of decline such that the methane emissions are equivalent to 0 GWP\* CO<sub>2</sub>-w.e. emissions. Figures show annual methane emissions (upper), annual CO<sub>2</sub>-equivalent emissions derived using both GWP<sub>100</sub> (CO<sub>2</sub>-e, red line) and GWP\* (CO<sub>2</sub>-w.e., blue line) (middle), and the relative temperature change resulting from the methane emissions (orange dashed line) overlaid with cumulative CO<sub>2</sub>-e (red line) and CO<sub>2</sub>-w.e. (blue line) emissions (lower).

suggesting continuing warming at odds with the real temperature response.

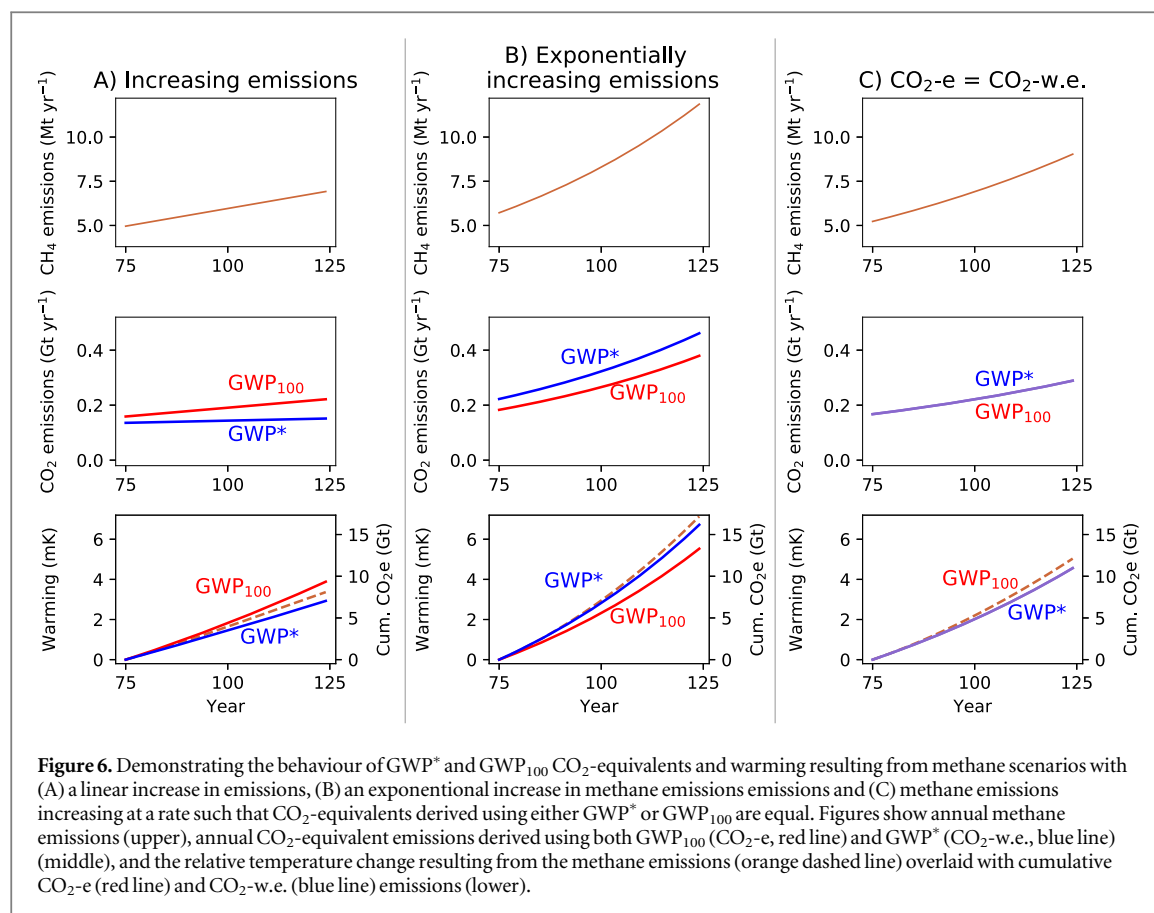
We can consider a special case where the decline in methane emissions rate is such that it is described by 0 GWP\* CO<sub>2</sub>-w.e. emissions (figure 5(c)). This can be achieved through an annual decline in methane emissions of approximately 0.3% per year (for the  $r$  and  $s$  values suggested above, see supplementary material for derivation). As shown (figure 5(c)-lower), this scenario results in negligible additional warming despite ongoing, relatively high, methane emissions. Meanwhile, the large ongoing GWP<sub>100</sub> CO<sub>2</sub>-e emissions would lead to significant continued temperature increases. A key point emerges which is obscured by conventional use of GWP<sub>100</sub>: to prevent further warming, it is necessary that net CO<sub>2</sub> emissions are reduced to zero, but this is not the case for methane, where it is possible to have climatically sustainable ongoing emissions.

Any decline in methane emissions rate faster than the 0.3% p.a. decline noted above suggests cooling relative to the current temperature (figure 5(b), see [16] for discussion of the physical origin and uncertainty in this rate of decline). This is broadly the role of methane in ambitious mitigation pathways, where significant, permanent, reductions in methane emission rates can permit the emissions of a fixed amount of extra CO<sub>2</sub>, and hence the additional long-term warming it will cause, under a given temperature ceiling [35, 36]. This concept is explored further below when

demonstrating the use of GWP\* to assess alternative mitigations.

It should be noted that these stable or declining temperatures are relative to present temperatures, as already experienced; not relative to before the emission was introduced. (i.e. for individual temperature subplots in figures 5 and 6, warming and cumulative CO<sub>2</sub>-equivalents are both from 0 in year 75, setting this as our reference point, but comparison with figure S4 (supplement) shows that this temperature is +5.3 mK relative to before the methane emission was introduced.) Long-term methane emitters therefore still have a warming legacy, and their continued emissions sustain elevated temperatures. It could thus be argued that, despite being able to achieve no additional warming through relatively small mitigations, continued methane emitters still have a responsibility to decrease emissions and mitigate climate change as much as possible, akin to holding countries responsible for their national contribution to observed global warming [37]. Where historical emissions are known, cumulative GWP\* CO<sub>2</sub>-w.e. emissions to date can be used to indicate this responsibility, while annual GWP<sub>100</sub> CO<sub>2</sub>-e, the basis of most policy targets, cannot.

But given that any CO<sub>2</sub> emissions yield continued warming, by communicating emissions and designing strategies based primarily on reductions to ongoing annual CO<sub>2</sub> emissions, there is an implicit baseline of no further CO<sub>2</sub> emissions and hence no additional warming (particularly in relation to a stated ambition



of net-zero CO<sub>2</sub> emissions). Alternatively, if we considered an emissions-accounting framework that did reflect total warming contribution, and could describe responsibilities to reverse warming rather than just encourage no further temperature increases, the baseline for CO<sub>2</sub> emitters would not just be their current or recent annual CO<sub>2</sub> emission rates, but total cumulative CO<sub>2</sub> emissions to date, and they would have a responsibility to sequester carbon and reverse historic contributions, rather than simply reduce ongoing emissions. GWP\* could provide a means to account for different gases within such a framework, setting climatically meaningful responsibilities for diverse sectors producing distinct emissions. Meanwhile, using annual GWP<sub>100</sub> CO<sub>2</sub>-emission rates, as is common at present, results in a lack of clarity on the different historical warming contributions between sectors or the distinct climate outcomes of reducing emissions of different gases.

### 3.3.2. Increasing methane emissions

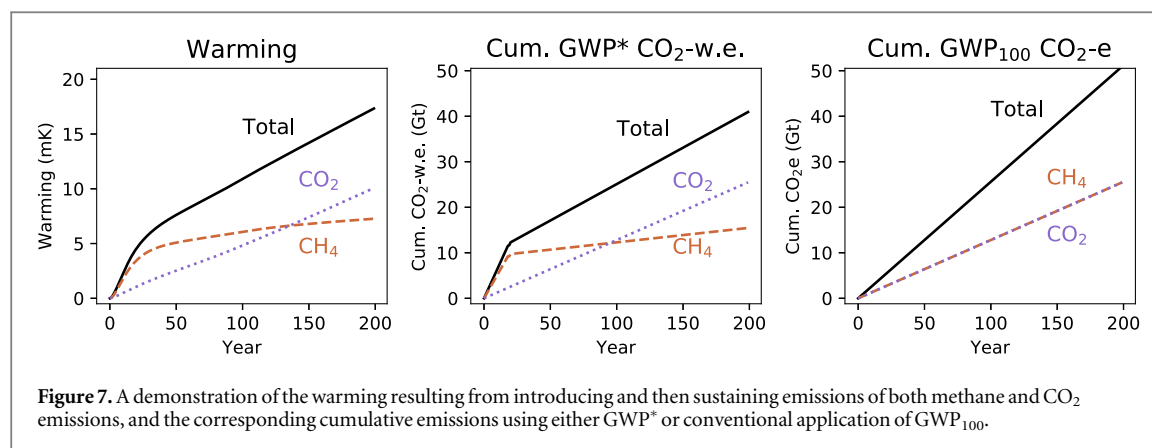
Next, we consider increases in methane emissions (figure 6; note the change in scales to expand the upper limits from figure 5). A linear increase in methane emissions (figure 6(a)) is represented by a relatively constant CO<sub>2</sub>-w.e. emission over time, as the change in rate of methane emissions  $\frac{\Delta E_{SLCP}}{\Delta t}$ , is stable, which translates to a mostly linear increase in temperatures. Conventional use of GWP<sub>100</sub>, however, implies a linear increase in the rate of CO<sub>2</sub>-e emissions,

corresponding to a more strongly exponential temperature increase.

(Note that for this period, the real temperature response lies approximately between the illustrated cumulative GWP\* and GWP<sub>100</sub> CO<sub>2</sub>-equivalents, but figure S5 in the supplementary materials below reveals that the more linear fit for GWP\* CO<sub>2</sub>-w.e. is a much better match over the longer-term.)

In all of the 50 year scenarios described thus far, GWP<sub>100</sub> CO<sub>2</sub>-e has been greater than GWP\* CO<sub>2</sub>-w.e., but this is not a universal feature of GWP\*. For an exponential increase in methane emissions, as shown in Fig 6, GWP\* will appropriately describe the methane emissions as a greater CO<sub>2</sub>-equivalent quantity than GWP<sub>100</sub> (see also the large initial GWP\* CO<sub>2</sub>-w.e. for introducing a methane emission shown in figures 3 and 4).

Under both of these scenarios of increasing methane emissions the CO<sub>2</sub>-equivalent emissions from GWP<sub>100</sub> are closer to those derived using GWP\*, and consequently the actual warming from methane, than the stable and declining emissions scenarios. Another interesting case in this context is where methane emissions increase at a rate such that both GWP<sub>100</sub> and GWP\* CO<sub>2</sub>-equivalents are consistently equal (i.e. GWP CO<sub>2</sub>-w.e. = GWP<sub>100</sub> CO<sub>2</sub>-e, figure 6(c)), which occurs under an exponential increase in methane emission rates of approximately 1% per year for the coefficient values suggested above (see supplementary material for derivation). If



methane emissions increase at greater than 1% per year, GWP\* CO<sub>2</sub>-w.e. will therefore be greater than GWP<sub>100</sub> CO<sub>2</sub>-e, but vice versa if the increase is less than 1% per year.

### 3.4. Cumulative GWP\* CO<sub>2</sub>-w.e. emissions and timing of emissions reductions

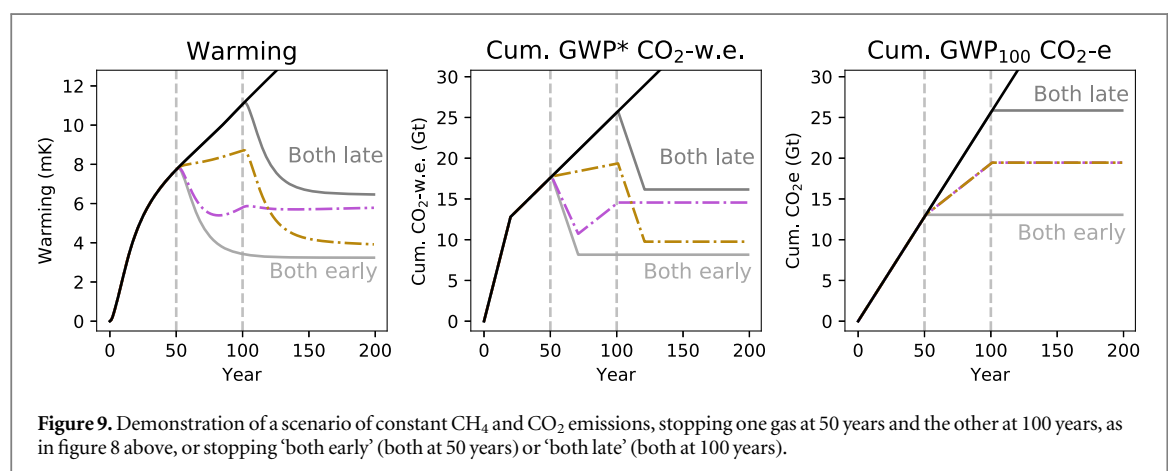
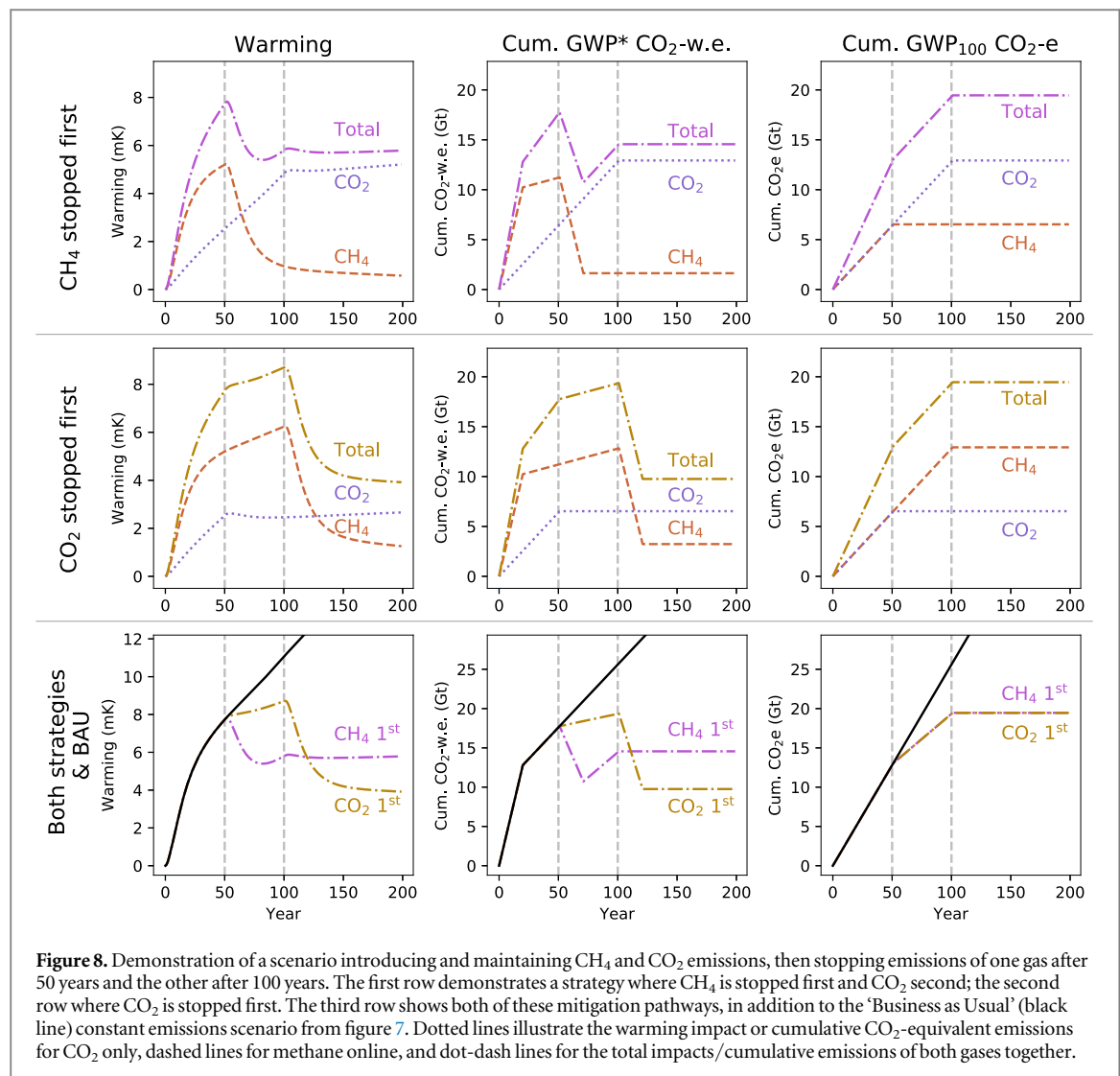
Finally, we build on the principles and demonstrations above to provide a simple example of how GWP\* can be used to better appraise GHG mitigation strategies. These mitigations are made to a baseline multi-gas scenario (figure 7), where emissions of both methane and CO<sub>2</sub> are introduced and then maintained at the annual emission rates used in figure 1. This scenario leads to a rapid initial increase in warming, primarily from the methane, followed by a slower temperature increase driven predominantly from the consistent rate of CO<sub>2</sub>-induced warming. Summing the two sets of cumulative CO<sub>2</sub>-w.e. emissions provides an approximation of this, while the two sets of cumulative CO<sub>2</sub>e emissions suggest they have the same linear impacts, and so the total is simply a greater rate of linear increase.

We can demonstrate the utility of multi-gas cumulative CO<sub>2</sub>-w.e. totals in a decision making context by considering how they would describe alternative mitigation pathways, as in figure 8. In this scenario, the emissions of one gas cease in year 50, and then the emissions of the remaining gas in year 100. Stopping methane first results in a large initial reversal of recent warming, but temperatures then start to rise again due to the ongoing CO<sub>2</sub> emissions. Temperature then stabilises at the temperature reached in year 100 when CO<sub>2</sub> emissions are also stopped. Stopping CO<sub>2</sub> first, we see that the rate of warming declines, and then when methane emissions stop in year 100 we have a significant reversal of warming, stabilising at a lower long-term temperature than in the methane-first scenario. Cumulative CO<sub>2</sub>-w.e. provides a clear indication of these dynamics, while cumulative CO<sub>2</sub>e suggests either strategy would lead to the same response, but which represents neither scenario.

These two strategies illustrate an important principle: that focussing on methane at the expense of (a

GWP<sub>100</sub> equivalent quantity of) CO<sub>2</sub> is not simply a prioritisation of short- over long-term impacts, it is a trade-off. There is a large initial benefit (indeed, a significant reversal of total warming, in this scenario) from focussing on methane, but the more that action on CO<sub>2</sub> is postponed, the higher the temperature that we are locked in to. Consequently, reducing methane emissions, though beneficial, does not ‘buy time’ for delayed CO<sub>2</sub> mitigation in the sense that it provides an equivalent pathway to acting on CO<sub>2</sub>. It is universally better to stop CO<sub>2</sub> emissions early, as the sooner they are stopped, the sooner they stop compounding and the less CO<sub>2</sub>-induced warming we are committed to for the very long-term [38]. Rather, the negative CO<sub>2</sub>-w.e. generated by *permanently reducing methane emission rates* expands the allowable space for emissions of cumulative GHGs within a total [CO<sub>2</sub>-w.e.] emissions budget, and hence permits a greater *one-off fixed quantity* of CO<sub>2</sub> emissions under a given temperature ceiling. The inverse implication is that the longer we fail to decarbonise, and hence add to the cumulative stock of CO<sub>2</sub> emitted, then the smaller the permissible rate of ongoing, sustainable methane emissions within a given emissions budget (and hence also a given temperature ceiling). In this context, it is worth noting that annual fossil fuel CO<sub>2</sub> emissions were the highest ever in 2019 and predicted to continue increasing in 2020 [39].

We can complete the range of scenarios in this framework by adding the cases where we stop emissions of both gases earlier or later figure 9. As should be self-evident, the climatically optimum strategy is to reduce emissions of any greenhouse gases as early as possible. Stopping both gases early results in rapid cooling from the cessation of methane emissions, and also prevents the ongoing temperature increases that would occur from sustained CO<sub>2</sub> emissions. The scenario in which both emissions are stopped later highlights a further implication of the principles described above: while the point at which methane emissions are stopped can have an important impact on peak warming (so long as CO<sub>2</sub> are also stopped contemporaneously or shortly afterwards), as most of the warming impact of methane depends on the rate of emissions, it is largely time-independent. Delaying action on methane does



not have as significant an impact on long-term temperature as delaying action on CO<sub>2</sub> emissions; the eventual temperature we remain committed to, once both emissions are stopped, is predominantly determined by the timing of CO<sub>2</sub> mitigation.

The 'stock' component, representing the long-term temperature adjustment to methane emissions,

is still important, and the scale of contemporary methane emissions is such that this element could equate to a significant increase in total allowable CO<sub>2</sub> emissions for warming of 1.5° C if action is taken on methane earlier rather than later [35], but by a much smaller amount than the direct GWP<sub>100</sub> equivalence between methane and CO<sub>2</sub> would suggest.

## 4. Concluding remarks

CO<sub>2</sub>-equivalents have become a near-universal means of reporting greenhouse gas emissions, and in many cases are used to directly infer their climate impacts or role in mitigation strategies—even if such an expansive application was never intended. Given this, it is important to have a means of deriving CO<sub>2</sub>-equivalents that provides a reliable link between reported emissions and their warming impacts. As demonstrated, in many cases conventional use of GWP<sub>100</sub> does not achieve this, while GWP\* does.

Using GWP<sub>100</sub> to direct climate change mitigation strategy could be unfair, inefficient, and dangerous. Unfair, as it does not provide a clear link between emissions and climate change contribution, and could lead to an expectation that some actors (long-term methane emitters) have to undo their past warming, while others (CO<sub>2</sub> emitters) merely have to limit further temperature increases. Inefficient, as it would overstate the level of action needed to offset long-term sustained methane emissions, while simultaneously undervaluing the potential short-term benefits of reducing these methane emissions. Dangerous, as it can greatly understate the impacts of increasing methane emissions, and obscure the fundamental need for net-zero CO<sub>2</sub> emissions as soon as possible, regardless of what mitigations are made to shorter-lived climate pollutants.

There is an additional danger, which is to the perceived environmental integrity of climate policy. Basing climate policies and emission trading systems on a metric that demonstrably fails to reflect the impact of different emissions on global temperature, while at the same time claiming these are designed to deliver a long-term temperature goal, risks undermining confidence in the entire strategy. GWP\* provides a straightforward means of dealing with these issues, calculating genuinely warming-equivalent emissions using information that is already being reported in the UNFCCC system.

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## Data availability statement

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

background emissions data used are as described in [20], and can be found at <https://github.com/OMS-NetZero/FAIR>.

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