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Further improvement of warming-equivalent emissions calculation

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GWP* was recently proposed[1] as a simple metric for calculating warming-equivalent emissions by equating a change in the rate of emission of a short-lived climate pollutant (SLCP) to a pulse emission of carbon dioxide. Other metrics aiming to account for the time-dependent impact of SLCP emissions, such as CGWP, have also been proposed[2]. In 2019 an improvement to GWP* was proposed by Cain et al.[3], hereafter CLA, combining both the rate and change in rate of SLCP emission, justified by the rate of forcing decline required to stabilise temperatures following a recent multi-decade emissions increase. Here we provide a more direct justification of the coefficients used in this definition of GWP*, with a small revision to their absolute values, by equating CO_2 and SLCP forcing directly, without reference to the temperature response. This provides a more direct link to the impulse-response model used to calculate GWP values and improves consistency with CGWP values.

The formula for CO_2-warming-equivalent emissions using GWP* in CLA is:

$$E^*(t) = \frac{(1-s)H\Delta E(t)}{\Delta t} + sE(t), \tag{1}$$

where $E(t)$ are CO_2-equivalent emissions defined using GWP with a time-horizon H, much longer than the SLCP lifetime, and s was a coefficient introduced by CLA and estimated by reproducing the response to a simple climate model to various emission scenarios. $\Delta E(t) = E(t) - E(t - \Delta t)$, the change in emissions over a recent time period Δt. Twenty years has been used in implementations of GWP* to date[1,3] and appears to work well for methane (here we explain why this is the case).

Setting $E^*(t)$ to zero in Eq. (1) shows the ratio $s/[H(1-s)]$ defines the decay rate of SLCP emissions required to have the same warming impact as zero CO_2 emissions. CLA justify a value of 0.33% per year, giving $s = 0.25$ for $H = 100$ years, as the decline rate required to give stable temperatures under typical values of the Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR). They further justify this formulation using the constraint that total CO_2-warming-equivalent emissions over H years corresponding to a steady emission of an SLCP starting in year zero should be equal to total CO_2-equivalent emissions over the same period, arguing that equal constant CO_2-equivalent emissions give, by construction, the same forcing at the GWP time-horizon, and redistributing CO_2 emissions over time has minimal impact on final warming. An advantage of the above formula is that it involves no new model-dependent coefficients other than s.

Although confirmed by fitting the warming response to methane emissions in an explicit climate model, this justification is not entirely satisfactory: if the aim is to produce a CO_2 emissions series that generates the same forcing trajectory as that generated by the SLCP, there should be no need to invoke the warming response. The relationship between CO_2-warming-equivalent emissions and radiative forcing should, by construction, replicate the relationship between CO_2 emissions and radiative forcing.

We can focus on timescales of 30–200 years, on the grounds that on shorter timescales the temperature response is dominated by internal variability[4], so exact reproduction of forcing timeseries is irrelevant, while 200 years captures at least the initial cumulative impact of CO_2 emissions. By restricting the timescale of interest, CO_2 emissions and radiative forcing can be approximately related by the first-order equation:

$$\alpha E_{CO2}(t) = \frac{dF(t)}{dt} + \rho F(t), \tag{2}$$

where ρ is the rate of decline of radiative forcing over these timescales under zero emissions, and α is a constant representing the forcing impact of ongoing CO_2 emissions. In terms of the linear impulse-response model used to provide GWP values in AR5[5,6], this formulation assumes the short adjustment timescales are fully equilibrated and neglects the very long cumulative timescale, in effect fitting an exponential to the mid-range impulse-response function. As we show below, this turns out to be a surprisingly good approximation.

We express α in familiar terms by noting that the forcing response after H years to steady CO_2 emissions of 1 kg per year, starting in year 0, is by definition the Absolute Global Warming Potential of CO_2, or $AGWP_H$ (this is identical to the standard definition[5,6] because the calculation of $AGWP_H$ values is based on a linear model). Hence, integrating equation (2) for $E_{CO2} = 1$

$$F(H) = AGWP_H = \alpha \frac{(1 - e^{-\rho H})}{\rho}. \tag{3}$$

So $\alpha = AGWP_H \rho (1 - e^{-\rho H})^{-1}$, or 1.08 W m^{-2} per 1000 $GtCO_2$ with $\rho = 0.33\%$ per year, $H = 100$ years and the AR5 value[5] of $AGWP_{100}$ of 91.7 W-years m^{-2} per 1000 $GtCO_2$. With these coefficients, this expression (solid black line in Fig. 1) reproduces the forcing response to constant unit CO_2 emissions computed using the full impulse-response model used for GWP calculations in AR5 (solid red line) accurately over multi-decade to century timescales. Decreasing ρ (dotted line) causes the fit to deteriorate on all timescales, since it fails to capture the curvature of the AGWP as a function of H, while increasing ρ (dashed line) causes

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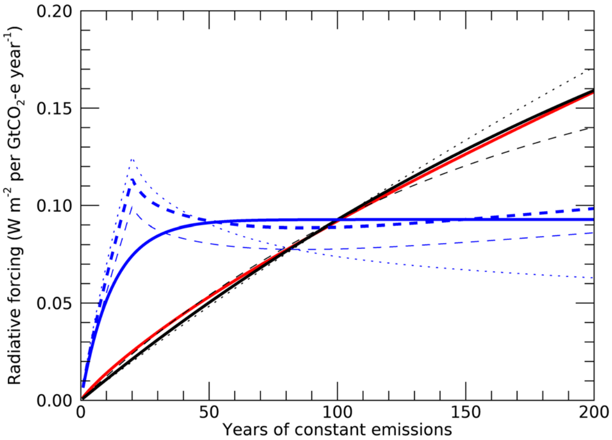

Fig. 1 Radiative forcing due to constant 1 $GtCO_2$ per year CO_2 emissions (red) and 1 $GtCO_2$-e per year (using GWP_{100}) methane emissions (blue solid line) calculated using Absolute Global Warming Potentials given in AR5. Black lines show exponential approximation to the CO_2 forcing with $s = 0.25$ (solid), $s = 0.143$ (dotted) and $s = 0.4$ (dashed), implying a forcing decay rate ρ of 0.33%, 0.167% and 0.67% per year, respectively, for zero CO_2 emissions. This exponential decay rate in forcing is equivalent to assuming a simple exponential decay of CO_2 emissions following a pulse emission, a simplification of the linear CO_2 decay model used in AR5[6], focussing on intermediate timescales. Thick blue dashed line shows forcing due to CO_2 warming-equivalent emissions calculated using the coefficients provided in this note (4.53 $GtCO_2$ per year for 20 years, followed by 0.28 $GtCO_2$ per year), while thin dashed and dotted lines show, respectively, corresponding forcing using coefficients provided in Cain et al. (2019) (4 $GtCO_2$ per year for 20 years, followed by 0.25 $GtCO_2$ per year) and Allen et al. (2018) (5 $GtCO_2$ for 20 years, followed by zero, corresponding to $s = 0$). Comparing the blue dashed lines show how including the factor $g(s) > 1$ increases the estimated forcing due to methane emissions relative to CO_2 under GWP*.

the fit to deteriorate on greater than 100-year timescales, by failing to capture the cumulative impact of CO_2 emissions. Clearly there is an element of subjectivity inherent in all metric approximations as to what constitutes a 'good enough' approximation, but the above expression with $\rho = 0.33\%$ per year appears to capture the forcing response to constant CO_2 emissions very well, and certainly well within the uncertainties of the climate and carbon cycle response[6]. Defining an 'optimal' value of ρ depends on the choice of goodness-of-fit statistic: we focus here on reproducing the absolute forcing per tonne of CO_2 as plotted in Fig. 1. This is most relevant to expressing forcing changes in terms of cumulative CO_2 emissions, and represents the time-integral of the forcing impulse-response function. Using a higher value of ρ gives better agreement on short timescales at the expense of downplaying the cumulative impact of CO_2 emissions, and vice versa. The fact that the value of ρ implied by the time-dependence of the AGWP coincides with the value implied by the ECS and TCR in CLA is the reason net zero CO_2 emissions is expected to be consistent with no further CO_2-induced warming, and a further reason to use a consistent value.

Using the substitution $\rho = s/[H(1-s)]$ we can re-express Eq. (2) in a form similar to Eq. (1):

$$E_{CO2}(t) = E^*(t) = \frac{g(s)}{\mathrm{AGWP}_H}\left[H(1-s)\frac{dF(t)}{dt} + sF(t)\right], \quad (4)$$

where

$$g(s) = \frac{1-\exp(-s/(1-s))}{s}, \text{ so } \alpha = \frac{\mathrm{AGWP}_H}{Hg(s)(1-s)}. \quad (5)$$

The function $g(s)$ is approximately unity for small s, and is implicitly approximated to unity by CLA, but it actually has a value $g = 1.13$ for $s = 0.25$ and $H = 100$ years.

The radiative forcing due to a constant SLCP emission of 1 kg CO_2-equivalent per year starting in year 0 can be expressed:

$$F(t) = \mathrm{AGWP}_H\left(1 - e^{-t/\tau}\right) = \alpha Hg(s)(1-s)\left(1 - e^{-t/\tau}\right), \quad (6)$$

provided $\tau \ll H$, so $e^{-H/\tau} \ll 1$,where AGWP_H is the AGWP of CO_2 for the time-horizon used to evaluate CO_2-equivalent emissions and τ is the SLCP lifetime.

Substituting this into Eq. (4) gives an expression for the CO_2-warming-equivalent emissions corresponding to this constant SLCP emission:

$$E^*(t) = g\left[\left(\frac{H(1-s)}{\tau} - s\right)e^{-t/\tau} + s\right] \approx g\left[H(1-s)\frac{e^{-t/\tau}}{\tau} + s\right]. \quad (7)$$

Hence the CO_2-warming-equivalent emissions corresponding to this CO_2-equivalent SLCP emission are a constant gs kg per year plus an emission totalling of $gH(1-s)$ kg almost all of which occurs in the first ~2τ years (using $\int_0^\infty \left(e^{-t/\tau}/\tau\right)dt = 1$. GWP* approximates this pulse as a constant additional emission spread over the first Δt years, and explains why $\Delta t = 20$ years works for an SLCP with a lifetime of order one decade. The initial adjustment time of the solid blue curve in Fig. 1 is of this order: hence using 20 years approximately matches the initial gradients of the blue solid and dashed lines, which correspond to the instantaneous radiative forcing impact of the release of one tonne of methane relative to that of CO_2.

Hence a more consistent definition of CO_2-warming-equivalent emissions under GWP* is:

$$E^*(t) = g\frac{(1-s)H\Delta E(t)}{\Delta t} + gsE(t). \quad (8)$$

This is identical to that of CLA but scaled by $g = 1.13$ and now justified without reference to the temperature response. Including this scaling improves the consistency with simulated warming responses under ambitious mitigation scenarios, at the expense of consistency with warming responses under higher emissions, as shown in Fig. 2, which reproduces Fig. 1 of CLA but now including the scaling factor g. It appears that the reproduction of simulated warming under the higher emissions scenarios noted in CLA was coincidental: additional methane emissions have less warming impact per tonne if introduced into a higher background emission scenario, compensating for the use of $g = 1$ in the calculation of warming-equivalent emissions.

Given the approximations involved in greenhouse gas metrics in the first place, such as the choice of background emissions trajectory against which to linearise, it is debateable whether scaling factors of order 10% are worth any additional complexity. The parameter g, however, is an unambiguous function of s, not an additional tuneable parameter, so we propose that it should be included in the definition of GWP* for greater consistency with the linear models used for metric calculations. As these linear models are updated the forcing decay rate corresponding to zero CO_2 emissions will change, potentially resulting in a change in s; however, given the weak dependence seen in Fig. 1, any changes are likely to be small. Including g means that the expression for CO_2 warming-equivalent emissions of methane becomes $E^*(t) = 128 \times E_{CH4}(t) - 120 \times E_{CH4}(t-20)$, where E_{CH4} is methane emissions in tCH_4 per year, with AR5 GWP values. For a generic SLCP, $E^*(t) = 4.53 \times E_{100}(t) - 4.25 \times E_{100}(t-20)$, where E_{100} are CO_2-equivalent emissions calculated using GWP_{100}, with residual discrepancies due to rounding. A shorter than 20-year period might be better suited to representing shorter-lived climate pollutants, but given this choice has no impact on cumulative warming-equivalent emissions, we propose a consistent value is used for all SLCPs for simplicity.

DATA AVAILABILITY

The code to produce Figs 1 and 2 is available at https://gitlab.ouce.ox.ac.uk/OMP_climate_pollutants/co2-warming-equivalence.

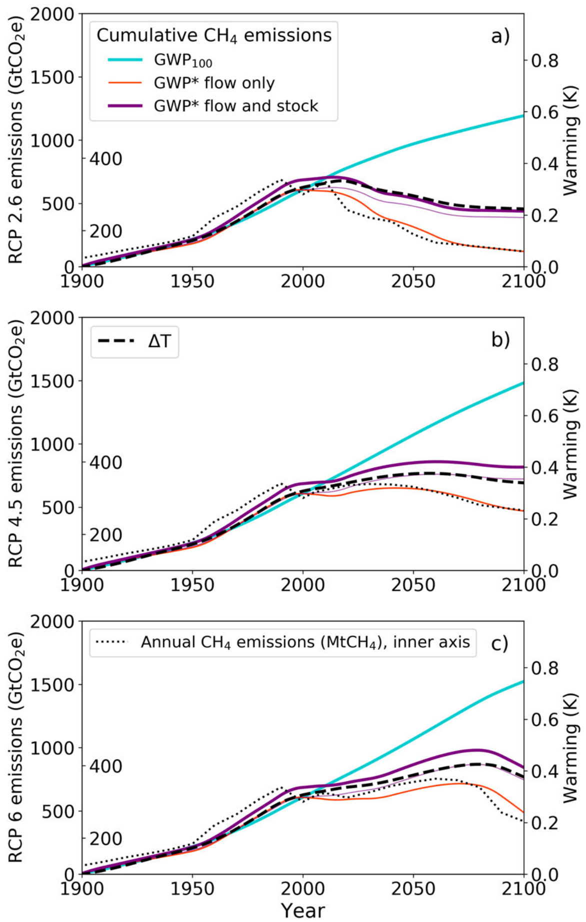

Fig. 2 A reproduction of Fig. 1 from CLA with scaling factor *g* applied to GWP* (purple solid lines). Cumulative emissions of methane are shown for three scenarios, (**a** RCP2.6, **b** RCP4.5 and **c** RCP6) aggregated using GWP_{100} (cyan), GWP* with s = 0 (orange), GWP* with s = 0.25 and g = 1.13 (purple solid), and GWP* with s = 0.25 and g = 1 (thin purple, largely hidden behind dashed black line in **b**, **c**).

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AUTHOR CONTRIBUTIONS

M.R.A. initiated the work with M.A.S. and M.C. developing the work to bring it to submission. M.R.A. produced Fig. 1. M.C. produced Fig. 2. All authors contributed to developing the scientific questions, discussion of the results, subsequent drafts of the paper and in editing the final version.

COMPETING INTERESTS

M.C. and M.R.A. are both authors of "Improved calculation of warming-equivalent emissions for short-lived climate pollutants".

ADDITIONAL INFORMATION

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