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:

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

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. 20 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 equation (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 on 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:

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

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.

We express α in familiar terms by noting that the forcing response after H years to steady CO_2 emissions of 1kg 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 $E_{\mathrm{CO2}} = 1$

$$F(H) = \mathrm{AGWP}_H = \alpha \frac{(1 - e^{-\rho H})}{\rho}\,. \tag{3}$$

So $\alpha = \mathrm{AGWP}_H \rho (1 - e^{-\rho H})^{-1}$, or 1.08 W/m^2 per 1,000 $GtCO_2$ 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 1,000 $GtCO_2$. With these coefficients, this expression (solid black line in figure 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 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].

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

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

where

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

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.

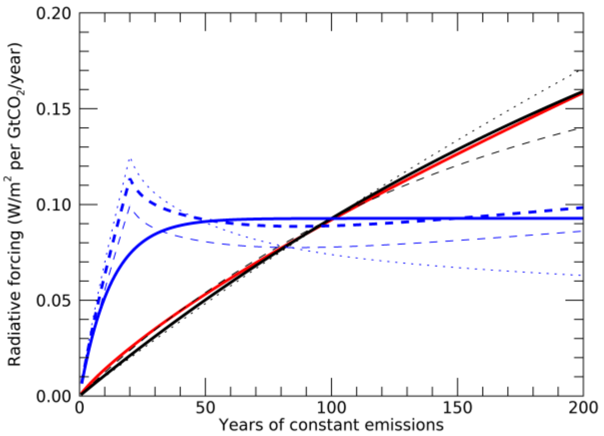

Figure 1: Radiative forcing due to constant 1 $GtCO_2$ per year CO_2 emissions (red) and 1 $GtCO_2$-e/year (using GWP_{100}) methane emissions (blue solid line) calculated using Absolute Global Warming Potentials given in AR5. Black lines show exponential approximation to the CO_2 forcing with $s = 0.25$ (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. Thick blue dashed line shows forcing due to CO_2 warming-equivalent emissions calculated using the coefficients provided in this note (4.53 $GtCO_2$/year for 20 years, followed by 0.28 $GtCO_2$/year), while thin dashed and dotted lines show, respectively, corresponding forcing using coefficients provided in Cain et al (2019) (4 $GtCO_2$/year for 20 years, followed by 0.25 $GtCO_2$/year) and Allen et al (2018) (5 $GtCO_2$ for 20 years, followed by zero, corresponding to $s = 0$).

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

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

provided $\tau \ll H$, so $\mathrm{e}^{-H/\tau} \ll 1$, 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 equation (4) gives an expression for the CO_2-warming-equivalent emissions corresponding to this constant SLCP emission:

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

Hence the CO_2-warming-equivalent emissions corresponding to this CO_2-equivalent SLCP emission are a constant gs kg/year plus a pulse of $gH(1-s)$ kg concentrated in the first $\sim 2\tau$ years (using $\int_0^\infty \left(\mathrm{e}^{-t/\tau}/\tau\right)dt = 1$). GWP* approximates this pulse as a constant additional emission spread over the first Δt years, and explains why $\Delta t = 20$ years works for a SLCP with a lifetime of order one decade. Hence a more consistent definition of CO_2-warming-equivalent emissions under GWP* is

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

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 figure 2, which reproduces figure 1 of CLA but now including the scaling factor g. This is understandable because the linear response model used for metric calculations is itself based on a very ambitious "mitigation scenario" (constant composition).

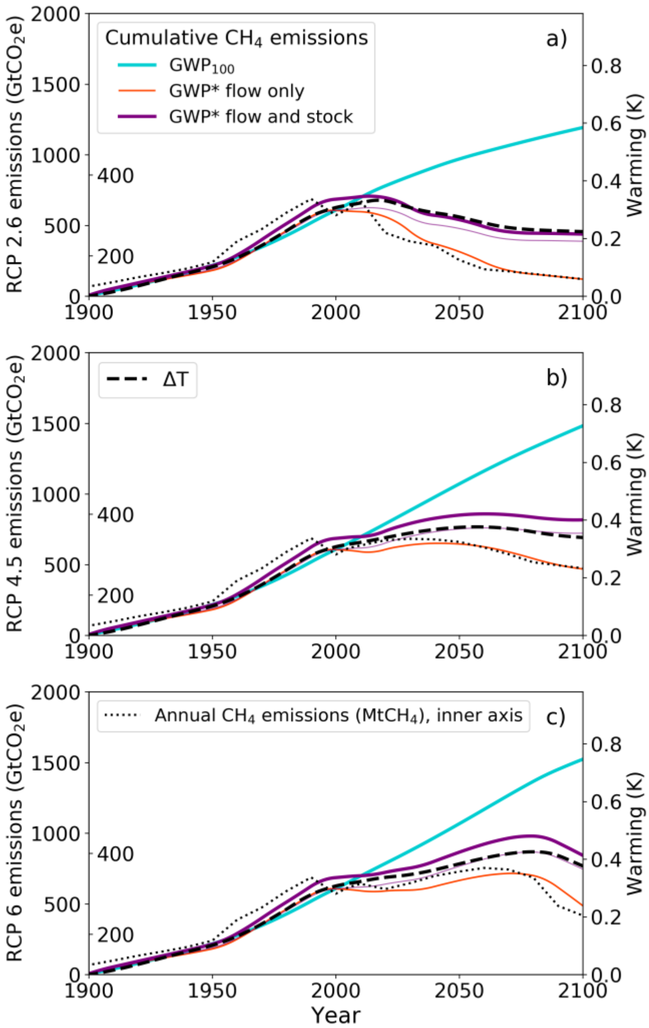

Figure 2: A reproduction of figure 1 from CLA with scaling factor g applied to GWP* (purple solid lines). Cumulative emissions of methane are shown for three scenarios (RCP2.6, RCP4.5 and RCP6) aggregated using GWP_{100} (cyan), GWP* with s=0 (orange), GWP* with s=0.25 and g=1.13 (purple solid), and GWP* with s=0.25 and g=1 (thin purple).

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 figure 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.

Data Availability

https://github.com/mosssmith/Further-Improvement-GWP-Star

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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 Figure 1. M. C. produced Figure 2. All authors contributed to developing the scientific questions, discussion of the results, subsequent drafts of the paper and in editing the final version.

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