**Accounting for non-CO2 forcing in outstanding carbon budgets**

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**A simple and model-independent way of estimating the remaining carbon budget to a given temperature threshold would help inform national emissions policies and stocktakes of progress towards a long-term temperature goal. Recent work on greenhouse gas metrics has focussed on implications for short-lived climate pollutants, but also has implications for estimating remaining carbon budgets1–4. Here, we discuss these implications and introduce an additional term that improves accuracy and clarity without substantially increasing complexity. This provides a simple, quantitative and model-independent interpretation of the statement that “the maximum temperature reached is then determined by cumulative net global anthropogenic CO2 emissions up to the time of net zero CO2 emissions, and the level of non-CO2 radiative forcing in the decades prior to the time that maximum temperatures are reached”.**

A number of papers recently have discussed the use of a simple relationship to estimate the remaining CO2 budget to a given level of warming.1,5 Leach *et al.* (2018) provide a carbon budget based on future warming arising entirely from CO2 emissions which represents an upper limit assuming a net-positive non-CO2 forcing contribution between now and peak warming. This is a robust assumption since even in the most ambitious mitigation scenarios the non-CO2 forcing continues to increase in the near-term because of a reducing aerosol atmospheric burden.6 Leach et al (2018) note further that an estimate of the actual carbon budget, rather than an upper bound, can be provided by assuming a constant fractional contribution of non-CO2 forcing to warming. This is of limited use because although CO2 and non-CO2 forcing have been correlated to date, they evolve very differently in ambitious mitigation scenarios.

Allen *et al.* (2018) go one step further in using the TCRE relationship to determine the warming contribution for a given quantity of cumulative CO2 emissions (the first term in equation 1 below), whilst accounting for the warming contribution from non-CO2 forcing using the first order approximation that the warming response will depend on both the transient climate response (TCR) parameter and the change in non-CO2 forcing between now and the time of peak warming (the second term in equation 1 below). In Leach *et al.* (2018) figure 2a shows the capability of their zeroth order budget calculation, where only CO2 emissions are considered. The remaining warming correlates but doesn’t predict the remaining CO2 emissions exactly because of the neglected non-CO2 forcing contribution. Allen *et al.*’s figure 1c shows a better accounting for this non-CO2 forcing—a more TCRE-like relationship exists between cumulative emissions and peak warming value than in Leach’s figure 2a. This means the ability to predict the remaining CO2 emissions to a given warming threshold is improved compared to Leach et al.’s treatment and is shown to be better than other often-used metrics for greenhouse gas (GHG) comparisons such as GWP.

However, in Allen *et al.*’s paper only the fast-response timescale of the climate system to the non-CO2 contribution (TCR) was considered. A constant non-CO2 forcing between now and the time of peak warming would have no impact on estimated carbon budgets using their expression. While this is correct to first order, the climate system will still be adjusting to a constant radiative forcing assuming it results from an increase within the past couple of centuries. Cain et al (2019) introduce an additional term to their metrics calculations to account for this centennial adjustment. Here, we apply this to the calculation of carbon budgets—the aim being to improve the physical representation of the true carbon-equivalence of different GHGs and other forcing agents whilst maintaining a transparent metric for use in policy.

On decade to century timescales (but not outside this time-range), CO2 forcing-equivalent emissions (CO2-fe, or the time-history of CO2 emissions that would give a particular radiative forcing path) may be approximated by the following relationship

(1)

where is a constant, a timescale, and an adjustment rate. This adjustment rate depends on the past forcing history, but an indication is given by noting that zero CO2-fe emissions is consistent with stable temperatures, and forcing would need to decline at a fractional rate of to maintain stable temperatures in the decades immediately following forcing stabilisation after a 70-year linear increase, where ECS is the Equilibrium Climate Sensitivity, TCR the Transient Climate Response and the longer of the two adjustment timescales9,10 of the physical climate system.

The instantaneous forcing at time resulting from a sustained unit injection of CO2 starting at time zero, or is equivalent, in a linear system, to the Absolute Global Warming Potential, AGWP*H*, or the forcing integrated over resulting from a pulse unit injection at time zero. For the simple system described by (1),  
where is of the order of but less than unity: for years and per year.10–12

If is considered constant, then cumulative CO2-fe emissions corresponding to radiative forcing over a given time interval of a few decades are given by:

where represents the average, and the change, in radiative forcing over this time interval.

Including this longer timescale term in a similar way to the short timescale term in Allen *et al.* (2018), the full expression for warming (ΔT) resulting from a combination of cumulative CO2 emissions and non-CO2 radiative forcing over a given time-interval is

(2)

where the TCRE is the transient climate response to emissions7,8, , the average and the change in non-CO2 radiative forcing over that time-interval. This expression does not capture sub-decadal adjustments, so must be defined between periods each of at least a decade in duration. Allen et al (2018) give a similar expression, but with and , so neglecting the centennial adjustment to non-CO2 radiative forcing. This more accurate expression is important for calculating carbon budgets for scenarios in which non-CO2 forcing peaks and declines between now and the time of peak warming.

**Predicting budgets for ambitious mitigation scenarios**



**Figure 1** **–** IIASA SR15 database 1.5℃ compatible, 2℃ lower and 2℃ higher scenarios are plotted in panels a (Global annual CO2 emissions) and b (non-CO2 radiative forcing contribution). These scenarios are extended with the RCP8.5 emissions and radiative forcing datasets back to 1765 (treated as a pre-industrial reference point) and are run through a simple climate model (FaIRv1.3). Temperature response is plotted in panel c, where the distinction between each scenario category is evident (1.5℃ compatible = dark blue, 2℃ lower = light orange, 2℃ higher = dark orange). Panel d uses equation 2 to calculate the cumulative CO2 emissions remaining to peak warming, comparing to the actual remaining CO2 emissions in each scenario. Open circles use RCP3 as a baseline when calculating AGWPH,CO2, closed circles use RCP45.

The IIASA database13,14 of scenarios used in the recent IPCC Special Report on Global Warming of 1.5℃15 (SR15) are a useful testing ground for equation 2. Figure 1 plots a range of IIASA scenarios in panels a (CO2 emissions between 2005-2100) and b (non-CO2 radiative forcing between 2005-2100) for models and scenarios contributing to IPCC’s SR15. The scenarios which are labelled as consistent with a “below 1.5℃ in 2100” target in the IIASA database (determined with a run through the MAGICC6 Simple Climate Model (SCM) with best-estimate parameters) are plotted in blue, “2℃ lower” are plotted in light orange and “2℃ higher” are plotted in dark orange.

Panel c shows the temperature response for each scenario plotted in panels a,b. The temperature response is calculated using the FaIR SCM11, tuned to the same TCR and ECS as the MAGICC default (ECS=3.0, TCR=1.85). The scenarios agree with their IIASA classification (1.5℃, 2℃ lower, 2℃ higher) and demonstrate a range of plausible ambitious mitigation options. Panel d shows the estimated remaining cumulative carbon emissions, G, calculated with equation 2 plotted against their actual remaining carbon budget to peak warming (estimated from panel c). Comparing to figures 2a-c in Leach *et al.* (2018) the predicted remaining carbon budgets in each scenario here are significantly more accurate when compared to using total warming whilst only accounting for CO2 emissions (Leach *et al.* figure 2a). The process produces a CO2-fe-like quantity but without requiring model output (results in similar predictive power diagnosed CO2-fe emissions in Leach *et al.*’s figure 2b,c).

The predictions from equation 2 are dependent on the AGWPH, CO2 value, and this number is model and scenario dependent.1 For each coloured sub-category of scenarios we calculate the FaIR derived AGWPH, CO2 from a pulse emission of CO2 at present day over a baseline RCP emissions scenario. For 1.5℃-compatible scenarios we use RCP26, and for 2℃-compatible scenarios we use RCP4.5. The derived H/ AGWPH, CO2 values are 1163 GtCO2/Wm-2 and 1239 GtCO2/Wm-2 respectively, consistent with the MAGICC derived value1 with standard parameters of 1216 GtCO2/Wm-2 and with the AR5 likely range (866-1474 GtCO2/Wm-2)16.

Equation 2 links the physically-representative CO2-fe metric to the more policy-implementable GWP\* metric without compromising significantly on accuracy. This affords national policy-makers the tools to accurately assess the implications of their emissions trajectories for global temperature. Equally, it provides the tools for auditors to quickly assess the likely damage of a given Nation’s emissions and assess if their policies are consistent with Paris Agreement commitments.

Determining equitable sharing of the remaining global cumulative carbon budget is a complex ethical and technical challenge exacerbated by the lack of robust techniques to assess each Nation’s progress towards net-zero emissions and likely requirements from the remaining carbon budget. We hope here to provide one such technique and have demonstrated its use over a range of policy-relevant scenarios.

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**Competing interests**

**Author contributions**

**References**

1. Allen, M. R. *et al.* A solution to the misrepresentations of CO 2 -equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Npj Clim. Atmospheric Sci.* **1**, 16 (2018).

2. Jenkins, S., Millar, R. J., Leach, N. & Allen, M. R. Framing Climate Goals in Terms of Cumulative CO2-Forcing-Equivalent Emissions. *Geophys. Res. Lett.* **45**, 2795–2804 (2018).

3. Danny Harvey, L. D. A guide to global warming potentials (GWPs). *Energy Policy* **21**, 24–34 (1993).

4. Lashof, D. A. & Ahuja, D. R. Relative contributions of greenhouse gas emissions to global warming. *Nature* **344**, 529 (1990).

5. Leach, N. J. *et al.* Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nat. Geosci.* **11**, 574 (2018).

6. Allen et al. *Chapter 1: Framing and Context. In: Special Report on the Global Warming of 1.5℃.* (IPCC, 2018).

7. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).

8. Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832 (2009).

9. Held, I. M. *et al.* Probing the Fast and Slow Components of Global Warming by Returning Abruptly to Preindustrial Forcing. *J. Clim.* **23**, 2418–2427 (2010).

10. Geoffroy, O. *et al.* Transient Climate Response in a Two-Layer Energy-Balance Model. Part I: Analytical Solution and Parameter Calibration Using CMIP5 AOGCM Experiments. *J. Clim.* **26**, 1841–1857 (2012).

11. Smith, C. J. *et al.* FAIR v1.3: a simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* **11**, 2273–2297 (2018).

12. Millar, R. J., Nicholls, Z. R., Friedlingstein, P. & Allen, M. R. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmospheric Chem. Phys.* **17**, 7213–7228 (2017).

13. Huppmann, D. *et al.* *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA*. (Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018). doi:10.22022/SR15/08-2018.15429

14. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. A new scenario resource for integrated 1.5 °C research. *Nat. Clim. Change* 1 (2018). doi:10.1038/s41558-018-0317-4

15. IPCC. Summary for Policymakers of the Special Report on the Global Warming of 1.5°C. (2018).

16. Myhre, G. *et al.* *Chapter 8--Anthropogenic and Natural Radiative Forcing, In IPCC AR5 WG1 - The Physical Science Basis.* 82 (IPCC, 2013).