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

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**Defining a simple and model-independent way of estimating the remaining carbon budget to a given temperature threshold is important for the science-informing-policy community in the coming years. In order to facilitate the implementation of the Paris Agreement a way of identifying our progress towards net-zero emissions and our time remaining to reach net-zero is vital. Whilst work has been done to introduce metrics and measures for estimating remaining cumulative emissions to a given temperature threshold1–4, there are limitations to the commonly accepted methods employed in policy. Here, we discuss recent publications and introduce some additional terms to metrics they introduce. We show these additions improve the accuracy & clarity of statements and tie ideas together without adding significant complication. We provide a model-independent, simple method to estimate the remaining carbon budget to key temperature thresholds, informing policy for activities such as auditing national commitments & evaluating national contributions to the total remaining budget.**

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 In Leach *et al.*’s 2018 paper the carbon budget is treated as having an upper limit based on all the warming arising entirely from CO2 emissions and otherwise assume a net-positive and constant fractional 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 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. Here, we propose that including an additional longer timescale in this estimate of the total warming attributable to a given scenario allows for more accurate estimation of the carbon budget corresponding to a given warming level. This will make the prediction of total CO2-equivalent budgets more accurate without adding unnecessary complexity—the aim being to improve the physical representation of the true carbon-equivalence of different GHGs whilst maintaining a transparent metric for use in policy.

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

— (1)

where the TCRE is the transient climate response to emissions7,8, G is the cumulative carbon emissions released in time Δt between now and the peak in warming (the carbon budget), F1 is the average non-CO2 forcing for the 10-20 years prior to peak warming, F0 is the average non-CO2 forcing for the 10-20 years prior to present day, F2x is the radiative forcing caused by a doubling of atmospheric CO2 concentrations and d2 is the long thermal response timescale of the climate system (considering the thermal response of the globally averaged climate system to be represented by a two box model9,10). The long timescale response is proportional to the difference between the TCR and ECS values, the time remaining to temperature peak Δt (related to the time over which CO2 emissions continue or non-CO2 forcing increases) and the average level of non-CO2 forcing in the 10-20 years prior to present day (assuming the long timescale response is slow enough for the climate system to still be adjusting to the present day forcing, F0. This is a reasonable assumption since best estimate values of d2 = 239 ± 63 yrs10–12).

Using the relationship between TCR and TCRE noted by Allen ()1 we rewrite equation 1 to give a relationship between the remaining warming and the total CO2-forcing-equivalent (CO2-fe) emissions quantity remaining to peak warming

— (2)

where . The AGWPH,CO2 is the integral over the radiative forcing resulting from a unit pulse emission of CO2 for time horizon H as defined in the definition of GWP.3 This gives a relationship between a given level of peak warming above present day (ΔT) and a quantity of cumulative carbon-equivalent emissions (square brackets in equation 2) using TCRE. G is the CO2 emissions (the carbon budget accounted for in Leach *et al.*’s work), the fractional term accounts for the non-CO2 forcing contribution to the total warming response. The (F1 – F0) term estimates the additional warming due to the short timescale thermal adjustment, while the term accounts for the slower timescale thermal response and is proportional to the difference between ECS and TCR parameters.

Equation 2 demonstrates the link between the simplified metrics such as GWP or GWP\* and the more physically sensible CO2-fe metric for comparing greenhouse gases. The non-CO2 CO2-fe emissions contribution to the total carbon budget, approximated with the second term in equation 2, applies for scenarios where the forcing follows a peak-and-decline pathway (any mitigation-type pathway). In Allen *et al.* (2018) their equation is used to predict contributions to total warming on a nation-by-nation basis based on their national emissions inventories. By including the additional long-timescale response we improve the accuracy of such predictions. This has clear applications in the policy community and it demonstrates a transparent way to quickly predict realistic warming from multi-gas emissions scenarios, or equivalently to predict remaining carbon budgets to a given warming threshold without relying on the output of climate models.

**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 cirlces 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 (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 having to compromise significantly on accuracy. This affords national policy-makers the tools to accurately represent their countries climate impacts and should mean better emissions trajectories are designed at a national level. 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 which is exasperated 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**

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