**The contributions of non-CO2 pollutants to the outstanding carbon budget for policy-relevant applications**

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**A simple, transparent 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 show this provides a quantitative 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”.**

Since the Paris Agreement a significant focus of mitigation research has built upon the concept of a global carbon budget–that is the total allowable emissions of CO2 remaining before we surpass a set warming threshold. This has coincided with a shift in the political framing of the mitigation requirements to the same end. These two re-framings have been facilitated by the TCRE; the relationship between total globally summed, or cumulative, emissions and warming response. The warming response has been shown to be nearly linear to the cumulative emissions of CO2, with the constant of proportionality the Transient Climate Response to cumulative CO2 Emissions (TCRE). Hence, a carbon budget acts as a guide to policy-makers on the severity and timeframe of emissions reductions required to achieve a given climate policy worldwide, or equivalently a thermometer to check the likely temperature response to an emissions scenario.

However, the carbon budget concept has a number of contributing uncertainties which have so far hindered major adoption in policy. Rogelj *et al.*, (2019) argue there are 5 decisions which drive uncertainty in the remaining carbon budget; the value of the TCRE, the contributions from non-CO2 pollutants to warming between now and the time of net-zero carbon emissions, the anthropogenic contribution to warming to date, the extra warming ‘in the pipeline’ still to be accounted for as the system reaches equilibrium after net-zero (or the Zero Emissions Commitment), and the contributions to warming of any Earth system feedbacks. In Jenkins et al., (2019) we argue there are two key uncertainties which require reducing in order to secure the carbon budgets utility in policy; one being uncertainty in the TCRE, and the other being uncertainty in the contribution of non-CO2 pollutants to global warming. This reduction is based on the assumption that the Zero Emissions Commitment is small, we have a number of robust ways of estimating the anthropogenic contribution to warming to date, and that Earth system feedbacks are varied in sign and order of magnitude with wide uncertainties, and therefore are not going to be quantified in this study.

Addressing the uncertainty in the TCRE are a number of studies focussing on the response of components of the contemporary carbon cycle to additional emissions of CO2 and better understanding the physical climate response to a perturbation in atmospheric CO2 concentrations. In particular, studies contributing to the Horizon2020 project CCiCC are aiming to …. \*\*maybe?? carbon and heat cycling in the oceans and potential variations over a range of scenarios.\*\*

The second key uncertainty looks at the comparison of different greenhouse gases to account for their warming contribution. A number of studies have considered the best practise for this comparison, in particular the GWP and GTP metrics which are long-standing and widely accepted by the policy community. Recent work has highlighted flaws in the GWP metric, with the key argument being its overweighting of short-lived climate pollutants (SLCPs). Metrics which attempted to correct for the physical inaccuracies of GWP100 are proposed by Allen *et al.*, (2018), and furthered for CH4 in particular in Cain *et al.*, (2019). Allen *et al.* (2018) introduced the GWP\* metric, which offers a better way to compare short-lived pollutants to CO2 whilst maintaining the use of GWP100 values as the conversion metric. For the policy community this is appetising since it provides a way to maintain status quo whilst significantly improving the performance of the metrics prediction of warming resulting from a multi-gas emissions scenario.

When we choose a metric for the comparison of GHGs we must first understand the type of comparison we are requiring. In climate policy there are a myriad of disciplines, all with differing and valid requirements on the weighting of different GHGs with regards to their CO2-equivalence statement. Here we argue that since the Paris Agreement focusses on thresholds of globally averaged temperature anomaly, we should aim to provide a metric for the conversion of GHGs which, unambiguously and without a time horizon, provides a clear comparison of the warming impact of these GHGs. Here we propose a simple formula for the calculation of the remaining carbon budget to a given temperature threshold. The methodology includes a way to account for the contributions from non-CO2 pollutants, meaning the budget can be split by component, and allows for the calculation of a timeseries to see how a chosen scenario’s CO2-forcing-equivalent emissions vary with time. Importantly, the formula uses GWP100 values as the GHG metric so provides continuity for policy-makers and industry users, whilst providing a carbon budget estimate which accounts for the physical climate response of non-CO2 pollutants significantly better than using GWP100 values alone.

**A simple relationship for the remaining carbon 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 Leach *et al.* (2018) provide a carbon budget based on future warming arising entirely from CO2 emissions. This represents an upper limit assuming a net-positive non-CO2 forcing contribution between now and peak warming: 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, but 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 2 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 2 with ). 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.

An even simpler way of accounting for non-CO2 forcing in carbon budgets is to convert everything to CO2 forcing-equivalent (CO2-fe) emissions, or the time-history of CO2 emissions that would give a particular radiative forcing path . This provides the most accurate definition of an ‘all-pollutants CO2 budget’ and is discussed in detail in Jenkins *et al.*, 2019. This requires an invertible carbon cycle model, but on decade to century timescales CO2-fe emissions may be approximated by the following relationship

(1)

where is the Absolute Global Warming Potential of CO2, or the forcing integrated over time-horizon resulting from a one-tonne pulse emission of CO2, and is a constant. To understand why, consider the instantaneous forcing at time resulting from a sustained one tonne-per-year emission of CO2 starting at time zero, or (Shine *et al.*, 2005). This is equivalent, for a linear response, to the AGWP*H*, and increases approximately linearly over these timescales (figure 8.29 of Myhre *et al.*, 2013). Hence and the RHS of equation (1) becomes , the LHS.

The value of depends on the fractional rate at which forcing is expected to decline over the decades after CO2 emissions are set to zero. This depends on the past forcing history, but an indication is given by noting that zero CO2 emissions is consistent with stable temperatures, and forcing would need to decline at a rate 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 timescales7,8 of the physical climate system. This implies per year and with years.8–10

If non-CO2 forcing is defined using effective radiative forcing, then human-induced warming ΔT over a multi-decade time-interval is

(2)

where the TCRE is the transient climate response to emissions11,12, represents cumulative CO2 emissions, 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 , so neglecting the centennial adjustment to non-CO2 radiative forcing (which is only the case if either or ). 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. That said, in almost all global mitigation scenarios the term dominates future warming, followed by the term proportional to , followed in turn by the , so any error introduced by assuming is smaller than the impact of climate variability on .

Parties to the UNFCCC have agreed to aggregate emissions using consistent GWP100 values. If and only if emissions of long-lived pollutants (those with lifetimes longer than 100 years) are aggregated separately, this allows a further simplification of equation (2) for future warming (with ):

(3)

where and are future cumulative long-lived and short-lived climate pollutants and is the change in SLCP emission rate between the most recent decade and the decade prior to peak warming, all expressed as aggregate CO2-equivalent using GWP100.

**Predicting budgets for ambitious mitigation scenarios**

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 SCM9, 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 RCP3PD, 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.

**Revising estimates of the remaining carbon budget**

We can provide estimates of the likely budget to the Paris Agreement’s temperature thresholds based on the observationally constrained TCRE estimate and equation 2 providing an estimate of the likely contributions from non-CO2 RF.

Figure 2 shows distributions of the range of remaining carbon budgets to 1.5℃ (blue) and 2.0℃ (red) global average temperature anomaly from present day (assumed to be around 1.0℃ above pre-industrial in line with IPCC SR15). The total budget is first calculated using a randomly drawn sample from a lognormal TCRE distribution with 5-95th percentiles 0.8-2.4 ℃/TtC. The carbon-only budget is then found by removing a non-CO2 contribution assuming 3 possible evolutions: ΔF = -0.1, 0.0, +0.1 Wm-2 between present day and the time of peak warming. The second term in equation 2 is assumed to add only a small contribution to the non-CO2 budget and is thus ignored in this calculation??? Check calculation method here?

**Conclusions**

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.

The benefit of a technique such as presented above is it is simple enough to be readily employed in real world calculations, whilst still providing a reasonably accurate representation of the relative contributions of CO2 and other climate pollutants to warming at any given time. Provided one can supply a schematic radiative forcing pathway representing their climate ambition for non-CO2 pollutants along with a CO2 emissions timeseries, equation 2 provides an estimate of the cumulative CO2 emissions quantity which produces the same warming response; a quantity we have named Global Warming Equivalent (CO2-gwe) emissions.

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 in figure 1.

We also demonstrated the utility of the CO2-forcing-equivalent emissions concept for clarifying the definition of the TCRE by including the contributions of non-CO2 pollutants to observed anthropogenic warming. By doing this we provided an observational constraint on the TCRE value. There is scope to take this further, by including. The CO2-fe metric provides the gold standard for the comparison of GHG emissions scenarios based on their policy relevance for the Paris Agreement objectives. This paper explores an adapted GWP\* metric, showing how the GWP metric can be adapted to provide accurate warming equivalent emissions budgets for use in policy and other communities.

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**Competing interests**

**Author contributions**

**References**

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**Figure 2** **–** Distributions of likely 1.5℃ and 2.0℃ carbon budgets. NOT THE FINAL FIGURE BUT SOMETHING SHOWING DISTRIBUTIONS LIKE THIS COULD WORK WELL?



**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.