**Quantifying the non-CO2 contributions to remaining carbon budgets**

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***Abstract***

**The carbon budget allows the goals of the Paris Agreement to be translated into remaining emissions of CO2. This provides policy with a means to assess the speed at which emissions must reduce to remain consistent with the Paris Agreement text. CO2-forcing-equivalent emissions make the carbon budget concept more useful by extending their domain to include multi-gas emissions scenarios. Here, the CO2-fe metric is applied to the scenarios used in the IPCC’s Special Report on Global Warming of 1.5℃. A simple formula is introduced to allow policymakers to convert multi-gas emissions and radiative forcing scenarios into carbon budgets and warming response. We use the CO2-fe metric to calculate an observationally constrained estimate of the TCRE, finding a likely range of 0.8-2.4℃/TtC, consistent with previous assessments. We explore the sampled budget space and assess how well current scenarios capture the full range of possible carbon budgets to key temperature targets, finding likely remaining CO2 budgets to 1.5℃ of 540 GtCO2 (peak warming, range 325-1160 GtCO2) and 60 GtCO2 (2100 warming, range -220-660 GtCO2). We argue the CO2-fe metric is the gold standard for the calculation of carbon budgets from multi-gas, real-world scenarios and is a vital tool to inform decision-making as we approach key policy thresholds.**

***1. Introduction***

The IPCC’s Special Report on the Global Warming of 1.5℃1 (SR15), released in December 2018, summarised a wealth of research into the feasibility of achieving the most ambitious of the Paris Agreement’s2 specified targets; a global temperature anomaly below 1.5℃ above pre-industrial levels. It discussed the physical boundaries of the target using physical climate models of varying complexity (GCMs & SCMs), showed what is required at a technical level using Integrated Assessment Models (IAMs), and compared the severity of impacts experienced under both 1.5℃ and 2.0℃ targets.

The discussion of the technical feasibility of such an ambitious temperature goal has recently been reframed as the feasibility of achieving the rapid decarbonisation required globally to remain within a specified total quantity of carbon emissions, termed the ‘Carbon Budget’3–6. This reframing can happen because of a number of useful points about the nature of our emissions and the response of the physical climate system: 1) We are emitting a wide range of climate pollutants but the majority is in the form of CO27,8; 2) A portion of this CO2 remains in the atmosphere for a number of centuries following emission and acts to warm the climate system9–11; and 3) The global average temperature anomaly is linearly proportional to the total quantity of carbon emitted up to that point, where the constant of proportionality termed the Transient Climate Response to cumulative carbon Emissions, or TCRE6,12. The TCRE acts in principle to simplify the implementation of the Paris Agreement by providing a global cumulative carbon budget for all time (at least over policy-relevant timescales). However, as discussed by Rogelj *et al.,* (2019)3 the value of this reframing in terms of a remaining carbon budget is reduced by a number of complicating factors. These include: the estimate of the present-day temperature anomaly; the future contribution of non-CO2 climate pollutants; the committed warming ‘in the pipeline’ or Zero Emissions Commitment (ZEC); the contributions of Earth System Feedbacks; and the estimated value of the TCRE.

Following the design of many previous budget assessments[!!] we assume the ZEC is negligible and ignore Earth System Feedbacks. In the case of ZEC this is justified by assuming it contributes a small amount to remaining warming[!!] and this contribution is centred around zero[!!]. Further, the ZEC and Earth System Feedbacks can be accounted for later by reducing the final budget, as is done when accounting for Earth System Feedbacks in some studies in Rogelj *et al.* (2019).

To attribute the anthropogenic contribution to the historical temperature anomaly we use the ‘fingerprinting approach’ outlined in Haustein *et al.* (2017). Haustein runs estimates of the anthropogenic and natural radiative forcing timeseries through a simple climate model to find the temperature response shapes for anthropogenic and natural sources. These are regressed onto a timeseries of historical temperature observations to find the most-likely anthropogenic contribution. In Haustein *et al.* (2017), SR15 chapter 1, and in this study we use the FaIR[!!] simple climate model to diagnose warming from CO2 emissions and RF inputs.

The problem with the typical methodology for the definition of a remaining carbon budget, such as that used in the definition of the budget for SR15, is that it relies on taking the percentile of a distribution of likely warming responses to non-CO2 and CO2 sources. If the scenarios considered were truly a statistical distribution of possible remaining warming, this would be acceptable. But the IAM outputs together do not define a statistical distribution of non-CO2 contributions, since they inherently rely on underlying modelling decisions. This means the combination of all scenarios into a group does not constitute a distribution which can be sampled at the 66th percentile to find the likely non-CO2 contribution to warming. We argue here that a better approach uses the CO2-forcing-equivalent emissions metric to convert all pollutants into a physically sensible CO2-only timeseries.

In this paper we consider both the contribution from non-CO2 pollutants and the value of the TCRE in estimating the remaining global carbon budget. In the IPCC’s 5th assessment report (AR5[!!chapter 12!!]), the TCRE was assessed to lie between 0.8-2.5℃/TtC. Studies based on observational constraints[!!] and model outputs[!!] agree on the likely range of values, where the shape of the TCRE distribution is typically taken as either log-normal (historical record) or normal (model output)[!!]. We use a number of IAM studies of 1.5℃-compatible scenarios to explore the likely-remaining budget space, and consider the use of the TCRE to help explore mitigation options.

We argue the gold-standard method for budget estimation which correctly accounts for the non-CO2 contribution uses CO2-forcing-equivalent emissions and demonstrate this for a number of 1.5℃ and 2℃ compatible scenarios in section 2. Further, we introduce a simple formula for use in policy and business for the calculation of the warming contribution of an emissions scenario. Section 3 discusses the TCRE uncertainty and demonstrates an observationally constrained TCRE distribution, discussing possible methods to reduce this uncertainty further. Section 4 pulls together the preceding work, showing how varying the TCRE and contributions from non-CO2 pollutants defines a remaining carbon budget. Section 5 includes a discussion of the work and concludes.

[FIGURE 1 HERE]

***2. CO2-forcing-equivalent emissions simplify the budget discussion***

CO2-forcing-equivalent emissions, defined by Jenkins *et al.* (2018)13, converts an emissions timeseries of any climate pollutant to an emissions timeseries of CO2 by requiring they correspond to the same radiative forcing pathway. This distils the communication of a complex multi-gas emissions scenario where the pollutants act over a range of timescales and with various efficacies into a single carbon-equivalent budget which behaves in a physically sensible manner, i.e. like that of a CO2-only emissions scenario (figure 1f).

Comparing to GWP100 (the standard metric for use in policy and the agreed metric for emissions accounting in the UNFCCC ‘ratcheting process’[!!]) we find the CO2-fe metric accurately represent the warming contribution of different pollutants without requiring a time horizon, as GWP100 does[!!]. This results in a carbon budget estimate which is physically sensible, that is one which reflects the warming contribution from that pollutant at any time. Questions of fairness have been posed of warming-equivalent emissions [!Rogelj and Schleussner 2019!], but the same approaches can be used to counter the use of GWP100 for national accounted. The reality is the use of several metrics to define carbon-equivalence and warming contributions should be required for a robust assessment.

Figure 1a plots a number of scenarios for future CO2 emissions from the IIASA SR15 scenario database8. They are coloured by ambition according to their label in the database; dark blue corresponds to scenarios tagged as 1.5℃-compatible, light orange corresponds to lower-2℃-compatible, and dark orange corresponds to higher-2℃-compatible. The corresponding non-CO2 radiative forcing (RF) pathways are plotted in panel 1b (the difference between the total RF and the CO2 RF pathways). Panel 1c shows the cumulative CO2 emissions and panel 1d shows the corresponding cumulative non-CO2 CO2-fe emissions timeseries as computed with FaIRv1.0 SCM10,13. FaIR uses a 2-box temperature model and 4-pool carbon cycle model as with many other simple models9,14, with timescales which are state-dependent. The axes of panels 1c and 1d are rescaled so that the contributions from CO2 and other pollutants can be directly compared (over policy relevant timescales 1 W/m2 ~ 1000 GtCO2[AR5 RF chapter?]) and all timeseries are re-baselined to give cumulative budgets/temperatures relative to 2018.

Panel 1e plots the global temperature anomaly as solid lines, again coloured by scenario category. Dotted lines show the cumulative CO2-fe emissions timeseries for each scenario. Because of the CO2-fe emissions quantity behaves exactly like a CO2-only budget we find the cumulative CO2-fe emissions timeseries match the temperature response shapes (the budgets exhibit the desired TCRE-like behaviour). Panel 1f confirms this assessment: solid lines show the CO2-fe emissions plotted against temperature response, giving a straight-line response (as expected for the TCRE-like relationship between the cumulative CO2-fe emissions and warming response). Just using CO2 emissions (dotted lines) we fail to capture all the contributions to warming and so the linearity between warming and CO2 emissions is lost.

There are other ways to calculate a TCRE-like quantity for multi-gas scenarios, e.g. Damon Matthews’/Richard Millar’s effective TCRE. But these require assumptions such as the fractional contribution of non-CO2 pollutants contribution to warming to remain constant, which looking over a range of plausible mitigation scenarios is not necessarily a robust assumption.

Converting a multi-gas emissions scenario into CO2-fe emissions is the gold-standard method for carbon budget calculations. Other methods bring in additional uncertainty either by deriving a further quantity (temperature response) between raw emissions and the CO2-equivalent quantity, or are simply approximations of this method[!!]. By not requiring the sampling of a percentile from a group of scenario outputs, we create a more robust methodology for the definition of a remaining carbon budget.

To further demonstrate the utility of the CO2-fe metric, figure 2a shows a breakdown of the total annual CO2-fe emissions timeseries for the median scenario taken from all 1.5℃-compatible scenarios plotted in figure 1. Annual emissions are stacked in the positive and negative direction and coloured by pollutant; red is CO2, blue is CH4, green is N2O, purple is F-Gases, and orange is aerosols. We extend the median scenario back to preindustrial using the RCP8.5 emissions/RF timeseries for each component before the conversion to CO2-fe is applied.

The annual emissions in CO2-forcing-equivalent track the expected physical behaviour of the different pollutants under an ambitious mitigation scenario, e.g. for a 1.5℃-compatible pathway. CO2 emissions (red) contribute an increasing fraction of the total CO2-fe annual emissions over the historical period until just after present day where they rapidly decline to zero and eventually net-negative contributions in the second half of the 21st century. Methane emissions contribute a net-positive CO2-fe emissions quantity until they begin to rapidly decline just after present day. Thereafter they contribute net-negative CO2-fe emissions because of the shorter atmospheric residence time of CH415.

Other long-lived pollutants (N2O and F-Gases) behave similarly to CO2 because of their longer residence times in the atmosphere. Aerosols produce a net-negative CO2-fe annual emissions contribution through the historical period until mitigation of aerosol emissions just after present day. After this time the RF contribution from the rapidly declining aerosol burden translates into net-positive CO2-fe emissions as airborne aerosols mask a quantity of warming which is now revealed.

[FIGURE 2 HERE]

The fact that aerosols contribute as much to remaining warming as CO2 over the future for 1.5℃ is important and needs mentioning.

In this way the CO2-fe metric offers a simple way to reconcile the behaviour of climate pollutants with various efficacies and lifetimes, including accounting for all actions creating an RF response. Deriving the total CO2-fe emissions from total observed RF offers a way to include any feedbacks as well as the direct RF from emissions themselves. So long as we can attribute the climate feedbacks and indirect forcing to a particular perturbation we can account for these directly. The challenge for delivering accuracy in the diagnosed carbon budget then is two-fold: 1) to pull apart the contributions to the total RF including indirect and feedback effects; and 2) to understand the contemporary carbon cycle and how its evolution under different future scenarios will impact the carbon-equivalence of different RF contributions.

Figure 2b shows the cumulative emissions timeseries for each pollutant plotted in panel 2a. Since each pollutant has been converted into an equivalent quantity of CO2, comparing the contributions from each agent becomes trivial. All pollutants provide a net-positive CO2-fe budget over the interval plotted (1900-2100), except for aerosols which are cooling and are therefore net-negative. CO2 is the biggest single contributor to the total cumulative emissions quantity, followed by aerosols (negative contribution) or CH4 (positive contribution).

Should add table and paragraph talking about their contributions to the total remaining budget over the 21st century.

-------------- BOX for Simple Formula --------------

**A simple formula for accounting for the non-CO2 contribution to remaining CO2 budgets**

A simple 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 defined in Jenkins *et al.*, 2018[!!]. This requires an invertible carbon cycle model, but on decade-to-century timescales CO2-fe emissions may be approximated with a simple formula.  If non-CO2 forcing is defined using effective radiative forcing, then human-induced warming T over a multi-decade time-interval t is

(1)

where the TCRE is the transient climate response to emissions, is the 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. 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.

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 d2 the longer of the two adjustment timescales of the physical climate system. This implies % per year and with years.

Equation 1 is a generalisation to the CH4 emissions relationship employed in Cain *et al.*, 2019[!!]. We reduce to Cain’s formula if years, years, and convert RF to emissions assuming rough linearity, i.e. / :

(2)

Using this form, we have an equation for the temperature change over a 20 year period in terms of – the average LLCP annual emission rate over that 20 year period (in CO2e using GWP100), – the annual average SLCP emission rate over that 20 year period (in CO2e using GWP100), and – the change in the average SLCP emission rate over the 20 year period. Equations 1 and 2 together allow the calculation of the temperature response to any multi-gas emissions and RF scenario, including both SCLPs and LLCPs, split component-by-component. For agents with significantly shorter lifetimes than that of CH4 (e.g. aerosols) is typically fit to smaller values (e.g. for aerosol RFs in equation 1).

Figure 3 shows the application of equation 1 to a set of radiative forcing timeseries to estimate the temperature response to each component. The right panel shows the contributions to the total temperature response using CO2-forcing-equivalent emissions (solid), while dotted lines show the application of equation 1 to the emissions timeseries (for LLCPs) and radiative forcing timeseries (for SLCPs). What does figure 3 tell us?

[FIGURE 3 HERE]

Equation 1 and 2 have components which mimic the behaviour of different GHG metrics. The first term (for LLCPs) looks like CO2e emissions calculated with the GWP100 metric. The second term, for the calculation of the impact of trends in the RF or emissions rate of SLCPs, takes the form of a shorter timescale GWP (e.g. GWP20) while the third behaves like GTP100. The combination of these three terms creates a metric which accounts for a pollutant’s contribution to warming over policy relevant timescales.

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***3. Observational constraints on the TCRE***

The CO2-fe metric allows us to extend the TCRE behaviour of a CO2-only emissions scenario to multi-gas emissions scenarios. This is demonstrated most clearly in figure 1f, where the typical depiction of the TCRE relationship is reproduced for each scenario. CO2-fe emissions produce a near-linearity to temperature response and much better represent the relationship between warming and cumulative emissions than the CO2-only lines. This replicates the results found by Leach et al.4 in their figure 2, where an equivalent calculation is completed over the AR5 scenario database.

The TCRE represents a key climate parameter both with regards to the understanding of the physical climate response to human actions and regarding effective policy design in the near-future. This makes it the attention of significant research effort over recent years6,16[add more refs. here!] aiming to reduce the uncertainty range from the previous assessment in IPCC’s AR5 (0.8-2.5 ℃/TtC for the 5-95th percentile range). In the section above, we have demonstrated the TCRE concept can be extended to multi-gas scenarios with the correct choice of metric. Having shown the continued utility of the TCRE for scenarios computed using the CO2-fe metric, we now consider the uncertainty range of the TCRE.

To explore the range of TCREs we use the FaIR simple climate model to find most-likely histories for the global temperature anomaly given a number of possible RFs as input. Using a 1000-member ensemble of equiprobable RF timeseries split component-by-component[!Piers RF ensemble!] we can compute the most-likely anthropogenic and natural contributions to the observed temperature anomaly since pre-industrial. Throughout, temperature observations are based on a 4-dataset mean as in the IPCC SR15 Chapter 1 text (HadCRUT3, Cowtan-Way, NOAA and GISTEMP; re-baselined to common reference period 1850-1900 and mean taken for each month).

Figure 4a plots a representative 10 timeseries from the 1000-member RF ensemble. Anthropogenic radiative forcing timeseries are plotted in orange, natural radiative forcing timeseries are plotted in light blue. The majority of the uncertainty in the present day radiative forcing comes from uncertainty in the anthropogenic contribution17,18. Further, we are confident this uncertainty is attributable to non-CO2 sources17,18, in particular the indirect and feedback contributions of aerosols17,19,20. In panel 4b these 10 RF timeseries are used to calculate temperature anomalies. The 4-dataset mean historical temperature observations are shown in black. The attribution method used to find the most-likely contributions to the observed temperatures from natural/anthropogenic sources is the ‘optimal fingerprinting’ technique detailed in Haustein *et al.*, 201721.

Converting each anthropogenic RF timeseries into a best-estimate CO2-fe emissions pathway using FaIRv1.010 we can find an observationally constrained estimate of the TCRE, where the uncertainty is found by sampling the anthropogenic RFs in the 1000-member RF ensemble[ref. for ensemble?]. Cumulative CO2-fe emissions are plotted against attributed anthropogenic temperatures in figure 4c, where the gradient of a straight line fit to each timeseries defines the TCRE. The plume shows the 5-95th percentile range of TCREs from the full 1000-member ensemble. The 10 representative pathways are plotted in black. Once again we demonstrate the CO2-fe conversion produces a CO2-like emissions quantity (linear dependence with temperature). Inset in panel 4c is the TCRE distribution, binned by their angular distribution in cumulative CO2 emissions vs. temperature anomaly space (tan-1(TCRE)). The distribution is almost gaussian; plotting instead as a distribution of TCRE value the shape is log-normal. The inset panel has two vertical black lines showing the locations of the 5th and 95th percentile values in the distribution [quote values for 5th and 95th percentiles]. Supplementary material contains further studies of the angular distribution of TCRE values. The median TCRE is !!!!, the mean is pulled slightly higher (!!!!) owing to the distribution’s long tail at higher TCRE values. Comment on how this is low compared to model estimates of the TCRE – WHY?

Since the 1000-member RF ensemble is split by component, we can also compute a timeseries of CO2-fe emissions of the CO2 and non-CO2 RFs over the historical period for each ensemble member, which is plotted in figure 4d. The 5-95th percentile uncertainty in 2018 is shown with the error bars to the right of the figure. For each component (CO2, non-CO2 and total) the 10 representative scenarios are plotted; red lines correspond to CO2 emissions, blue are non-CO2 CO2-fe emissions, and total CO2-fe emissions are plotted in orange. Non-CO2 RF uncertainty dominates the uncertainty in anthropogenic warming contribution in the present day (as demonstrated by the uncertainty contribution to CO2-fe emissions in present day in panel 4d). This assessment agrees with previous studies[!!].

***4. 1.5℃ and 2.0℃-compatible carbon budgets***

The combination of a physically sound metric to account for the contribution of non-CO2 pollutants to global warming and an assessment of the best estimate and uncertainty on the TCRE parameter provide much needed information towards designing optimal climate policy. They allow us, in a physically representative way and with no reliance on any specific model, a way of comparing estimates of the remaining carbon budget to a given climate target such as those set out in the Paris Agreement2 text.

Similarly to the method outlined in Rogelj *et al.*, 20193, we chose to diagnose the carbon budget as the carbon emissions available to remain within a certain temperature threshold, but in our case accounting for sources of non-CO2 warming using the CO2-fe metric. By computing CO2-fe emissions directly instead of inferring them from a temperature response to the non-CO2 pollutants the uncertainty we compute for the likely-range of carbon budgets is reduced. As explained above, because of the nature of designed scenarios, they do not represent a distribution over which we can sample a percentile. This makes accounting for the non-CO2 warming contribution more difficult than if we simply calculate its impact on the carbon budget directly.

Figure 5a shows how a range of cumulative CO2 and non-CO2 CO2-fe budgets combine to create 1.5℃-compatible total CO2 budgets. We again use the Haustein *et al*.21 optimal fingerprinting technique with best-estimate RF timeseries to estimate the present day temperature anomaly (1.04℃ above 1850-1900 preindustrial period). Should we use GSAT instead since they are IAM output? Along with this we choose a range of TCRE values to calculate total remaining carbon budgets, which are split between CO2 (horizontal axis) and non-CO2 (vertical axis) sources. Supplementary material contains the same calculation for 2.0℃ compatible budgets. \*\*Should quote best estimate remaining total budget to 1.5℃?\*\*

The panel is shaded according to the TCRE, with each region marked with the TCRE value to the nearest 0.5 ℃/TtC. Higher TCREs correspond to smaller remaining total budgets and vice versa. Black filled circles show the position of each scenario’s CO2 and non-CO2 CO2-fe emissions budgets for all 1.5℃-compatible scenarios plotted in figure 1c,d (coloured dark blue). Vertical and horizontal dashed lines highlight the range of budgets sampled by the IIASA SR15 scenario database8. Diagonal dash-dotted lines show the 5-95th percentile range of TCRE values from the distribution plotted inset in figure 4c, and verified with the quoted likely-range in IPCCs AR522. The large blue dot shows the median SR15 1.5℃-compatible scenario (CO2 = 540 GtCO2, non-CO2 = 190 GtCO2, Total = 700 GtCO2).

Figure 5a suggests the IIASA SR15 database under-samples the total ‘budget space’ accessible to remain consistent with a 1.5℃ world. However, this judgement makes no assessment of each budget’s feasibility in reality. For example, there are scenarios in which the remaining CO2 budget is assumed near-zero and the majority of remaining emissions come in the form of other pollutants contributions to warming. The reality of almost immediate cessation of CO2 emissions to allow the allocation of the remainder of the budget to other climate pollutants is extremely unlikely considering the investment in CO2-based infrastructure likely to demand continued emissions for at least the next decade[!Chris Smith paper!].

Disregarding this point, figure 5a still tells us something about the scenarios sampled in the SR15 report. Because of their underlying model assumptions the scenarios used in SR15’s budget calculations seem to assume (on average) a relatively high TCRE (1.85 K/TtC) Does it though if we use GSAT? and therefore a relatively low remaining budget, while the historical record suggests a lower TCRE (!quote median value of TCRE here!, we should have explained why in section 3). The SR15 database of scenarios represents a number of modelling groups making myriad assumptions on the coevolution of CO2 and other climate pollutants in to the future, based on their own sub-models of an economy and society along with assessments of likely evolution of climate policy. They are not a complete distribution of scenarios which can be sampled over, as is demonstrated in figure 5a, and we argue this practise should be avoided.

Figure 5b compares a number of studies assessing the 66% remain-below 1.5℃ carbon budget (based on the Carbon Brief article figure discussing the same topic[!!]). On figure 5b we show a number of studies which were cited in SR15 when defining the remaining carbon budget. These are coloured by the input information in the study: yellow for Earth System Models, blue for observations and red for studies involving IAMs.

In general this suggests the studies using historical observations appear to find a larger budget than those using Integrated Assessment or Earth System Models. For example, Millar et al. (2017)[!!] used the FaIR SCM to work out a likely remaining carbon budget when basing present day warming off the HadCRUT4 GMST observations and following an adaptive mitigation scenario requiring the budget to be 1.5℃-consistent under a range of possible physical climate parameters. In effect this defines an avoidance budget, but the near-linearity of the physical climate response at such small changes in temperature between present day and 1.5℃ means the exceedance budget is nearly identical in size. Millar finds a central estimate of the 66th percentile remain-below 1.5℃ carbon budget of 625 GtCO2[!!] and similar studies by Goodwin et al. (2018) and Richardson et al. (2018, HadCRUT) find 693 GtCO2[!!] and 779 GtCO2[!!] respectively. Richardson completes the same study using an alternative temperature observations dataset (Berkeley) and finds a budget of 467 GtCO2[!!], where the difference arises largely from the value of the present day temperature anomaly. Finally, Leach et al. (2018) find a best-estimate budget of 800 GtCO2 when using a simple geometric approach4.

Alternatively, the studies using IAM output typically use the MAGICC6 SCM with GSAT and determine the budget by requiring the end-of-century warming to be below 1.5℃. Many of these studies (e.g. Rogelj et al. (2018), Peters et al. (2018), AR5 IAMs (2018)[!!]) find 21st century carbon budgets with temperatures (calculated with MAGICC) peaking above 1.5℃ and returning to below-1.5℃ by the end of 2100. Budgets calculated from IAM outputs are estimated with physical climate parameters set to 66th percentile values. With Rogelj et al.’s (2018) study, the median budget estimate for 66% remain-below 1.5℃ is 193 GtCO2[!!]. A similar study by Peters et al. (2018) calculates a likely range of IAM exceedance budgets of 318-518 GtCO2[!!].

At the bottom of figure 5b are the median and range for carbon budgets predicted using the methodology outlined in this paper in the production of figure 5a. Our median carbon budget at peak warming is 540 GtCO2 and the range is 325-890 GtCO2. Interestingly, scenarios found with the MAGICC6 model to be consistent with 1.5℃ in 2100 are found to be roughly consistent with 1.5℃-peak-warming budgets using the FaIR SCM and similar physical climate parameters (see supplementary material). The peak warming budgets we find are consistent with those found by Millar, Richardson and Leach in their 2018 studies using observational estimates of warming to date, and are also consistent with the best-estimate carbon budgets to 1.5℃ as quoted in SR15 (570 GtCO2, 66% chance remain-below with GMST).

If we repeat the calculation for 21st century budgets we find budgets comparable to the IAM studies of Peters, Rogelj and the central estimate of AR5 (60 GtCO2, with full range -220-660 GtCO2). This goes a large way to reconciling the estimates of remaining budget to 1.5℃ estimates found in the literature, with other sizable contributions coming from choice of physical climate parameters and SCM and the use of GMST vs. GSAT for the present day temperature anomaly.

Finally, we provide budget estimates for all-gas CO2-fe budgets remaining for 1.5℃-consistent scenarios. The methodology is identical to that used in the production of figure 5a and is shown for both peak-warming and 2100 budgets on figure 5b. For all-pollutants, the remaining budgets are 700 GtCO2 (median, peak) and 230 GtCO2 (median, 2100) respectively, with ranges spanning 365-1160 GtCO2 (peak) and -175-725 GtCO2 (2100) respectively. We complete the study for 2℃ budgets, and quote numbers for 50% chance and 66% chance remaining below in the supplementary material.

Put SR15 budget estimates on figure 5b.

***5. Conclusions***

The IAMC scenarios database[!!] offers a testing ground for the calculation of carbon budgets, since these IAM studies were direct inputs into the SR15 budget estimates and should be comparable with reported estimates. In this study we first show all 1.5℃-compatible scenarios in figure 1, plotting the range of possible CO2 emissions and non-CO2 RF reported by modelling groups. We use the CO2-fe metric to convert the non-CO2 contributions to the remaining budget into a quantity of CO2 (panel 1d) and show that this corrects the TCRE-like relationship for a multi-gas emissions pathway we expect for a physically sensible metric (panels 1e,f).

Using the median emissions and radiative forcing timeseries for each constituent in 1.5℃-compatible scenarios from figure 1a and b, in figure 2 we plot the annual (panel 2a) and cumulative (panel 2b) CO2-fe emissions timeseries. Panel 2b shows that for both the total and components of the total CO2-fe emissions produce a physically accurate representation of the warming response. We also discuss a simple formula for the implementation of ‘warming-equivalent’ emissions in industry and policy settings. Introduced in box 1, we show that equations 1 and 2 predict the temperature response for CO2, CH4, N2O and RF timeseries such as aerosols and the total RF. This provides an application of warming-equivalent emissions, with users able to calculate both their carbon-equivalent emissions timeseries and corresponding warming impact.

Using CO2-fe we can provide estimates of remaining emissions for a given scenario in terms of CO2 only. We can use this metric to provide an observational constraint on the TCRE over the historical period by comparing temperatures to the total CO2-fe emissions. Figure 4c plots the range of TCREs calculated using best estimate physical climate parameters in FaIR and a 1000-member ensemble of equiprobable anthropogenic RF timeseries and historical temperature observations from 4 datasets as in SR15[!!]. This provides an observationally constrained TCRE range of 0.8-2.4℃/TtC (0.22-0.65℃/TtCO2) with median values at 1.3℃/TtC (0.35℃/TtCO2) and a log-normal shape. This is consistent with the best estimate TCREs found in other studies using the observational record[!!].

The use of CO2-fe emissions significantly reduced the complexity of a carbon budget analysis. Whereas in previous studies a number of the modelling decisions act to muddy the result and purport to result in multiple possible remaining budgets, here in figure 5 we show that many of the differences arise from methodological choices in the design of studies, as is also discussed in work by Rogelj and Peters[!!]. We reconcile the differences between IAM budget estimates and observationally-constrained budget estimates which were used to inform the estimated remaining budgets in SR15.

Our median remaining budget to 1.5℃ (at the 66th percentile) is 540 GtCO2, with a range of 325-890 GtCO2. This is consistent with a number of previous studies of the budget to the 1.5℃-threshold, but is useful because it shows the full range of IAM outputs used for the SR15 reports budget assessment can be made consistent with the observationally constrained budgets reported over 2017-18.

We argue that this methodology provides a much more transparent way to compute the remaining carbon budget, by accounting for the non-CO2 pollutants in a physically sensible way. By not converting the non-CO2 contributions into a warming response we avoid some additional uncertainty and do not have to sample over the range of reported non-CO2 warming contributions in a way inconsistent with the scenario database (figure 5a).

Further research is required to see how the CO2-fe metric can be applied to CMIP6 models output. By pulling apart the contributions of different pollutants to the warming response as is done in figure 2, one can understand the contributions policies on particular sectors or GHGs could make. The addition of a simple formula to calculate the warming-equivalent emissions budget for any pollutants RF or emissions pathway provides extra utility to this approach.

Determining equitable sharing of the remaining global 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 techniques which transparently and simply approximate the remaining budget and have demonstrated its use over a range of policy-relevant scenarios. 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 at a global level.

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***Author contributions***

SJ completed the study and produced the figures. MC contributed to the design and testing of the simple formula. MA and SJ designed the study and all authors contributed to writing.

***Data Availability***

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**Figure 1**: Panel a plots a range of CO2 emissions scenarios (2000-2100) from that IIASA SR15 scenario database8. Panel b plots the corresponding non-CO2 radiative forcing scenarios for each CO2 emissions timeseries. Panel c plots the cumulative CO2 emissions, and panel d plots the cumulative non-CO2 timeseries in terms of cumulative CO2-fe emissions. The axes of panels c and d are rescaled so a direct comparison of the relative contributions from CO2 and non-CO2 pollutants can be made. Panel e plots the temperature response of CO2 emissions and non-CO2 RF from panels a and b in solid lines, and the total cumulative CO2 emissions timeseries in black dotted lines. Panel f plots temperature anomaly as a function of cumulative CO2-fe (solid) and CO2-only (dotted) emissions, demonstrating how CO2-fe emissions produce a physically representative CO2-equivalent emissions timeseries. In all panels the colours correspond to different levels of ambition in the scenarios as tagged in the IIASA database: dark blue refers to 1.5℃-compatible, light orange refers to 2.0℃-lower-compatible, dark orange refers to 2.0℃-higher-compatible scenarios.



**Figure 2:** SR15 median 1.5℃ scenario as found from all compatible scenarios in the IAMC database. Annual CO2-fe emission stacked in panel a. Panel b shows the temperature response stacked and coloured by component in the same was as panel a, where corresponding cumulative CO2-fe emissions are plotted with dotted lines. Total warming is shown with the solid black line and the thick dotted line showing the total cumulative CO2-fe emissions. The baseline period (1850-1900) is shaded.



**Figure 3:** SR15 median scenario RF timeseries (panel a). Before 2005 the timeseries are RCP8.5 RF timeseries for each component, rescaled to join the corresponding SR15 median RF scenario in 2005. Panel b plots the corresponding contribution to the global temperature anomaly from 01/01/2018, as computed using the simple formula (dotted) and directly with FaIR SCM (solid). For CO2 and N2O GWP100 values convert raw emissions into CO2-only timeseries, for CH4 we use equation 2 (equivalent to Cain et al.’s (2019) formula) and for RF timeseries we use equation 1. By adjusting the parameter value, we can make equation 1 fit the behaviour of a range of RF sources.



**Figure 4**: Panel a plots anthropogenic (orange) and natural (sky blue) components of the globally averaged radiative forcing. 10 representative scenarios are plotted which span the range of a 1000-member ensemble of equiprobable RFs are chosen. Panel b plots the most-likely contribution to the global temperature anomaly for these 10 representative timeseries. We use the method of Haustein *et al. (2017)* to define the most-likely anthropogenic and natural contributions to observed temperatures. Panel c plots cumulative CO2-fe emissions against the best estimate anthropogenic contribution to warming for each RF ensemble member. The grey shaded region shows the 5-95th percentile range. Inset is the distribution of TCREs, binned by their angle in cumulative emissions vs. temperature anomaly space. Panel d plots timeseries of the anthropogenic total (orange), CO2 (red) and non-CO2 (blue) contributions to a historical CO2-fe budget (baselined over period 1850-1900). Error bars show the 5-95th percentile range from the full 1000-member ensemble.



**Figure 5**: The total CO2-fe budget allowable to remain below 1.5℃ temperature anomaly is plotted showing possible combinations of a CO2 (horizontal axis) and non-CO2 (vertical axis) budgets. Colours are marked with their corresponding TCRE value – higher TCREs correspond to reduced total budget size remaining to 1.5℃ from 2018 (2018 temperature anomaly calculated as 1.04℃ compared to preindustrial). Black dots show the position of the IIASA SR15 1.5℃-compatible scenarios from figure 1c,d. The horizontal and vertical dashed lines show the extremities of the distribution of the IIASA SR15 1.5-compatible scenarios. The blue dot shows the median 1.5℃-compatible scenario. Diagonal dot-dashed lines show the likely-range of TCRE values, computed in section 3 and similar to the quoted likely range in IPCC’s AR5 text. Right hand plot shows our calculated budgets compared to other studies, in a plot similar to that shown in the Carbon Brief article[!!]. We disply both CO2-only and CO2-fe budgets for peak warming and 21st century warming.