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

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***Abstract***

**The IPCC Special Report on 1.5°C concluded that the maximum level of anthropogenic global warming is “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 of peak warming. Here we quantify this statement, using CO2-forcing-equivalent (CO2-fe) emissions to relate changes in non-CO2 radiative forcing with cumulative CO2 emissions. This allows a non-prescriptive calculation of remaining carbon budgets, without treating available mitigation scenarios as a representative sample of possible futures. A simple formula is introduced to convert multi-gas emissions and radiative forcing scenarios into carbon budgets and warming response. Forcing-equivalent emissions are used to calculate an observationally-constrained estimate of the Transient Climate Response to Emissions (TCRE), giving a likely range of 0.8-2.4℃/TtC, implying a remaining total CO2-fe budget from 2018 to 1.5°C of 325-1160 GtCO2-fe if global warming is defined in terms of increase in Global Mean Surface Temperature. Of this total, between 30 and 290 GtCO2 is taken up by non-CO2 forcing changes in available 1.5°C-compatible scenarios, implying remaining CO2 budgets for a 33, 50 or 66% chance of limiting peak warming to 1.5°C are X1, X2 & X3 respectively for a mid-range value of non-CO2 forcing.**

***1. Introduction***

One of the most important conclusions of the IPCC’s Special Report on Global Warming of 1.5℃1 (SR15), commissioned under the Paris Agreement2, was “Reaching and sustaining net zero global anthropogenic CO2 emissions and declining net non-CO2 radiative forcing would halt anthropogenic global warming on multi-decadal time scales. 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 prior to the time that maximum temperatures are reached.” This highlights the importance of cumulative CO2 emissions in determining whether the increase in global mean surface temperature (GMST) is limited to any particular level, often termed the ‘remaining carbon budget’3–6, together with the fact that the relative importance of non-CO2 climate drivers increases as peak warming is approached. SR1.5 did not, however, give any further scenario-independent quantification of this statement, beyond noting in passing that an increase of 1 W/m2 of non-CO2 radiative forcing and a cumulative emission of 1000 GtCO2 “represent approximately equal effects on GMST.”

The carbon budget framing is helpful because most warming to date has been caused by CO27,8; CO2 emissions, of all major pollutants, have the most permanent impact on the climate system9–11; and CO2-induced warming is linearly proportional to the total quantity of CO2 emitted up over any multi-decade time interval, where the constant of proportionality is termed the Transient Climate Response to cumulative carbon Emissions, or TCRE6,12. However, as discussed by Rogelj *et al.,* (2019)3 this framing is subject to several complications, including the precise definition and estimated present-day level of global warming; the committed warming due to past CO2 emissions, or Zero Emissions Commitment (ZEC); possible contributions of Earth System Feedbacks to future warming; the estimated value of the TCRE; and the future contribution of non-CO2 climate pollutants. Of these confounding factors, the contribution of non-CO2 pollutants is unique in that it depends on future policy decisions, not simply scientific uncertainty.

Following SR1.5, we focus here on the challenge of halting warming on multi-decade timescales, acknowledging uncertainty in the level of positive or negative emissions that may be required to maintain stable temperatures in the very long term [!!]. This allows us to assume the ZEC is negligible and ignore long-term Earth System Feedbacks. Most studies find the ZEC contributes a small amount to remaining warming[!!] under ambitious mitigation scenarios and this contribution is centred around zero[!!]. To estimate the present-day level of the anthropogenic warming, we regress expected responses to anthropogenic and natural forcing onto the timeseries of historical temperature observations to find the most-likely anthropogenic contribution to the increase in GMST. For consistency with AR5 (chapter 2 ref) and WMO (2019 WMO ref), we define present-day and future global warming in terms of GMST, but results are naturally sensitive to the use of another convention, such as global mean surface air temperature.

Most recent estimates of a remaining “multi-gas” carbon budget rely on subtracting a distribution of warming responses to non-CO2 sources from the target total warming and estimating a CO2 budget for the remainder. If available scenarios represented a statistical distribution of possible futures, this would be a coherent approach. But the outputs of Integrated Assessment Models (IAMs) do not define a statistical distribution, since they rely on prescriptive, often normative, decisions of the IAM modelling teams. The distribution of non-CO2 warming also depends on which IAMs converge at all, which may even be a minority of attempts for the most ambitious scenarios, and hence depends on even more arbitrary and opaque constraints. This would not matter if future cumulative CO2 emissions determined the level of non-CO2 warming, but it does not. As we show below, there is no correlation between these two quantities across ambitious mitigation scenarios. This means that the 66th percentile of available scenarios is not a robust estimate of the “likely” non-CO2 contribution to warming. A more coherent method of relating non-CO2 climate drivers with CO2 emissions is to use CO2-forcing-equivalent (CO2-fe) emissions to express each non-CO2 driver in terms of the CO2 emissions timeseries that would give precisely the same impact on effective radiative forcing (ERF) as that non-CO2 driver.

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 (if constrained by the historical record) or normal (if based on model output)[!!]. Here we consider both interpretations of the AR5 range as well as a new observationally-constrained distribution based on the comparison of cumulative CO2-fe emissions to date with the historical record of GMST.

In section 2, we demonstrate the advantages of CO2-fe emissions using a number of 1.5℃ and 2℃ compatible scenarios. Further, we introduce a simple formula for the calculation of “warming equivalent” emissions that provide an accurate approximation CO2-fe emissions without requiring a carbon cycle model. Section 3 introduces an observationally constrained TCRE distribution and discusses possible methods to reduce TCRE uncertainty. Section 4 shows how uncertainty in TCRE and contributions from non-CO2 pollutants define a remaining carbon budget and Section 5 concludes.

[FIGURE 1 HERE]

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

Originally proposed by Tom Wigley in 1998 under the name of a “Forcing Equivalent Index”, CO2-fe emissions13 express an emissions timeseries of any climate pollutant in terms of a timeseries of CO2 emissions that would provide the same radiative forcing pathway as that which is caused that climate pollutant. They are obtained by converting the radiative forcing due to that pollutant (specifically, the radiative forcing that would result from removal of that pollutant) to changes in CO2-equivalent concentrations and then computing the CO2 emissions required to produce that concentration pathway using a carbon cycle model. This distils a complex multi-gas emissions scenario where the pollutants act over a range of timescales and with various efficacies into a single quantity that behaves in a physically coherent manner, with the same cumulative impact as CO2 (figure 1f).

In contrast to GWP, GTP and other conventional metrics, there is no need to specify a time-horizon to compute CO2-fe emissions, since the CO2 emissions required to produce a particular concentration pathway are unambiguously determined by the behaviour of the carbon cycle. Fig. 1, panel a plots a number of scenarios for future CO2 emissions from the IIASA SR1.5 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. Panel b below shows cumulative CO2 emissions relative to 2018, while panel c shows corresponding non-CO2 radiative forcing (RF) pathways (dotted lines, right axis NOTE TO STUART: ALSO EXPRESS RF RELATIVE TO 2018), also expressed as cumulative CO2-fe emissions (solid lines, left axis). CO2-fe emissions timeseries are computed with FaIRv1.0 SCM10,13, a four-pool carbon cycle model based closely on the Impulse Response model used for metrics calculations in AR59,14, but with a minor modification to allow state-dependent timescales: this has little impact for these ambitious mitigation scenarios, so very similar results would be obtained using the AR5 formula. The similarity of the dotted and solid lines in panel c shows that, over these scenarios and timescales, a 1 W/m2 change in radiative forcing is approximately equivalent to 1000 GtCO2-fe, consistent with figure 8.29 of Myhre et al, 2013.

Fig. 1 panel d plots global temperatures as reported in the SR1.5 database, also relative to 2018, against cumulative CO2 emissions (dotted lines), cumulative total CO2-fe emissions (solid lines) and cumulative “CO2-warming-equivalent” emissions, a simple approximation to CO2-fe emissions described in the box. The temperature response to CO2-fe emissions is, by construction, exactly like the response to pure CO2, so cumulative total CO2-fe emissions multiplied by the Transient Climate Response to Emissions (TCRE) predicts the temperature response. If non-CO2 radiative forcing were correlated with cumulative CO2 emissions, then the latter would also predict the response with a simple scaling factor, or “effective TCRE”, to account for a constant fractional contribution to warming from non-CO2 drivers. Fig. 1d shows this is not the case for these mitigation scenarios: hence the impact of non-CO­22 forcing needs to be treated explicitly.

To further demonstrate the utility of the CO2-fe metric, fig. 2 panel a 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, extended back to preindustrial using the RCP8.5-hist radiative forcing for each component. Annual emissions are stacked and coloured by pollutant; red is CO2, blue is CH4, green is N2O, purple is F-Gases, and orange is aerosols. Panel b shows cumulative emissions, with superimposed dotted lines showing the temperature response (computed with the FaIR model with tuned to match the model used in figure 1d) to each component. In contrast to CO2-equivalent emissions, whether computed with GWP100 or any other conventional metric, CO2-fe emissions actually reflect the impact of individual climate drivers on global temperature, allowing them to be compared objectively without relying on an arbitrary choice of scaling factors. Methane emissions make a net positive contribution to annual CO2-fe emissions until they begin to rapidly decline. Thereafter, annual methane CO2-fe emissions become negative: the short atmospheric residence time of methane15 means that falling methane emissions give a declining radiative forcing, equivalent to negative CO2-fe emissions. Aerosols behave similiarly, with the opposite sign, while long-lived pollutants like nitrous oxide behave like CO2. Total cumulative CO2-fe emissions and temperature response are very close to cumulative pure CO2 emissions and CO2-induced warming up to the present day, but diverge rapidly over the coming decades as aerosol forcing declines. Strikingly, this aerosol decline contributes as much to future warming as remaining CO2 emissions, highlighting the importance of common and comparable presentations of all climate drivers (aerosols are often left off figures showing multi-gas scenarios because of the lack of a non-arbitrary way of displaying them on a common axis, a problem resolved by CO2-fe). Median values and ranges for individual contributions to CO2-fe emissions from 2018, both to the time of peak warming and to 2100, are given in table 1.

[FIGURE 2 HERE]

[TABLE 1 HERE]

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

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

Converting all climate forcing agents to CO2-forcing-equivalent (CO2-fe) emissions provides the most accurate and physically justified definition of an ‘all-pollutants CO2 budget’ but requires full forcing histories and an invertible carbon cycle model. On decade-to-century timescales, however, CO2-fe emissions associated with any individual forcing agent may be approximated by “warming equivalent” emissions, CO2-we, or a simple linear combination of the current emission level and how this has changed over a recent time-interval, . If non-CO2 climate forcers are expressed as CO2-equivalent (CO2-e) emissions by multiplying emissions by their Global Warming Potential, GWP (or, for components such as aerosols, by dividing their contribution to effective radiative forcing by the Absolute Global Warming Potential (AGWP) of CO2) then

(1)

where is the time-horizon used for the GWP and AGWP (conventionally 100 years), depends on the properties and time-history of that forcing agent, being the fractional rate at which would need to decline to cause no further warming in the decades following year , and is approximately double the atmospheric lifetime for a short-lived climate pollutant.

For long-lived climate pollutants (LLCPs, with lifetimes longer than ) such as CO2 and N2O, . For methane, and years, reflecting its recent emissions history and lifetime (Cain et al, 2019). For aerosols, the best-fit year while , reflecting their very short lifetime and the fact that GMST is already partially equilibrated with current net global aerosol forcing.

Hence human-induced warming over a multi-decade interval to may be approximated by

(2)

where the TCRE is the transient climate response to emissions and the term in curly brackets represents total warming-equivalent emissions over the interval to . represents combined CO2 and N2O emissions, while represents methane emissions, all in units of GtCO2-e using GWP100 (which conventionally includes the impact of tropospheric ozone changes into the GWP of methane),  is the average and the change in other radiative forcing (primarily aerosols), in units of W/m2, all computed over the interval to . All coefficients here are based on values from the IPCC 5th Assessment Report: years; 0.092 W-yr/m2/GtCO2; for ; GtCO2 per W/m2 as noted in figure SPM.1 of ref. (SR1.5); and GtCO2 per W-yr/m2 for . The AR5 likely range for TCRE is 0.45±0.23°C per 1000 GtCO2, which far outweighs uncertainty in other coefficients.

Figure 3 shows contributions to cumulative CO2-fe emissions relative to 2018 in the median 1.5°C-compatible scenarios (solid lines, left axis), cumulative warming-equivalent emissions (dashed lines) computed using equation 2 applied to the emissions of CO2, N2O and CH4 and radiative forcing from aerosols, and contributions to warming (dotted lines, right axis) using the same model as figure 2b. This single equation is a much better predictor of total future warming than CO2 emissions alone or cumulative CO2-equivalent emissions, and almost as accurate as CO2-fe emissions.

[FIGURE 3 HERE]

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

The CO2-fe metric allows us to extend the linear relationship between cumulative emissions and warming that is observed in CO2-only emissions scenarios to multi-gas scenarios, demonstrated clearly in fig. 1d and fig. 2 of ref. [Leach et al], where an equivalent calculation is applied to the AR5 scenario database. The constant of proportionality, or TCRE, represents a key climate parameter both with regards to the understanding of the physical climate response and effective policy design in pursuit of a global temperature goal. This makes it the focus of significant research effort over recent years6,16[add more refs. here!]. In the section above, we have demonstrated the TCRE concept can be extended to multi-gas scenarios using the TCRE. We now consider how CO2-fe emissions can be used to investigate the TCRE itself by comparing total anthropogenic warming with total cumulative CO2-fe emissions over the historical record. Previous estimates [Gillett et al, 2013] have compared cumulative CO2 emissions with warming attributable to CO2, but the fractional uncertainty in the latter is higher than uncertainty in total anthropogenic warming, suggesting this is a potentially useful complementary approach.

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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.