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

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***Abstract***

***1. Introduction***

The IPCC’s Special Report on the Global Warming of 1.5℃1 (SR15), released in December 2018, reviewed and 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/political level to achieve such targets 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 overwhelming 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.

If we assume the ZEC is negligible and ignore Earth System Feedbacks (as in Rogelj *et al.*, (2019)3 – these should both be second order corrections) we are left with three key assumptions: 1) the present day global average temperature, 2) the value of the TCRE, 3) the contributions to future warming from non-CO2 climate pollutants. Addressing the first assumption: SR15 used a ‘fingerprinting approach’ to find the anthropogenic contribution to the historical temperature record and we keep the same methodology13 here. Anthropogenic and natural contributions to the global temperature anomaly can then be constrained using a least-squares fit on to a chosen historical temperature record. Addressing the second assumption: the IPCC fifth assessment report’s (AR5) assessed likely range for the TCRE is 0.8-2.4 K/TtC14. Reducing this range is the subject of a significant research effort over the coming years. Finally, for the third assumption: accounting for non-CO2 pollutant emissions requires a greenhouse gas metric to convert the ‘unit-tonne’ emission of a species X into a ‘Y-tonnes’ emission of CO2. There are a number of ways to achieve this in the literature, most famously the GWP[!] and GTP[!] metrics. These metrics fail to properly account for the multi-timescale nature of a multi-gas emissions scenario15, such as those calculated in IAMs for SR158. CO2-forcing-equivalent emissions16,17 (CO2-fe), that is the CO2 emissions timeseries which results in the same radiative forcing pathway as the emissions timeseries of species X, provide a physically justified and time-horizon independent conversion to a CO2-equivalent emissions timeseries for all pollutants causing a radiative perturbation.

Here, we consider both the contribution from non-CO2 pollutants and the value of the TCRE in estimating the remaining global carbon budget. 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. 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.

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

CO2-forcing-equivalent emissions, defined by Jenkins *et al.* (2018)16, 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.

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



**Figure 1**: Panel a plots a range of CO2 emissions scenarios (2000-2100) from that IIASA SR15 scenario database. Panel b plots the corresponding non-CO2 radiative forcing scenarios for each CO2 emissions timeseries. Panel c plots the cumulative CO2 emissions, while panel d plots the cumulative non-CO2 CO2-fe emissions timeseries. 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 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**: CO2-forcing-equivalent emissions timeseries for the median of all IIASA SR15 database 1.5℃-compatible scenarios plotted in figure 1. Panel a shows annual emissions timeseries, panel b shows cumulative emissions. The solid line in panel b shows the total cumulative CO2-fe emissions with the dotted line plotting the temperature response to those emissions. CO2-fe emissions can go negative quickly because of a spike in emissions of a pollutant with a negative RF contribution (e.g. aerosols before 2015) or because of declining emissions of a short-lived pollutant with a positive RF contribution (e.g. methane after 2025).

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 the FaIRv1.0 simple climate model10,16. FaIR uses a 2-box temperature model and 4-pool carbon cycle model as with many other simple models9,18, 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 and all timeseries are re-baselined to give cumulative budgets relative to 2018.

Panel 1e plots the global temperature anomaly as solid lines, coloured by scenario category as before. 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 (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) fails to capture all the contributions to warming and so the linearity between warming and CO2 emissions is lost.

Converting a multi-gas emissions scenario into CO2-fe emissions represents the ‘gold-standard’ method for budget calculations. Other methods bring in further uncertainty by deriving a further quantity (most commonly temperature response) between the raw emissions and the CO2-equivalent quantity, or are simply approximations of this method. \*\*should we have a figure showing the reason CO2-fe gives lower uncertainty – i.e. going from uncertainty in RF to CO2-fe ems adds less uncertainty than using uncertainty in warming and reducing budget by that amount of warming? (is that true??). I.e. a schematic for the first section? Would then have 3 figures in the first section, is that okay? Also add somewhere ”The CO2-fe metric requires use of model but this is only as other methods.”\*\*

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, orange is aerosols and yellow is other. The median scenario is extended back to preindustrial using the RCP8.5 emissions/RF timeseries for each component of the total 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 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 as discussed in Allen *et al.*, (2018)15.

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 in the median scenario. 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. Finally, the ‘other’ contribution to figure 2a (yellow) is the CO2-fe emissions timeseries for any RF unaccounted for by the named pollutants already plotted. 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 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 change impact the carbon-equivalence of different RF contributions.

Figure 2b shows the cumulative emissions timeseries for each pollutant plotted in panel 2a. Equivalently, the area under each curve in panel a corresponds to the value plotted in panel b. 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). Interestingly, this isn’t true for all time, at the turn of the 21st century it is the ‘other’ component which provides the largest single contribution to cumulative CO2-fe emissions. By the end of the century this ‘other’ fraction of the total has declined to be much smaller, probably because of the short timescales of many of the pollutants making up this contribution[??].

\*\*if we were to put a box in this paper detailing the approximation it would probably best fit here?\*\* \*\*or it could just be a total section at the end, or before last section\*\*

\*\*Some closing remark about CO2-fe and how it brings the concept of TCRE and linear response of warming to emissions to multi-gas emissions/to any climate pollutant, before we go on to discuss the TCRE and observational constraints.\*\*

***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 considered. CO2-fe emissions produce a near-linearity to temperature response and clearly 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 years6,19[add more refs. here!] aiming to reduce the uncertainty range from the previous assessment in IPCC’s AR5 (0.8-2.4 K/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, this section now considers the uncertainty range of the TCRE.

To explore the range of accessible TCREs we use a 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[!there must be a reference for this!] 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). \*\*MUST update to include most recent update to HadCRUT temperatures in figure?\*\*

Figure 3a plots a representative 10 timeseries from the 1000-member 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 contribution20,21. Further, we are confident this uncertainty is attributable to non-CO2 sources20,21, in particular the indirect and feedback contributions of aerosols20,22,23. In panel 3b 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.*, 201713.

Converting each anthropogenic RF timeseries into a best-estimate CO2-fe emissions pathway (using the carbon cycle model in FaIRv1.010 – 4-pool impulse response model) 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 3c, 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 3c is the TCRE distribution, binned by their angle 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 and raw 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?\*\*



**Figure 3**: 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.

\*\*Replot inset panel in figure 3 to smooth line, choose 10 representative scenarios which better span range.\*\*

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, and is plotted in figure 3d. 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 3d), and 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, in our case accounting for sources of non-CO2 warming using the CO2-fe metric. By



**Figure 4**: 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.

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[!explain or reference!, or using schematic figure in second section?].

Figure 4 shows how a range of cumulative CO2 and non-CO2 CO2-fe budgets combine to create 1.5℃-compatible total CO2 budgets. We use the Haustein *et al*.13 optimal fingerprinting technique with best-estimate RF timeseries to estimate the present day temperature anomaly (1.04℃ above 1850-1900 preindustrial period). We use this and 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℃?\*\*

**Figure 4**: Remaining emissions budgets consistent with a 1.5℃ world split between a carbon and non-CO2 CO2-fe budget. The TCRE affects the total budget remaining to a given temperature anomaly (shading shows size of remaining total budget or equivalently TCRE value). The present day temperature anomaly is taken as 1.04℃ (computed using Haustein *et al.* (2017) methodology). Solid black circles show the location of all 1.5℃-compatible scenarios plotted in figure 1c,d (coloured in dark blue). Large blue circle shows the median of all 1.5℃-compatible scenario. Vertical and horizontal lines highlight the total spread of CO2 and non-CO2 CO2-fe emissions budgets, while diagonal lines show the range of budgets accessible over the full uncertainty range of the TCRE parameter.

Regions are coloured based on their TCRE, with each marked with the TCRE value on the left-hand edge of that region. Higher TCREs correspond to smaller remaining total budgets and vice versa. Black filled circles show the position of each scenarios 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 3c, and verified with the quoted likely-range in IPCCs AR514. The large blue dot shows the median SR15 1.5℃-compatible scenario.

Figure 4 suggests the IIASA SR15 database under-samples the total ‘budget space’ accessible to remain consistent with a 1.5℃ world. Equivalently, we could argue there are pathways to achieving a 1.5℃ world which aren’t represented in the SR15 scenario database. However, this makes no assessment of each budget split’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 and blowing the remainder of the budget to 1.5℃ on other climate pollutants is extremely unlikely considering the investment in CO2-based infrastructure likely to demand continued emissions for at least the immediate future.

Disregarding this point, figure 4 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) 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 ecomony and society along with assessments of likely evolution of climate policy. They are not a complete distribution of scenarios which can be sampled simply, as is demonstrated in figure 4, and we argue this practise should be avoided.

***5. Conclusions***

***Acknowledgements***

***Author contributions***

***Data Availability***

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