Quantifying the non-CO_2 contributions to remaining carbon budgets

Stuart Jenkins, ???, Myles Allen

Draft manuscript (25/07/19) (first draft)

Abstract

1. Introduction

The IPCC's Special Report on the Global Warming of 1.5℃[!], released in December 2018, reviewed and summarised a wealth of research into the feasibility of achieving the most ambitious of the Paris Agreement's 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'. 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 to those: 1) We are emitting a wide range of climate pollutants but overwhelmingly the majority is in the form of CO_2[!]; 2) A portion of this CO_2 remains in the atmosphere for a number of centuries following emission and acts to warm the climate system[!]; 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 is known as the Transient Climate Response to cumulative carbon Emissions, or TCRE[!]. 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)[1] 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-CO_2 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)[1] – 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-CO_2 climate pollutants. SR15 used a 'fingerprinting approach' to find the anthropogenic contribution to the historical temperature record and we keep the same methodology[2] here to define the present-day globally averaged temperature anomaly. The IPCC fifth assessment report's (AR5) assessed likely range for the TCRE is 0.8-2.4 K/TtC[!]. Reducing this range is the subject of a significant research effort over the coming years[??]. Finally, accounting for these non-CO_2 pollutant emissions requires a greenhouse gas metric to convert the 'unit-tonne' emission of a species X into a 'Y-tonnes' emission of CO_2. 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 scenario, such as those calculated in IAMs for SR15. CO_2-forcing-equivalent emissions[3] (CO_2-fe), that is the CO_2 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 CO_2-equivalent emissions timeseries for all pollutants causing a radiative perturbation.

Here, we consider both the contribution from non-CO_2 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-CO_2 contribution uses CO_2-forcing-equivalent emissions and demonstrate 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 likely methods to reduce this uncertainty. Section 4 pulls together the preceding work, showing how varying the TCRE and contributions from non-CO_2 pollutants defines a remaining carbon budget. Section 5 includes a discussion of the work together and concludes.

2. CO_2-forcing-equivalent emissions simplify the budget discussion

CO_2-forcing-equivalent emissions, defined by Jenkins *et al.* (2018)[3], converts an emissions timeseries of any climate pollutant to an emissions timeseries of CO_2 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 CO_2 emissions from the IIASA SR15 scenario database. 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

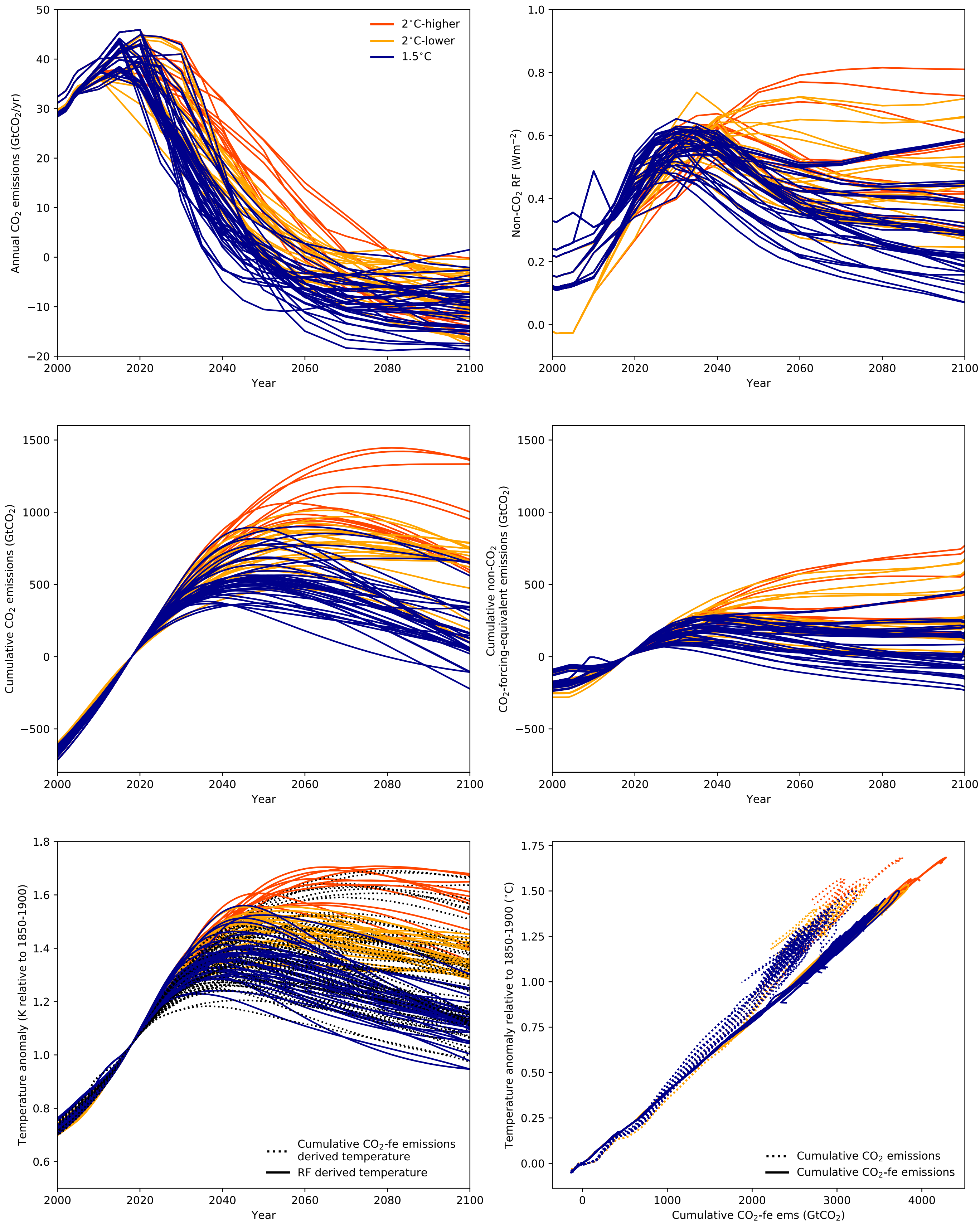

Figure 1: Panel a plots a range of CO_2 emissions scenarios (2000-2100) from that IIASA SR15 scenario database. Panel b plots the corresponding non-CO_2 radiative forcing scenarios for each CO_2 emissions timeseries. Panel c plots the cumulative CO_2 emissions, while panel d plots the cumulative non-CO_2 CO_2-fe emissions timeseries. The axes of panels c and d are rescaled so a direct comparison of the relative contributions from CO_2 and non-CO_2 pollutants can be made. Panel e plots the temperature response in solid lines, and the total cumulative CO_2 emissions timeseries in black dotted lines. Panel f plots temperature anomaly as a function of cumulative CO_2-fe (solid) and CO_2-only (dotted) emissions, demonstrating how CO_2-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.

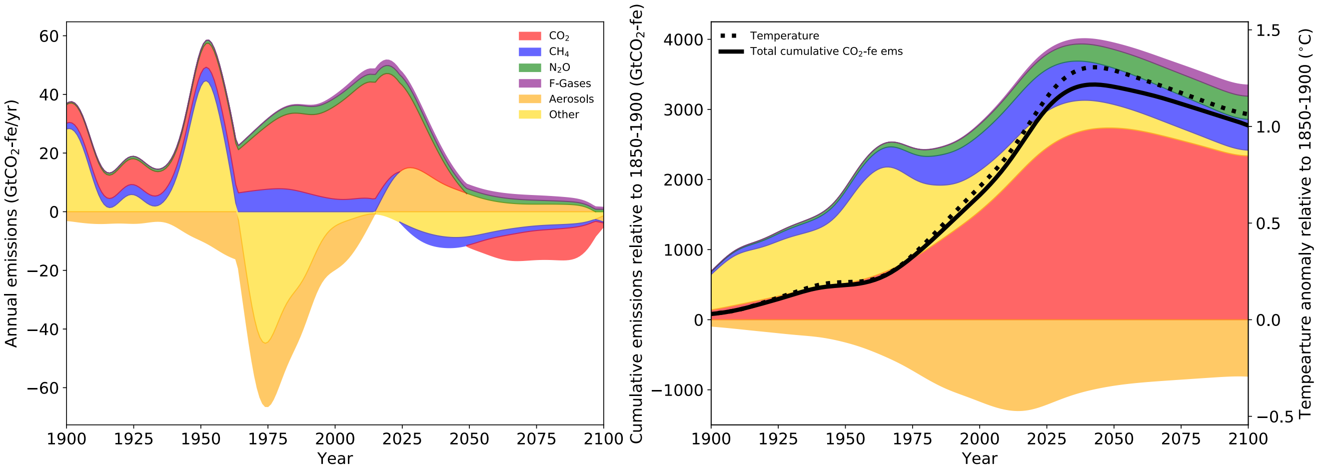

Figure 2: CO_2-forcing-equivalent emissions timeseries for the median of all IIASA SR15 database 1.5°C-compatible scenarios plotted in figure 1. Panel a shows annual emissions timeseries, panel b shows cumulative emissions. The solid line in panel b shows the total cumulative CO_2-fe emissions with the dotted line plotting the temperature response to those emissions. CO_2-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°C-compatible, and dark orange corresponds to higher-2°C-compatible. The corresponding non-CO_2 radiative forcing (RF) pathways are plotted in panel 1b (the difference between the total RF and the CO_2 RF pathways). Panel 1c shows the cumulative CO_2 emissions and panel 1d shows the corresponding cumulative non-CO_2 CO_2-fe emissions timeseries as computed with the FaIRv1.0 simple climate model[3,4]. FaIR uses a 2-box temperature model and a 4-pool carbon cycle model with timescales which are state-dependent. The axes of panels 1c and 1d are rescaled so that the contributions from CO_2 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. Dotted lines show the cumulative CO_2-fe emissions timeseries for each scenario. Because of the CO_2-fe emissions quantity behaves exactly like a CO_2-only budget we find the cumulative CO_2-fe emissions timeseries match the temperature response shapes. Panel 1f confirms this assessment. Solid lines show the CO_2-fe emissions plotted against temperature response, giving a straight line response (as expected for the TCRE-like relationship between the cumulative CO_2-fe emissions and warming response). Just using CO_2 emissions (dotted lines) fails to capture all the contributions to warming and the linearity is lost.

Converting a multi-gas emissions scenario into CO_2-fe emissions represents the 'gold-standard' method for budget calculations. **should we have a figure showing the reason CO_2-fe gives lower uncertainty – i.e. going from uncertainty in RF to CO_2-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?**

or at least a comment here about how CO_2-fe is the 'gold standard' approach for budget calculation and an explanation how other methods bring in further uncertainty or are simply approximations of this method. Discussion of how CO_2-fe requires use of model but this is only as other methods.

To further demonstrate the utility of the CO_2-fe metric, figure 2a shows a breakdown of the total annual CO_2-fe emissions timeseries for the median scenario taken from all 1.5°C-compatible scenarios plotted in figure 1. The annual emissions are stacked in the positive and negative direction and coloured by pollutant; red is CO_2, blue is CH_4, green is N_2O, 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 CO_2-fe is applied.

The annual emissions of CO_2-fe track the expected physical behaviour of the different pollutants under an ambitious mitigation scenario, such as that required for a likely 1.5°C-compatible pathway. CO_2 emissions (red) contribute an increasing fraction of the total CO_2-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 CO_2-fe emissions quantity until they begin to rapidly decline just after present day. Thereafter they contribute net-negative CO_2-fe emissions as discussed in [!!].

Other long-lived pollutants (N_2O and F-Gases) behave like CO_2 because they reside in the atmosphere longer-term. Aerosols produce a net-negative CO2-fe annual emissions contribution through history until aerosol emissions themselves decline in the median scenario. After this time the RF contribution from the rapidly declining aerosol burden translates into net-positive CO_2-fe emissions as the airborne aerosols mask a quantity of warming which is now revealed. Finally, the 'other' contribution to figure 2a (yellow) is the CO_2-fe emissions timeseries for the RF unaccounted for by the named pollutants already plotted. **CO_2-fe metric offers a way to reconcile the behaviour of climate pollutants with various efficacies and lifetimes.**

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 CO_2, comparing the contributions from each agent becomes trivial. All pollutants provide a net-positive CO_2-fe budget over the interval plotted (1900-2100), except for aerosols which are cooling and are therefore net-negative. CO_2 is the biggest single contributor to the total cumulative emissions quantity, followed by aerosols (negative contribution) or CH_4 (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 CO_2-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?

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 CO_2-fe metric allows us to extend the TCRE behaviour of a CO_2-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. CO_2-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.[5] 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 climates response to human actions and regarding effective policy design in the near-future. This makes it the attention of significant research effort over recent years[!!] aiming to reduce the uncertainty range from the previous assessment in IPCC's AR5 (0.8-2.4 K/TtC – 5-95th percentile range). Having shown the continued utility of the TCRE for scenarios computed using the CO_2-fe metric, this section now considers the uncertainty range of the TCRE.

Using a 1000-member ensemble of equiprobable radiative forcing timeseries split component-by-component[!!] we can compute the most-likely anthropogenic and natural contributions to the observed temperature anomaly since pre-industrial. Here the temperature observations are based on a 4-dataset mean as in the IPCC SR15 Chapter 1 text (HadCRUT3, Cowtan-Way, NOAA and GISTEMP; rebaselined 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 sky blue. **comment on how the vast majority of the uncertainty in the total RF arises from uncertainty in the anthropogenic component, even though we are confident it is net-positive (AR5 quote? SR15 quote?). Comment further this is largely down to uncertainty in the non-CO2 component, in particular aerosol RF.** In panel 3b these 10 RF timeseries are used to calculate temperature anomalies. These are plotted with the 4-dataset mean historical temperature observations 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.*, 2017[2].

Converting each anthropogenic RF timeseries into a best-estimate CO_2-fe emissions pathway (using FaIRv1.0[4]) gives us an observationally constrained estimate of the TCRE, where the uncertainty is found by sampling the range of the anthropogenic RFs in the 1000-member RF ensemble. This is plotted in figure 3c. 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 CO_2-fe conversion produces a CO_2-like emissions quantity (linear dependence with temperature). Each ensemble member has its TCRE calculated by finding the gradient of the cumulative CO_2-fe emissions vs. temperature anomaly. Inset in panel 3c is the TCRE distribution, binned by their angle in cumulative CO_2 emissions vs. temperature anomaly space ($\tan^{-1}$(TCRE)). In this space the distribution is almost gaussian, plotted 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. **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 long tail at higher TCRE values. **Comment on how this is low compared to model estimates of the TCRE – WHY?**

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 for each a timeseries of CO_2-fe emissions for the CO_2 and non-CO_2 RFs over the historical period. The 5-95th percentile uncertainty in 2018 is shown with the error bars to the right of the figure. For each 10 representative scenarios are plotted, red lines correspond to CO_2 emissions, blue are non-CO_2 CO_2-fe emissions, and total CO_2-fe emissions is plotted in orange. Non-CO_2 RF uncertainty dominates the uncertainty in anthropogenic warming contribution in the present day (as demonstrated by the uncertainty contribution to CO_2-fe emissions in present day in panel 3d).

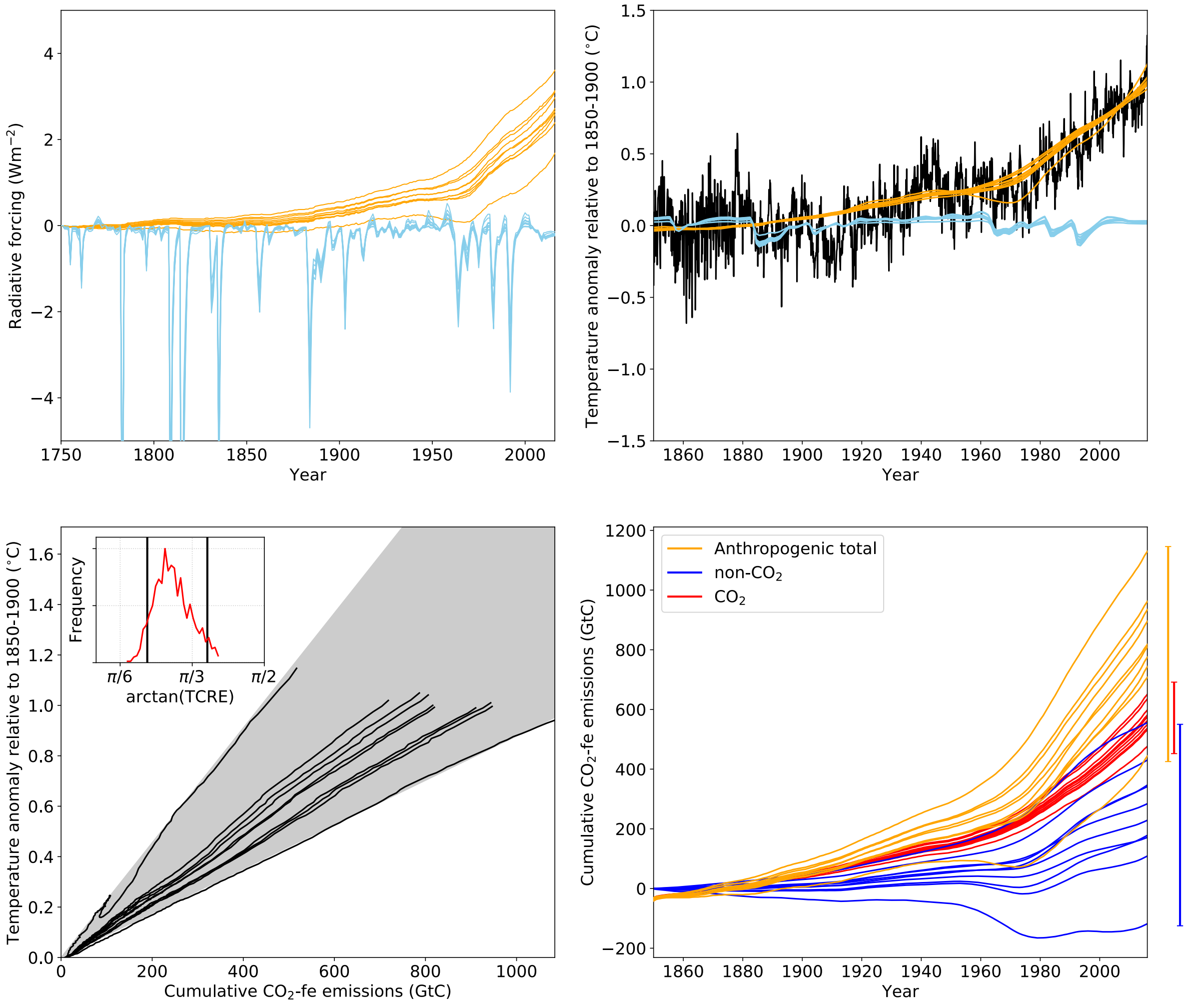

Figure 3: Panel a plots anthropogenic (orange) and natural (sky blue) components of the globally averaged radiative forcing. 10 representative scenarios are plotted which span the range of a 1000-member ensemble of equiprobable RFs are chosen. Panel b plots the most-likely contribution to the global 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 CO_2-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), CO_2 (red) and non-CO_2 (blue) contributions to a historical CO_2-fe budget (baselined over period 1850-1900). Error bars show the 5-95th percentile range from the full 1000-member ensemble.

4. 1.5°C and 2.0°C-compatible carbon budgets

The combination of a physically sound metric to account for the contribution of non-CO_2 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 completely 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 Agreement[!!] text.

Unlike the method outlined in Rogelj *et al.*, 2019 we chose to diagnose the carbon budget as the carbon emissions available to remain within a certain temperature threshold, once sources of non-CO_2 warming are taken into account using CO_2-fe emissions. By computing CO_2-fe emissions directly instead of inferring them from a temperature response to the non-CO_2 pollutants the uncertainty we compute for the likely range carbon budgets is reduced.

Figure 4 shows how a range of cumulative CO_2 and non-CO_2 CO_2-fe budgets combine to create 1.5°C-compatible totals such as is remaining under the most ambitious goal set in the Paris Agreement. We use the Haustein *et al.*[2] optimal fingerprinting technique with best-estimate RF timeseries to estimate the present day temperature anomaly (1.04°C above 1850-1900 preindustrial period). We use this and a range of TCRE values to calculate total remaining carbon budgets. These can be split between CO_2 and non-CO_2 sources.

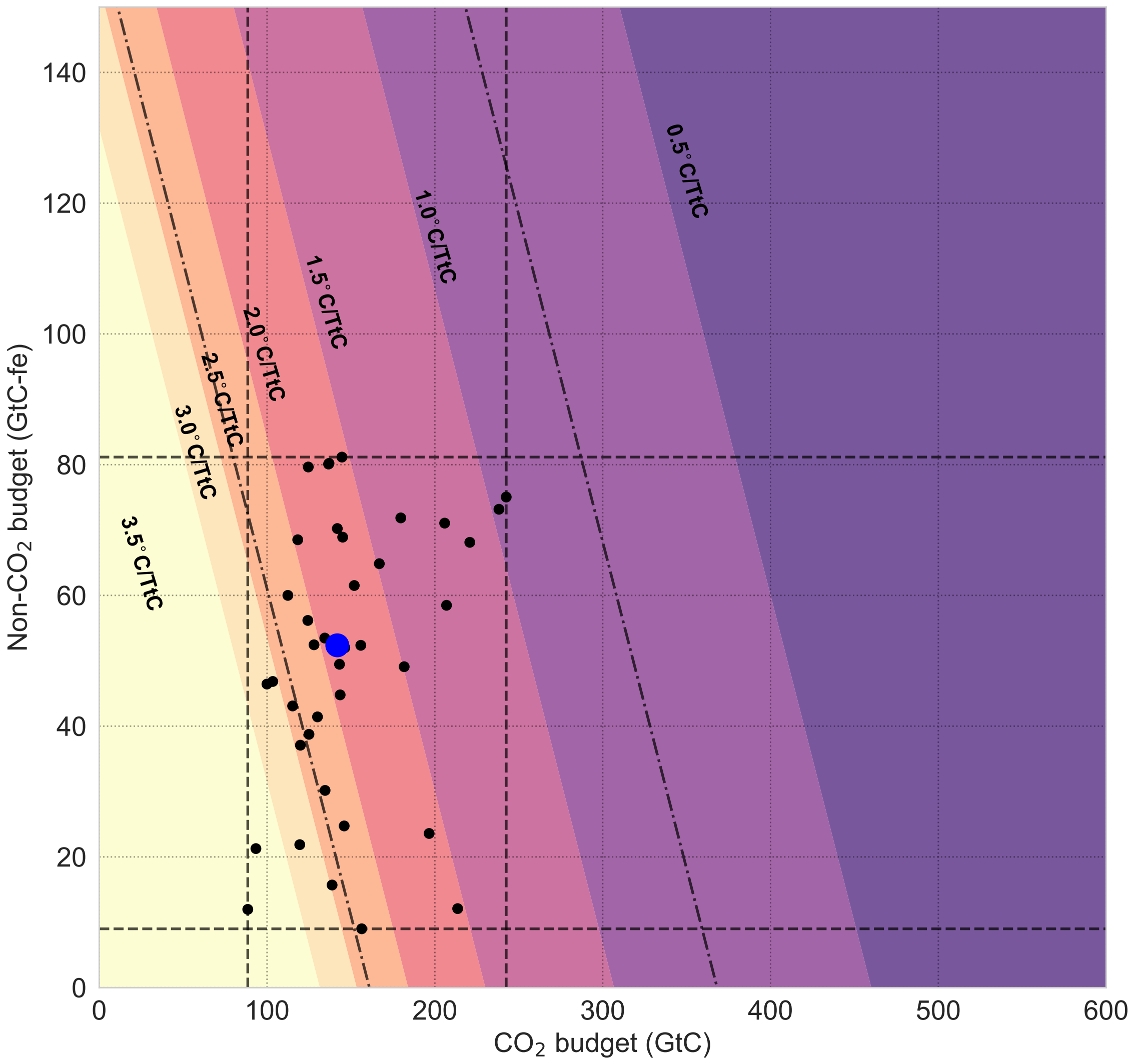

Figure 4: Remaining emissions budgets consistent with a 1.5°C world split between a carbon and non-CO_2 CO_2-fe budget. The TCRE affects the total budget remaining to a given temperature anomaly (shading shows size of remaining total budget or equivalently TCRE value). The present day temperature anomaly is taken as 1.04°C (computed using Haustein *et al.* (2017) methodology). Solid black circles show the location of all 1.5°C-compatible scenarios plotted in figure 1c,d (coloured in dark blue). Large blue circle shows the median of all 1.5°C-compatible scenario. Vertical and horizontal lines highlight the total spread of CO_2 and non-CO_2 CO_2-fe emissions budgets, while diagonal lines show the range of budgets accessible over the full uncertainty range of the TCRE parameter.

Supplementary material contains the same calculation for the Paris 2.0°C target. **Should quote best estimate remaining total budget to 1.5°C?**

Higher TCREs correspond to smaller remaining budgets and vice versa. Black filled circles show the position of each scenarios CO_2 and non-CO_2 CO_2-fe emissions budgets for all 1.5°C-compatible scenarios plotted in figure 1c,d (coloured dark blue). Vertical and horizontal dotted lines highlight the range of budgets sampled by the SR15 scenario database. Diagonal lines show the 5-95th percentile range of TCRE values from the distribution plotted inset in figure 3c. The large blue dot shows the median SR15 1.5°C-compatible scenario.

Figure 4 shows the IIASA SR15 database under-samples the total 'budget space' accessible to remain consistent with a 1.5°C world. Equivalently, there are pathways to achieving a 1.5°C world which aren't represented in the SR15 scenario database. However, this makes no assessment of their feasibility in practise. For example, there are scenarios in which the remaining CO_2 budget is assumed near-zero and the majority of remaining emissions come in the form of other pollutants contributions to warming.

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 (!!!!!). The SR15 database of scenarios represents a number of modelling groups making myriad assumptions on the coevolution of CO_2 and other climate pollutants in to the future, based on their own sub-models and assessments of likely evolution of climate policy. **They are not a distribution of scenarios which can be sampled for a likely budget range or other assessment and we avoid using them in this way.**

5. Conclusions

Acknowledgements

Author contributions

Data Availability

References

1. Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335 (2019).
2. Haustein, K. *et al.* A real-time Global Warming Index. *Sci. Rep.* **7**, 15417 (2017).
3. Jenkins, S., Millar, R. J., Leach, N. & Allen, M. R. Framing Climate Goals in Terms of Cumulative CO2-Forcing-Equivalent Emissions. *Geophys. Res. Lett.* **45**, 2795–2804 (2018).
4. Millar, R. J., Nicholls, Z. R., Friedlingstein, P. & Allen, M. R. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmospheric Chem. Phys.* **17**, 7213–7228 (2017).
5. Leach, N. J. *et al.* Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nat. Geosci.* **11**, 574 (2018).