**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 calculation of remaining carbon budgets without treating available mitigation scenarios as a representative sample of possible futures. CO2-fe emissions are used to calculate an observationally-constrained estimate of the Transient Climate Response to Emissions (TCRE), giving a likely range of 0.23-0.68℃/TtCO2 if global warming is defined in terms of increase in Global Mean Surface Temperature, implying a remaining total CO2-fe budget from 2018 to 1.5°C of 590-1740 GtCO2-fe. Of this total, between 30 and 585 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 1050, 900 & 760 GtCO2 respectively for a mid-range value of non-CO2 forcing.**

***1. Introduction***

The IPCC’s Special Report on Global Warming of 1.5℃1 (SR15), commissioned under the Paris Agreement2, concluded that “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 ‘carbon budget’3–6, together with the increasingly important role of non-CO2 climate drivers as peak warming is approached. SR1.5 did not, however, give any further scenario-independent quantification of this statement, beyond noting 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 approximately 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 refs. 1, 3, 10 & 13 [Millar et al, (2017)10; Matthews et al, (2018)13; SR1.5, (2018)1; Rogelj et al,(2019)3] this framing is subject to several complications, including the precise definition and estimated present-day level of global warming; 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 thereafter14. 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, centred around zero, to remaining warming under ambitious mitigation scenarios11,15. 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 selection of scenarios representing the most ambitious temperature goals also depends on which IAMs converge at all, an even more arbitrary and opaque constraint. This would not matter if future cumulative CO2 emissions determined the level of non-CO2 warming, but they do 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 should not be used to estimate of the “likely” non-CO2 contribution to warming. A more coherent treatment of non-CO2 climate drivers is to use CO2-forcing-equivalent (CO2-fe) emissions, meaning the CO2 emissions timeseries that would give precisely the same impact on effective radiative forcing (ERF) and thence GMST.

In section 2, we demonstrate the advantages of CO2-fe emissions using a number of 1.5℃- and 2℃- compatible scenarios. The supplementary material introduces a simple but accurate approximation CO2-fe emissions without requiring a carbon cycle model. Section 3 introduces an observationally constrained TCRE distribution and assesses how both TCRE and contributions from non-CO2 pollutants define remaining carbon budgets.

[FIGURE 1 HERE]

***2. CO2-forcing-equivalent emissions in ambitious mitigation scenarios***

Originally proposed by Tom Wigley in 1998 under the name of a “Forcing Equivalent Index”, CO2-fe emissions16 express an emissions timeseries of any climate pollutant in terms of the timeseries of CO2 emissions that would have an identical impact on GMST on all timescales. They are obtained by converting the radiative forcing due to that pollutant (specifically, the reduction in effective radiative forcing, ERF, that would result from removal of that pollutant, all other factors being the same) to changes in CO2-equivalent concentrations and then computing the CO2 emissions required to produce that concentration pathway using a carbon cycle model.

In contrast to GWP, GTP and other conventional metrics, there is no need to specify an arbitrary 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 ERF pathways (dotted lines, right axis), also expressed as cumulative CO2-fe emissions (solid lines, left axis). CO2-fe emissions timeseries are computed with a four-pool carbon cycle model10,16 based closely on the Impulse Response model used for metrics calculations in AR59,17, 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 ERF is approximately equivalent to 1000 GtCO2-fe, consistent with figure 8.29 in Myhre et al, (2013)18.

Fig. 1 panel d plots global temperatures as reported in the SR1.5 database, relative to 1850-1900, against cumulative CO2 emissions from 1870 (dotted lines) and cumulative total CO2-fe emissions form 1870 (solid lines). 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 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 drivers19. Fig. 1d shows this is not the case: hence the impact of non-CO2 forcing needs to be treated explicitly for these mitigation scenarios.

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, stacked and coloured by pollutant. Panel b shows cumulative emissions, with superimposed dotted lines and right-hand axis showing the temperature response to the radiative forcing due to each component. In contrast to CO2-equivalent emissions, whether computed with GWP100 or any other conventional metric, CO2-fe emissions reflect the impact of individual climate drivers on global temperature, allowing them to be compared objectively. 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 methane20 means that falling methane emissions give a declining radiative forcing, equivalent to negative CO2-fe emissions. Aerosols behave similarly, with the opposite sign, while long-lived pollutants like nitrous oxide behave like CO2.

Total cumulative CO2-fe emissions and total anthropogenic warming are similar to cumulative 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 for the three scenario categories.

[FIGURE 2 HERE]

[TABLE 1 HERE]

***3. Observational constraints on the TCRE and remaining carbon budgets***

Having demonstrated how the TCRE can be extended to multi-gas scenarios using the CO2-fe emissions, 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 TCRE estimates21 have compared cumulative pure-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.

To estimate anthropogenic warming over the historical period, we use conventional “optimal fingerprinting” applied to GMST, using the FaIR simple climate model to estimate responses to anthropogenic and natural forcing given a 1000-member ensemble of equiprobable RF timeseries22. GMST observations (monthly mean of HadCRUT4, Cowtan-Way, NOAA and GISTEMP) are regressed onto each pair of natural and anthropogenic response timeseries with added CMIP5 control simulations to account for internal climate variability. Estimated anthropogenic warming in 2018 relative to 1850-1900 is 1.10 (0.98-1.27) (5-95% confidence interval), slightly higher than ref. 1 (SR1.5) due to updates in the dataset.

We express each anthropogenic RF timeseries as a set of 1000 equiprobable CO2-fe emissions pathways10 accounting for uncertainty in cumulative CO2 airborne fraction to date (XXX±YYY)[GCP 2018] in carbon cycle parameters. Figure 3, panel a, shows the resulting joint distribution of cumulative anthropogenic CO2-fe emissions 1870 to 2013 inclusive and human-induced warming to the decade 2009-2018 relative to 1850-1900. Each symbol corresponds to the same RF timeseries to account for any covariance, while CO2 airborne fraction and internal climate variability are sampled independently. Shading indicates isolines of TCRE, while scatter points show the decadal co-evolution of these quantities from 1960 to 2018 for samples representing 5th-95th percentiles of the distribution, coloured by decade. The median TCRE is estimated as 0.35/TtCO2 (0.23-0.68/TtCO2 for 5th-95th percentile) with a log-normal shape. Corresponding percentiles of TCRE are shown in table 2.

[TABLE 2 HERE]

Remaining total CO2-fe emissions budgets for an additional 0.40°C and 0.90°C warming above 2018, corresponding to total warming of 1.5°C and 2°C respectively, are shown in table 2, which also shows remaining budgets using two variants of the TCRE distribution provided in AR5. We calculate remaining budgets for additional anthropogenic warming relative to the best-estimate current level for consistency with Table 2.2 of ref. 1, reflecting a policy focus on future warming relative to the recent past rather than including uncertainty in pre-industrial temperatures.

Fig. 3, panels b and c, show how future non-CO2 climate forcing impacts on remaining pure-CO2 budgets given these total CO2-fe budgets. Shading indicates values of the TCRE, as in panel a, while scatter points indicate cumulative CO2 and non-CO2 CO2-fe emissions to peak warming in 1.5°C-compatible and 2°C-lower and higher scenarios. Colours indicate the scenario category as in fig. 1 (supplementary information contains plots coloured by the IAM used to generate each scenario: these are not randomly distributed, nor is there a consistent relationship between CO2 and net non-CO2 contributions to future CO2-fe emissions under ambitious mitigation scenarios). Hence these scenarios cannot be treated as a representative sample of possible futures, as in refs. 1 and 3, since the contributions of non-CO2 forcing is dependent on subjective and/or normative decisions of individual modelling groups. Assuming the ratio of CO2 to non-CO2 forcing (8.0 over the past 2 decades23) remains unchanged in the future5,6,19 is also not supported.

The simplest and least prescriptive option left is to subtract a representative mid-range value for the non-CO2 contributions from estimated total CO2-fe budgets to give indicative pure-CO2 budgets, indicated by horizontal box-whisker symbols in panels b and c. The range of non-CO2 contributions implied by these scenarios indicates the potential for trade-offs between CO2 and non-CO2 warming, but exploring these trade-offs is a matter for policy-makers. The concept of CO­2-fe emissions, or warming-equivalent emissions that are very similar and much easier to calculate (see supplementary information), provides the necessary framework.

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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: IIASA IAMC database of scenarios in the IPCC Special Report on the Global Warming of 1.5°C. Panel a plots the annual CO2 emissions. Panel b (below a) shows the running sum (or cumulative) CO2 emissions from 2018. Panel c (bottom right) shows the non-CO2 radiative forcing for each scenario (dotted lines, right hand axis). Also on panel c are the cumulative non-CO2 CO2-fe emissions from 2018 corresponding to each non-CO2 RF line (solid lines, left hand axis). The axes of panels b and c are scaled so the cumulative emissions from CO2 and non-CO2 are directly comparable. Panel d plots the FaIRv1.3-derived temperature response against the diagnosed cumulative CO2-fe emissions (solid lines) and against the cumulative CO2-only emissions (dotted lines). For FaIR temperature response TCR=1.6°C, ECS=2.75°C. Scenarios are coloured by category in the IAMC database: red for 2°C-higher, orange for 2°C-lower and blue for 1.5°C-compatible.



Figure 2: Median 1.5°C-compatible scenario from the IAMC SR15 database. Panel a plots the annual CO2-fe emissions for each of the major contributing pollutant (red = CO2, blue = CH4, green = N2O, purple = F-Gases, gold = Tropospheric Ozone and orange = Aerosols + Other). Panel b shows the corresponding cumulative CO2-fe emissions timeseries. Panel c plots the temperature response for each component (coloured and stacked). Black solid lines show the total annual (panel a) and cumulative (panels b and c) CO2-fe emissions, while the total temperature response is shown with a black dotted line. Small back scatter points on panel c show the annual temperature observations using 4-dataset mean observations from SPM.1, SR15. FaIR-derived temperatures (panel c) uses thermal parameters chosen to best emulate historical temperatures (TCR=1.65°C, ECS=2.85°C). RFs before 2005 are taken for individual components from RCP8.5 RF dataset after rescaling to match median scenario’s RF component in 2005.

A close up of a map

Description automatically generated

Figure 3: Observational constraints on the TCRE and consequences for design of Paris Agreement-compatible scenarios. Panel a plots attributed human-induced warming against cumulative emissions of CO2. The space is shaded by the value of the TCRE and the points are coloured by decade in which the temperature (1850-1900 baseline) and cumulative CO2-fe emissions (relative to 1870) are diagnosed. An ellipse is drawn around points in the 5-95th percentile of both the diagnosed CO2-fe emissions in the present decade and human-attributed warming in the present decade. Black lines depict the 5th, 50th and 95th percentile of the overall TCRE distribution (based on 2009-2018 decade). Panels b and c show the remaining CO2 and non-CO2 CO2-fe budgets from 2018 for each scenario in figure 1, coloured by category according to assigned label in the IAMC database. Shading shows the AR5 gaussian TCRE likely range and best estimate on both panels b and c. The black line shows the historical best estimate TCRE. In panel b the shading corresponds to budgets for 0.4°C remaining warming to 1.5°C – consistent with 1.10°C warming in present day (GMST). In panel c the shading refers to budget for 0.3°C remaining warming to 1.5°C – consistent with 1.20°C warming in present day (GSAT).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Component** | **1.5C-compatible (Peak)** | **2.0C-lower-compatible (Peak)** | **2.0-higher-compatible (Peak)** | **1.5C-compatible (2100)** | **2.0C-lower-compatible (2100)** | **2.0-higher-compatible (2100)** |
| **CO2 (GtCO2)** | 495 |  |  | 91 |  |  |
| **CH4 (GtCO2-fe)** | -53 |  |  | -145 |  |  |
| **N2O (GtCO2-fe)** | 58 |  |  | 134 |  |  |
| **Tropospheric Ozone (GtCO2-fe)** | -60 |  |  | -128 |  |  |
| **F-Gases (GtCO2-fe)** | 38 |  |  | 117 |  |  |
| **Aerosols and Other (GtCO2-fe)** | 80 |  |  | 274 |  |  |
| **Total (GtCO2-fe)** | 558 |  |  | 343 |  |  |

**Table 1:** Peak-warming and 2100 CO2-fe budgets for median (±1σ) scenarios, categorised according to their label in the IIASA SR15 scenarios database[!!].

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Percentile** | **AR5 TCRE (gaussian) (**°**C/TtCO2)** | **AR5 TCRE (log-normal) (**°**C/TtCO2)** | **TCRE (this study) (**°**C/TtCO2)** | **Remaining budget (TtCO2) (0.4**°**C, AR5-gaussian)** | **Remaining budget (TtCO2) (0.4**°**C, AR5-log-normal)** | **Remaining budget (TtCO2) (0.4**°**C, this study)** | **Remaining budget (TtCO2) (0.9**°**C, AR5-gaussian)** | **Remaining budget (TtCO2) (0.9**°**C AR5-log-normal)** | **Remaining budget (TtCO2) (0.9**°**C, this study)** |
| **10th** | 0.14 | 0.18 | 0.24 | 2.86 | 2.22 | 1.67 | 6.43 | 5.00 | 3.75 |
| **20th** | 0.24 | 0.23 | 0.27 | 1.67 | 1.74 | 1.48 | 3.75 | 3.91 | 3.33 |
| **30th** | 0.32 | 0.28 | 0.29 | 1.25 | 1.43 | 1.38 | 2.81 | 3.21 | 3.10 |
| **40th** | 0.39 | 0.33 | 0.32 | 1.03 | 1.21 | 1.25 | 2.31 | 2.73 | 2.81 |
| **50th** | 0.45 | 0.39 | 0.34 | 0.89 | 1.03 | 1.18 | 2.00 | 2.31 | 2.65 |
| **60th** | 0.51 | 0.45 | 0.37 | 0.78 | 0.89 | 1.08 | 1.76 | 2.00 | 2.43 |
| **70th** | 0.58 | 0.53 | 0.40 | 0.69 | 0.75 | 1.00 | 1.55 | 1.70 | 2.25 |
| **80th** | 0.65 | 0.64 | 0.46 | 0.62 | 0.63 | 0.87 | 1.38 | 1.41 | 1.96 |
| **90th** | 0.76 | 0.83 | 0.56 | 0.53 | 0.48 | 0.71 | 1.18 | 1.08 | 1.61 |

**Table 2:** TCRE percentiles and corresponding remaining CO2-fe budgets for 0.4°C additional warming (1.5°C-compatible) and 0.9°C additional warming (2.0°C-compatible). TCRE percentiles for AR5-gaussian (columns 2,5,8), AR5-lognormal (columns 3,6,9) and this study (columns 4,7,10) are shown. AR5 distributions based on 0.22-0.68°C/TtCO2 (0.8-2.5°C/TtC) likely range as quoted in Chapter 12, AR5.