

## ARTICLE OPEN



# Quantifying non-CO<sub>2</sub> contributions to remaining carbon budgets

Stuart Jenkins<sup>1</sup>✉, Michelle Cain<sup>1,2</sup>, Pierre Friedlingstein<sup>3,4</sup>, Nathan Gillett<sup>5</sup>, Tristram Walsh<sup>1</sup> and Myles R. Allen<sup>1,6</sup>

The IPCC Special Report on 1.5 °C concluded that anthropogenic global warming is determined by cumulative anthropogenic CO<sub>2</sub> emissions and the non-CO<sub>2</sub> radiative forcing level in the decades prior to peak warming. We quantify this using CO<sub>2</sub>-forcing-equivalent (CO<sub>2</sub>-fe) emissions. We produce an observationally constrained estimate of the Transient Climate Response to cumulative carbon Emissions (TCRE), giving a 90% confidence interval of 0.26–0.78 °C/TtCO<sub>2</sub>, implying a remaining total CO<sub>2</sub>-fe budget from 2020 to 1.5 °C of 350–1040 GtCO<sub>2</sub>-fe, where non-CO<sub>2</sub> forcing changes take up 50 to 300 GtCO<sub>2</sub>-fe. Using a central non-CO<sub>2</sub> forcing estimate, the remaining CO<sub>2</sub> budgets are 640, 545, 455 GtCO<sub>2</sub> for a 33, 50 or 66% chance of limiting warming to 1.5 °C. We discuss the impact of GMST revisions and the contribution of non-CO<sub>2</sub> mitigation to remaining budgets, determining that reporting budgets in CO<sub>2</sub>-fe for alternative definitions of GMST, displaying CO<sub>2</sub> and non-CO<sub>2</sub> contributions using a two-dimensional presentation, offers the most transparent approach.

*npj Climate and Atmospheric Science* (2021)4:47; <https://doi.org/10.1038/s41612-021-00203-9>

## INTRODUCTION

The IPCC's Special Report on Global Warming of 1.5 °C<sup>1</sup> (SR1.5) concluded: 'Reaching and sustaining net zero global anthropogenic CO<sub>2</sub> emissions and declining net non-CO<sub>2</sub> radiative forcing would halt anthropogenic global warming on multi-decadal timescales. The maximum temperature reached is then determined by cumulative net global anthropogenic CO<sub>2</sub> emissions up to the time of net zero CO<sub>2</sub> emissions and the level of non-CO<sub>2</sub> radiative forcing prior to the time that maximum temperatures are reached.' This highlights the importance of future cumulative CO<sub>2</sub> emissions, often termed the 'remaining carbon budget'<sup>2–5</sup>, together with the increasingly important role of non-CO<sub>2</sub> 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/m<sup>2</sup> of non-CO<sub>2</sub> radiative forcing and a cumulative emission of 1000 GtCO<sub>2</sub> 'represent approximately equal effects on global mean surface temperature (GMST).' Here we provide this quantification.

The carbon budget framing is helpful because most warming to date has been caused by CO<sub>2</sub><sup>6–8</sup>, and CO<sub>2</sub>, of all major pollutants, has the most permanent impact on the climate system<sup>8–10</sup>. CO<sub>2</sub>-induced warming is approximately proportional to the total quantity of CO<sub>2</sub> emitted over any multi-decade time interval, where the constant of proportionality is termed the Transient Climate Response to cumulative carbon Emissions, or TCRE<sup>5,11</sup>. There are, however, complications<sup>1,2,9,12</sup> in the use of TCRE to derive the remaining carbon budget, including the precise definition and estimated current level of global warming; committed warming due to past CO<sub>2</sub> emissions, or the zero emissions commitment (ZEC); possible contributions of Earth System Feedbacks to future warming; uncertainty in the estimated value of the TCRE; and the future contribution of non-CO<sub>2</sub> climate pollutants. Of these, the contribution of non-CO<sub>2</sub> pollutants is

unique in that it depends on future policy decisions, not simply scientific uncertainty.

We focus here on carbon budgets corresponding to increases in GMST because this remains the index used to report observed increases in global temperatures<sup>1,13,14</sup>, and hence may be used to determine when a temperature threshold is reached. Previous studies have suggested that changing sea-ice cover precludes the use of GMST in projections<sup>15</sup>. However, Fig. 3f of ref. <sup>15</sup> indicates the very limited impact of sea-ice retreat on GMST under ambitious mitigation scenarios, while under sustained warming the impact would correspond to a couple of years of warming at most. Therefore, changing sea-ice cover does not present any fundamental impediment to the use of GMST in projections. Further, while in earlier GMST products the ratio of GSAT to GMST has differed by several percent<sup>16</sup>, recent updates to GMST datasets have largely accounted for these differences using statistical infilling of undersampled geographical regions.

Here, headline conclusions are communicated for a global temperature anomaly calculated from a four-dataset mean of these statistically infilled GMST products (similar to the approach taken in ref. <sup>17</sup>) to reduce the impact of any individual dataset, and to ensure that our conclusions are consistent with the estimates of the current level and rate of increase of human-induced global warming (see 3,13,17). Recent updates to these GMST datasets have revised the present decade's warming level up compared to earlier products. This presents a hazard for policymakers: using different indices to report observed warming (e.g. the reference period chosen in the Structured Expert Dialogue<sup>14</sup> informing the Paris Agreement) and to calculate carbon budgets<sup>15</sup> raises the possibility of the carbon budget being exhausted well before a temperature threshold is reached, potentially undermining confidence in the entire construct. Following SR1.5, we focus on budgets consistent with halting warming for a multi-decade period, acknowledging uncertainty in the level of positive or

<sup>1</sup>AOPP, Department of Physics, University of Oxford, Oxford, UK. <sup>2</sup>Centre for Environmental and Agricultural Informatics, Cranfield University, Cranfield, United Kingdom. <sup>3</sup>College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter EX4 4QF, UK. <sup>4</sup>Laboratoire de Meteorologie Dynamique, Institut Pierre-Simon Laplace, CNRS-ENS-UPMC-X, Departement de Geosciences, Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France. <sup>5</sup>Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC, Canada. <sup>6</sup>Environmental Change Institute, School of Geography, University of Oxford, Oxford, UK. ✉email: [stuart.jenkins@wadhams.ox.ac.uk](mailto:stuart.jenkins@wadhams.ox.ac.uk)

negative emissions that may be required to maintain stable temperatures in the very long term thereafter<sup>18</sup>. This allows us to assume the ZEC is negligible and ignore long-term Earth system feedbacks. Most studies find the ZEC contributes at most a small amount to remaining warming under ambitious mitigation scenarios<sup>10,19–21</sup>.

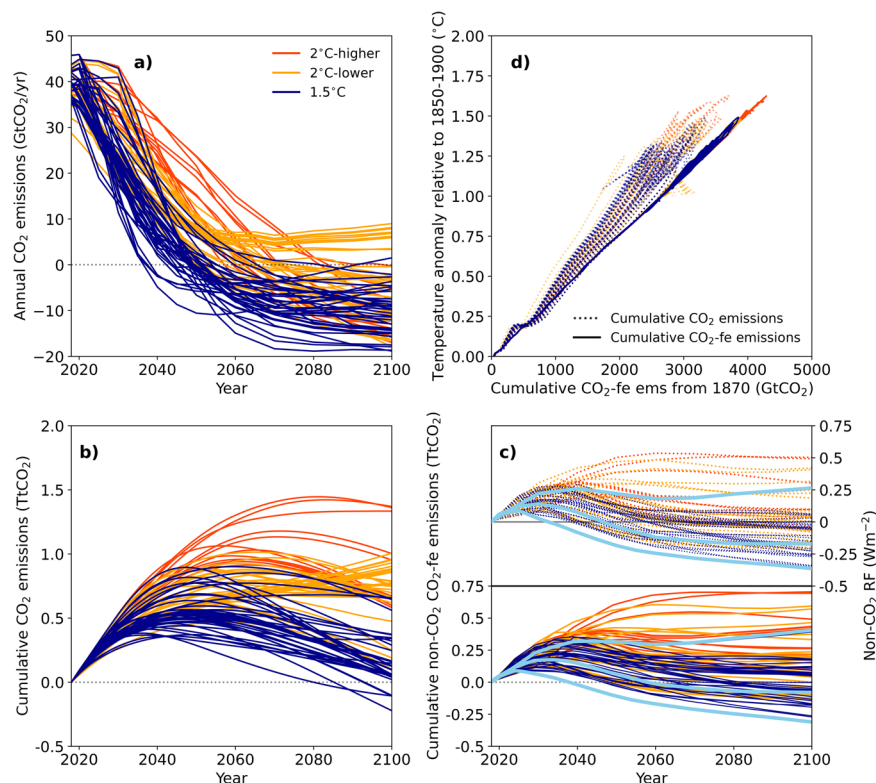
Most recent estimates of a remaining ‘multi-gas’ carbon budget rely on subtracting a distribution of warming responses to non-CO<sub>2</sub> sources from the target total warming and estimating a CO<sub>2</sub> budget for the remainder<sup>1,2,22</sup>. This approach relies on: (1) the careful treatment of covarying physical climate response uncertainty to both CO<sub>2</sub> and non-CO<sub>2</sub> contributions and (2) available scenarios from integrated assessment models (IAMs) representing a statistical distribution of possible futures. Guidelines on the use of scenarios in the SR1.5 database make clear they should not be treated as a statistical distribution<sup>23</sup>, since they rely on prescriptive, often normative, decisions such that the choice of model has more impact than within-model uncertainties (we show this in Fig. 3). Scenarios representing the most ambitious temperature goals also depend on which IAM set-ups converge at all, an even more arbitrary and opaque constraint. Therefore, percentiles of available scenarios cannot be used to estimate the ‘likely’ non-CO<sub>2</sub> contribution to warming. Further, a predetermined quantity of non-CO<sub>2</sub> warming should not be subtracted from the total remaining warming without considering the accompanying impact of covarying physical climate uncertainty implicit in the choice of TCRC. Refs. <sup>1,2,24</sup> all remove a quantity of warming attributed to non-CO<sub>2</sub> pollutants independent of the sampled TCRC percentile. A more transparent treatment of non-CO<sub>2</sub> climate

drivers uses CO<sub>2</sub>-forcing-equivalent (CO<sub>2</sub>-fe) emissions<sup>25</sup>, meaning the CO<sub>2</sub> emissions time series that would give precisely the same impact on effective radiative forcing (ERF) and thence GMST. This is similar to the approach of ref. <sup>26</sup>, although they use a single representative non-CO<sub>2</sub> forcing scenario. By doing this we can explicitly sample the physical climate response uncertainty for both CO<sub>2</sub> and non-CO<sub>2</sub> contributions identically, and more clearly separate scenario and physical response uncertainties in non-CO<sub>2</sub> contributions. We are therefore here assuming the climate response to effective non-CO<sub>2</sub> forcing is identical to the response to the same level and time-history as CO<sub>2</sub> forcing; while still an assumption, this is clearly preferable to assuming these responses are independent.

## RESULTS

### CO<sub>2</sub>-forcing-equivalent emissions in mitigation scenarios

Originally proposed by Tom Wigley in 1998 under the name of a ‘Forcing-Equivalent Index’, CO<sub>2</sub>-fe emissions<sup>27</sup> express an emissions time series of any climate pollutant in terms of the time series of CO<sub>2</sub> emissions that would have an identical impact on ERF, and hence GMST on all timescales. They are obtained by converting the ERF associated with that pollutant to a time series of change in CO<sub>2</sub>-equivalent concentrations, and then computing the CO<sub>2</sub> emissions required to produce that CO<sub>2</sub> concentration perturbation using a carbon cycle model<sup>25</sup> (see Methods for a full explanation of the CO<sub>2</sub>-fe methodology along with a simple formula which approximates the full calculation).



**Fig. 1** IIAA IAMC database of scenarios in the IPCC Special Report on the Global Warming of 1.5°C. Panel **a** plots the annual CO<sub>2</sub> emissions. Panel **b** (below **a**) shows the running sum (or cumulative) CO<sub>2</sub> emissions from 2018. Panel **c** (bottom right) shows the non-CO<sub>2</sub> radiative forcing for each scenario (dotted lines, right hand axis). Also on panel **c** are the cumulative non-CO<sub>2</sub> CO<sub>2</sub>-fe emissions from 2018 corresponding to each non-CO<sub>2</sub> RF line (solid lines, left-hand axis). The axes of panels **b** and **c** are scaled so the cumulative emissions from CO<sub>2</sub> and non-CO<sub>2</sub> are directly comparable. Panel **d** plots the FaIRv2.0-derived temperature response against the diagnosed cumulative CO<sub>2</sub>-fe emissions (solid lines) and against the cumulative CO<sub>2</sub>-only emissions (dotted lines). For FaIR temperature response TCR = 1.8 °C, ECS = 3.0 °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. Light blue scenarios in panel **c** highlight some example non-CO<sub>2</sub> pathways (lower bound, upper bound and a central scenario from 1.5°C-compatible dark blue plume) with the central light blue scenario (P3 scenario from SR15 SPM.3b) also used in Figs. 2 and 3.

Removing a temperature contribution from non-CO<sub>2</sub> forcing agents would be a valid approach to carbon budget estimation so long as the physical climate response uncertainty were sampled at the same percentile for both CO<sub>2</sub> and non-CO<sub>2</sub> warming contributions. SR1.5, and similar approaches<sup>2,24</sup>, remove a predetermined range of non-CO<sub>2</sub> warming before the TCRe is sampled. This is inconsistent since a low non-CO<sub>2</sub> warming contribution is significantly more likely if a low TCRe is sampled. A more transparent approach uses CO<sub>2</sub>-fe: the scenario uncertainty (fraction of total CO<sub>2</sub>-fe budget which is allocated to non-CO<sub>2</sub> forcing agents) is separated from the physical climate behaviour governing the overall size of the cumulative all-pollutant budget.

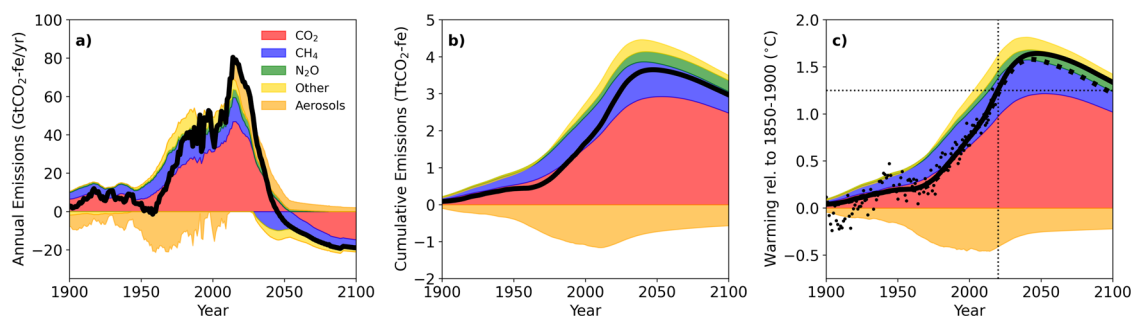
In contrast to conventional emission metrics, there is no need to specify an arbitrary time-horizon to compute CO<sub>2</sub>-fe emissions, since the CO<sub>2</sub> emissions required to produce a particular pathway of concentration anomalies are unambiguously determined by the behaviour of the carbon cycle. IPCC's SR1.5 did not systematically include CO<sub>2</sub>-fe in the estimation of remaining budgets<sup>28</sup> (it did address alternative metrics which approximate the behaviour of CO<sub>2</sub>-fe, namely GWP<sup>29–31</sup>, but not in the analysis of carbon budgets). There is a clear need for complementary approaches, given that CO<sub>2</sub>-fe is no less accurate than the temperature anomaly-based approach defined in SR1.5, and offers greater transparency since non-CO<sub>2</sub> forcing uncertainty is more clearly separated from physical climate uncertainty.

One benefit of the CO<sub>2</sub>-fe metric is that it allows direct comparison between the CO<sub>2</sub> and non-CO<sub>2</sub> contributions to warming. In Fig. 1a we plot a number of scenarios for future CO<sub>2</sub> emissions from the IIASA SR1.5 scenario database<sup>7</sup>. They are coloured by ambition according to their label in the database; dark blue corresponds to scenarios tagged as '1.5 °C-compatible', light orange corresponds to 'lower-2 °C-compatible', and dark orange corresponds to 'higher-2 °C-compatible'. Panel b below shows the cumulative CO<sub>2</sub> emissions relative to 2018, which can be translated into the CO<sub>2</sub> warming contributions by multiplying by the TCRe. Panel c shows the corresponding non-CO<sub>2</sub> ERFs for each CO<sub>2</sub> emissions pathway (dotted lines, right axis). We would like to compare these scenarios to the CO<sub>2</sub> emissions, but we cannot simply apply the TCRe as we did for CO<sub>2</sub> as the total warming is non-linear when plotted against cumulative CO<sub>2</sub> emissions alone (dotted lines in panel d). If, instead, we express the non-CO<sub>2</sub> ERFs as cumulative CO<sub>2</sub>-fe emissions, they are now physically equivalent quantities and the cumulative CO<sub>2</sub>/CO<sub>2</sub>-fe

emissions time series in panels b and c (solid lines, left axis) can be directly compared. This would not be possible with CO<sub>2</sub>-equivalent emissions calculated using the GWP or GTP metrics, which do not accurately reproduce the warming outcome for a complex multi-gas emissions pathway<sup>29</sup>.

By converting the full range of pollutants into cumulative CO<sub>2</sub>-fe emissions we can use the TCRe in the same way we did for CO<sub>2</sub> alone. Figure 1d shows global temperatures plotted against cumulative total CO<sub>2</sub>-fe emissions (solid lines). Cumulative total CO<sub>2</sub>-fe emissions multiplied by the TCRe predicts the temperature response, just as in a pure-CO<sub>2</sub> scenario. If non-CO<sub>2</sub> radiative forcing were correlated with cumulative CO<sub>2</sub> emissions in these scenarios, 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-CO<sub>2</sub> drivers<sup>3,32,33</sup>. Figure 1d shows this is not always the case (nor is there any physical reason for it to be the case in complex multi-gas future scenarios)<sup>34</sup>; hence the impact of non-CO<sub>2</sub> forcing needs to be treated explicitly.

Having explained the utility of the CO<sub>2</sub>-fe metric for assessing the relative CO<sub>2</sub> and non-CO<sub>2</sub> contributions to warming in mitigation scenarios, we now turn to a single scenario and explore the contributions from individual pollutants in greater detail. The three light blue scenarios in Fig. 1 display the range of non-CO<sub>2</sub> RF pathways exhibited in 1.5 °C-compatible scenarios, with the central light blue pathway highlighting the P3 scenario from SR1.5's SPM Fig. 3b<sup>1</sup> (middle of the road scenario which achieves 1.5 °C ambition). Figure 2 shows a breakdown of the total CO<sub>2</sub>-fe emissions time series for this central light blue scenario in Fig. 1c. We extend back to pre-industrial using the historical RF time series from ref. <sup>35</sup>, and calculate individual CO<sub>2</sub>-fe emissions contributions using a differencing approach (see Methods). These individual contributions are stacked and coloured by pollutant, with the panel a showing the annual CO<sub>2</sub>-fe emissions, and panel b showing the same cumulatively. In contrast to CO<sub>2</sub>-equivalent emissions, whether computed with GWP<sub>100</sub> or any other conventional metric, CO<sub>2</sub>-fe emissions reflect the impact of individual climate drivers on global temperature (panel c), allowing them to be compared objectively. CO<sub>2</sub>-fe provides a transparent and easily implementable approach which translates readily to warming: cumulative emissions contributions in panel 2b correspond to warming levels in panel 2c (we have used a TCRe of 0.4 °C/TtCO<sub>2</sub>—our best-estimate TCRe found using



**Fig. 2** Central light blue 1.5 °C-compatible scenario from Fig. 1 displayed showing component contributions to warming. Panel a plots the annual CO<sub>2</sub> emissions and CO<sub>2</sub>-fe emissions for each of the major contributing pollutants (red = CO<sub>2</sub>, blue = CH<sub>4</sub> + Ozone + Strat. H<sub>2</sub>O, green = N<sub>2</sub>O, gold = Other and orange = Aerosols). Panel b shows the corresponding cumulative CO<sub>2</sub> and CO<sub>2</sub>-fe emissions time series (stacked by contribution to total). Panel c plots the temperature response for each component. Black solid lines show the total annual (panel a) and cumulative (panels b and c) CO<sub>2</sub>-fe emissions, while the total temperature response is shown with a black dotted line (all calculated from total RF). Small backscatter points on panel c show the annual temperature observations using four-dataset mean observations updated from SPM.1, SR1.5. FaIR-derived temperatures (panel c) use thermal parameters chosen to best emulate historical temperatures (TCR = 1.8 °C, ECS = 3.0 °C). RFs before 2020 are taken for individual components from Dessler and Forster (2018) RF dataset, with future component RF rescaled to match the component's best-estimate historical RF in 2020. Methane forcing is scaled by 1.65 to account for Ozone and stratospheric H<sub>2</sub>O contributions, following refs. <sup>40,30</sup>. Aerosol forcing is ~-0.9 W/m<sup>2</sup> in 2011, consistent with recent observationally constrained estimates (e.g. Stevens et al., 2015; AR5, 2013). Thin dotted lines show present-day best-estimate anthropogenic warming level (1.23 °C in 2020).



an observationally constrained methodology described in section 3 below).

Methane emissions make a net positive contribution to annual CO<sub>2</sub>-fe emissions until they begin to rapidly decline. Thereafter, the short atmospheric residence time of methane<sup>30</sup> means that falling methane emissions give a declining radiative forcing, equivalent to negative CO<sub>2</sub>-fe emissions. Aerosol cumulative CO<sub>2</sub>-fe emissions in Fig. 2b are negative, but show a sharp increase towards zero in the 2020s and 2030s, corresponding to a high associated CO<sub>2</sub>-fe emissions rate (orange in Fig. 2a), and consequently a rapid removal of the cooling effect that aerosols have been contributing over history. Long-lived pollutants like nitrous oxide behave like CO<sub>2</sub>. Note that the calculation of CO<sub>2</sub>-fe emissions is not model specific: with a linear CO<sub>2</sub> impulse response (IR) function (as used for the calculation of GWPs) one can calculate CO<sub>2</sub>-fe emissions with a simple matrix inversion and get very similar results (see Methods and ref. <sup>36</sup>). The accuracy of CO<sub>2</sub>-fe emissions for representing the radiative forcing and therefore temperature impacts of long- and short-lived pollutants gives it clear advantages over GWP<sub>100</sub> for presenting mitigation scenarios aimed at limiting global warming<sup>29</sup>.

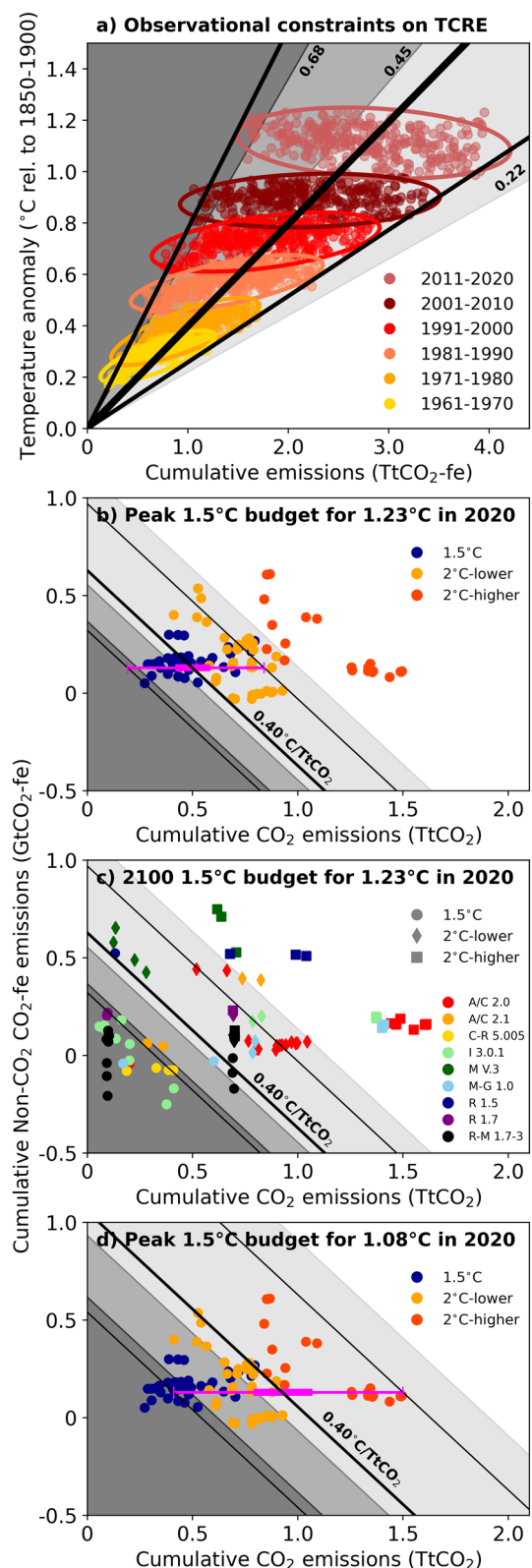
Total cumulative CO<sub>2</sub>-fe emissions and total anthropogenic warming are approximately proportional to the combined warming impact of CO<sub>2</sub> and methane, as indicated by cumulative CO<sub>2</sub>-plus-methane CO<sub>2</sub>-fe emissions, up to the present-day (red and blue in Fig. 2b, c), but diverge rapidly over the coming decades as aerosol forcing declines (orange). Strikingly, this aerosol decline contributes almost as much to future warming as the remaining CO<sub>2</sub> emissions in this central 1.5 °C-compatible scenario (panel c), highlighting the importance of common and comparable presentations of all climate drivers. Aerosols are often not included in figures showing multi-gas emission scenarios<sup>19</sup> because of the lack of a nonarbitrary way of displaying them on a common axis. This problem is resolved by CO<sub>2</sub>-fe. Individual contributions to CO<sub>2</sub>-fe emissions from 2020 to the time of peak warming under this scenario are CO<sub>2</sub>: 555 GtCO<sub>2</sub>-fe; methane: −65 GtCO<sub>2</sub>-fe; nitrous oxide: 65 GtCO<sub>2</sub>-fe; aerosols: 290 GtCO<sub>2</sub>-fe; other forcings: −45 GtCO<sub>2</sub>-fe; giving a total CO<sub>2</sub>-fe budget of 800 GtCO<sub>2</sub>-fe.

### Observational constraints on the TCRE

Having demonstrated how the TCRE can be extended to multi-gas scenarios using CO<sub>2</sub>-fe emissions, we now consider how CO<sub>2</sub>-fe emissions can be used to investigate the TCRE itself. Previous TCRE estimates<sup>37</sup> have compared cumulative pure-CO<sub>2</sub> emissions with warming attributable to CO<sub>2</sub> alone, but the fractional uncertainty in the latter is higher than uncertainty in total anthropogenic warming. Comparing total anthropogenic warming with total cumulative CO<sub>2</sub>-fe emissions over the historical record presents a useful complementary approach.

To estimate anthropogenic warming over the historical period, we use conventional ‘optimal fingerprinting’ applied to GMST, as is defined in Haustein et al. (2017)<sup>38</sup>. This uses a two-timescale IR model<sup>9,39,40</sup> to estimate temperature responses to anthropogenic and natural forcing (for which we use a 1000-member ensemble of representative ERF time series<sup>35</sup>). A four-dataset mean GMST observation time series is then regressed onto each pair of natural and anthropogenic temperature response time series to determine the most likely contribution from each component, with added CMIP6 PControl simulations included in the regression to account for internal climate variability. For a full discussion see Methods. Estimated anthropogenic warming in 2020 relative to 1850–1900 is 1.23 °C (1.06–1.42 °C) (5–95% confidence interval), higher than ref. <sup>1</sup> (SR1.5) due to updates in the datasets.

We express the 1000 anthropogenic ERF time series as CO<sub>2</sub>-fe emissions pathways<sup>25</sup> accounting for uncertainty in cumulative CO<sub>2</sub> airborne fraction to date ( $0.4 \pm 0.04$ <sup>41</sup>) in carbon cycle



parameters. Dots in Fig. 3a show estimates of the total anthropogenic warming and cumulative all-pollutant CO<sub>2</sub>-fe emissions, coloured by decade. For example, pink dots in Fig. 3a sample the resulting joint distribution of cumulative anthropogenic CO<sub>2</sub>-fe emissions 1875 to 2015 inclusive and human-induced warming to the decade 2011–2020 relative to 1850–1900.

**Fig. 3 Observational constraints on the TCRE and consequences for the design of Paris Agreement-compatible scenarios.** Panel **a** plots attributed human-induced warming against cumulative emissions of CO<sub>2</sub>. The space is shaded by the value of the TCRE (Gaussian distribution in best-estimate and likely range in AR5) and the points are coloured by the decade in which the temperature (relative to 1850–1900 baseline) and cumulative CO<sub>2</sub>-fe emissions (relative to 1875) are diagnosed. An ellipse is drawn around central 90% of points. Black lines in panel **a** depict the 5th, 50th and 95th percentile of the overall observationally constrained TCRE distribution based on the 2011–2020 decade. Panels **b–d** show the remaining CO<sub>2</sub> and non-CO<sub>2</sub> CO<sub>2</sub>-fe budgets for 2020 for each scenario in Fig. 1, coloured by category in the IIASA SR15 database. Panels **b** and **d** show remaining budgets to peak warming in each scenario, while panel **c** shows budgets to 2100 (instead coloured by IAM). In all three panels shading shows budgets compatible with limiting warming to 1.5 °C for the AR5 gaussian TCRE likely range, as in panel **a**. The solid black lines show the corresponding remaining total CO<sub>2</sub>-fe budgets instead of using our observationally constrained TCRE 5th–95th percentile range. In panels **b** and **c** the shading, therefore, corresponds to budgets for 0.27 °C remaining warming to 1.5 °C-consistent with 1.23 °C warming in 2020. In panel **d** the shading refers to budget for 0.42 °C remaining warming to 1.5 °C-consistent with 1.08 °C warming in 2020 (re-baselining historical GMST to 0.85 °C for the decade prior to 2015). Pink horizontal box-whisker plots in panels **b** and **d** show estimates of remaining CO<sub>2</sub> budgets for each assumed present-day warming level, assuming a mid-range non-CO<sub>2</sub> budget to peak warming (130 GtCO<sub>2</sub>-fe) and plotting the 5th, 33rd, 66th and 95th percentiles (see Methods for information on calculation). In panel **c** IAM abbreviations correspond to: A/C 2.0/2.1 – AIM/CGE 2.0/2.1; C-R 5.005 – C-Roads 5.005; I 3.0.1 – IMAGE 3.0.1; M V.3 – MESSAGE V.3; M-G 1.0 – MESSAGE-GLOBIOM 1.0; R 1.5/1.7 – REMIND 1.5/1.7; R-M 1.7-3 – REMIND-MaAqipe 1.7–3.0.

The cumulative anthropogenic CO<sub>2</sub>-fe emissions and human-induced warming estimate for each dot correspond to the same ERF time series to account for any covariance, while CO<sub>2</sub> airborne fraction and internal climate variability are sampled independently. Shading shows the AR5 gaussian TCRE distribution, with the likely range and median values highlighted. Ellipses are drawn around each decade's scatter of covarying temperature anomaly and cumulative CO<sub>2</sub>-fe emissions, encompassing the central 90% of the distribution, also coloured by decade. The best-fit TCRE is estimated as 0.40 °C/TtCO<sub>2</sub> (0.26–0.78 °C/TtCO<sub>2</sub> 90% confidence interval based on the most recent decade), marked with black lines in panel a. These could be interpreted as median and 5–95% percentiles of a probability distribution if the input ERF pathways are assumed to be equiprobable, but more research characterising the distribution of uncertainty in radiative forcing to date is needed<sup>42</sup>.

For comparison, SR1.5 uses a likely TCRE range of 0.22–0.68 °C/TtCO<sub>2</sub> taken from the assessment in AR5’s WG1 (SR1.5 also includes a 100–200 GtCO<sub>2</sub> budget correction accounting for differences between gaussian and log-normal TCRE distributions), while TCRES derived from the CMIP6 1%/yr CO<sub>2</sub> concentration increase experiment lie in the range 0.36–0.63 °C/TtCO<sub>2</sub> (see supplementary fig. 8, or ref. <sup>43</sup>). Other groups have separately diagnosed these (e.g. Williams et al. <sup>44</sup>), noting additionally that the inter-model spread is strongly affected by cloud feedbacks, particularly in high sensitivity models. Mengis and Matthews (2020) use the CO<sub>2</sub>-fe metric to demonstrate the bias introduced by assuming a constant fractional non-CO<sub>2</sub> contribution to warming in TCRE assessments and estimate the TCRE using a single warming pathway (~0.5 °C/TtCO<sub>2</sub>)<sup>34</sup>. Matthews et al. (2021) estimate an observationally constrained TCRE by removing a fractional warming contribution attributed to non-CO<sub>2</sub> pollutants, finding a median TCRE of 0.44 °C/TtCO<sub>2</sub> (0.32–0.62 °C/TtCO<sub>2</sub> 5–95th percentile range)<sup>45</sup>. We argue the contribution from

**Table 1.** TCRE percentiles and corresponding remaining carbon budgets to 1.5°C.

Percentile	TCRE (GMST) °C/ TtCO <sub>2</sub>	1.5 °C remaining CO <sub>2</sub> -fe budget (TtCO <sub>2</sub> ) (0.27 °C)	1.5 °C remaining CO <sub>2</sub> -fe budget (TtCO <sub>2</sub> ) (0.42 °C)	1.5 °C remaining CO <sub>2</sub> budget (TtCO <sub>2</sub> ) (0.27 °C) 130 (50–300) GtCO <sub>2</sub> -fe non-CO <sub>2</sub> budget	1.5 °C remaining CO <sub>2</sub> budget (TtCO <sub>2</sub> ) (0.42 °C) 130 (50–300) GtCO <sub>2</sub> -fe non-CO <sub>2</sub> budget	SR1.5 1.5 °C remaining CO <sub>2</sub> budget (TtCO <sub>2</sub> ) (GMST)	SR1.5 1.5 °C remaining CO <sub>2</sub> budget (TtCO <sub>2</sub> ) (GSAT)	Rogelj et al (2019) 1.5 °C remaining CO <sub>2</sub> budget (TtCO <sub>2</sub> ) (GSAT)
5th	0.26	1.04	1.62	0.91 (0.74–0.99)	1.49 (1.32–1.57)	–	–	–
17th	0.31	0.87	1.35	0.74 (0.57–0.82)	1.22 (1.05–1.30)	–	–	–
33th	0.35	0.77	1.20	0.64 (0.47–0.72)	1.07 (0.90–1.15)	1.08	0.84	0.74
50th	0.40	0.68	1.06	0.55 (0.38–0.63)	0.93 (0.76–1.01)	0.77	0.58	0.48
66th	0.46	0.59	0.92	0.46 (0.29–0.54)	0.79 (0.62–0.87)	0.57	0.42	0.32
83th	0.57	0.47	0.73	0.34 (0.17–0.42)	0.60 (0.43–0.68)	–	–	–
95th	0.78	0.35	0.54	0.22 (0.05–0.30)	0.41 (0.24–0.49)	–	–	–

Percentiles of the TCRE found in this study are shown in column 2. CO<sub>2</sub>-fe budgets for 0.27 °C additional warming (1.5 °C-compatible using GMST) and 0.42 °C additional warming (1.5 °C-compatible using GMST re-baselined to 0.85 °C over the decade up to 2015) shown in columns 3 and 4, respectively. Corresponding CO<sub>2</sub>-only budgets to 1.5 °C are shown in columns 5 and 6, with mid-range non-CO<sub>2</sub> contribution (range shown in brackets for a full range of 1.5-compatible non-CO<sub>2</sub> contributions). For comparison, the headline remaining budget estimates in SR1.5 and Rogelj et al. (2019) are shown in columns 7, 8 and 9.

Percentiles of the TCRE found in this study are shown in column 2. CO<sub>2</sub>-fe budgets for 0.27 °C additional warming (1.5 °C-compatible using GMST) and 0.42 °C additional warming (1.5 °C-compatible using GMST) re-baselined to 0.85 °C over the decade up to 2015) shown in columns 3 and 4, respectively. Corresponding CO<sub>2</sub>-only budgets to 1.5 °C are shown in columns 5 and 6, with mid-range non-CO<sub>2</sub> contribution (range shown in brackets for a full range of 1.5-compatible non-CO<sub>2</sub> contributions). For comparison, the headline remaining budget estimates in SR1.5 and Rogeli et al. (2019) are shown in columns 7, 8 and 9 (range shown in brackets for a full range of 1.5-compatible non-CO<sub>2</sub> contributions).

non-CO<sub>2</sub> pollutants should be determined explicitly using the CO<sub>2</sub>-fe methodology.

The remaining total CO<sub>2</sub>-fe emissions budgets for an additional 0.27 °C warming above 2020, corresponding to total warming of 1.5 °C, range between 350–1040 GtCO<sub>2</sub>-fe. A detailed breakdown by percentile are shown in Table 1 (see Supplementary Table 1 for equivalent budgets to 2 °C). We calculate the remaining budgets for additional anthropogenic warming relative to the best-estimate current level (1.23 °C) for consistency with Table 2.2 of ref. <sup>1</sup>, reflecting a policy focus on future warming relative to the recent past rather than including uncertainty in pre-industrial temperatures. The wide range of remaining total CO<sub>2</sub>-fe budgets we find here are largely a result of the range of present-day RF in our 1000-member total anthropogenic RF ensemble. Reducing RF component uncertainty and accounting for correlations between component RFs would better constrain this range, and is a focus for future research. Here we focus on defining the methodology to estimate the TCRE with CO<sub>2</sub>-fe.

Given these total remaining CO<sub>2</sub>-fe budgets, the question now becomes what fraction of this budget is used by CO<sub>2</sub> and non-CO<sub>2</sub> pollutants respectively. Figure 3b shows the proportions of the future total CO<sub>2</sub>-fe budget allocated to CO<sub>2</sub> and non-CO<sub>2</sub> in these scenarios. Shading indicates the remaining total budget compatible with 0.27 °C additional warming, again using the gaussian TCRE distribution reported in AR5 as in panel a, while solid black lines indicate the total remaining budget using our observationally constrained TCRE distribution from panel a. Scatter points indicate cumulative CO<sub>2</sub> and non-CO<sub>2</sub> CO<sub>2</sub>-fe emissions to peak warming in 1.5 °C-compatible, 2 °C-lower and 2 °C-higher scenarios from Fig. 1, with the colours indicating the scenario category as in Fig. 1. In these scenarios, the non-CO<sub>2</sub> contribution to the total remaining budget ranges from 50–300 GtCO<sub>2</sub>-fe, exactly the range determined in SR1.5 (where 250 GtCO<sub>2</sub> budget uncertainty was attributed to non-CO<sub>2</sub> scenario uncertainty). Depending on the TCRE, this means non-CO<sub>2</sub> scenario uncertainty contributes between 0.01 and 0.23 °C warming in these scenarios (using the observationally constrained TCRE 5th–95th percentile range). Importantly, dark blue 1.5 °C-compatible scenarios are consistent with their 1.5 °C peak warming categorisation—the scatter of blue dots sits over our best-estimate TCRE.

While individual scenario's CO<sub>2</sub> and non-CO<sub>2</sub> contributions to peak warming are shown in Fig. 3b, panel c instead plots the scenario's budgets out to 2100. Scenario categories are less clear if the budget is based on end of century warming—scenario categorisation appears overly conservative if the remaining budget is allocated to 2100, with around half of the 1.5 °C-consistent scenarios lying outside the likely range. Net-negative CO<sub>2</sub> emissions and declining non-CO<sub>2</sub> radiative forcing after mid-century reduce the cumulative contributions from both CO<sub>2</sub> and non-CO<sub>2</sub> pollutants (see Fig. 1b, c).

Further, Fig. 3c shows how this non-CO<sub>2</sub> contribution is influenced by the IAM choice. Colours indicate the IAM used to generate each scenario, confirming this is not a random distribution (as is discussed above in section 1), while the evident lack of correlation between cumulative CO<sub>2</sub> and non-CO<sub>2</sub>-fe emissions to peak warming undermines the use of an 'effective' (multi-gas) TCRE. Since CO<sub>2</sub> and non-CO<sub>2</sub> emissions are affected by different policies, it is potentially misleading to present them using a single index such as percentage aggregate CO<sub>2</sub>-equivalent emission reductions by a given date<sup>46</sup>. A two-dimensional presentation, separating CO<sub>2</sub> and non-CO<sub>2</sub> contributions to warming (as in panels 3b, c and d here), is the minimum required to ensure both indicators are on track to achieve a temperature goal. The sum of cumulative CO<sub>2</sub> and non-CO<sub>2</sub> CO<sub>2</sub>-fe emissions, multiplied by the TCRE, determines long-term warming.

The scenarios explored here do not represent a random distribution that can be sampled for a particular percentile, so accounting for non-CO<sub>2</sub> contributions to remaining CO<sub>2</sub>-only

budget estimates is more challenging. Subtracting a representative mid-range scenario's non-CO<sub>2</sub> contribution from estimated total CO<sub>2</sub>-fe budgets gives indicative pure-CO<sub>2</sub> budgets, indicated by horizontal box-whisker symbols in pink on Fig. 3 (using the central non-CO<sub>2</sub> RF scenario highlighted in Fig. 1). The range of non-CO<sub>2</sub> contributions implied by the non-CO<sub>2</sub> forcing scenarios as a whole indicates the potential for trade-offs between CO<sub>2</sub> and non-CO<sub>2</sub> warming.

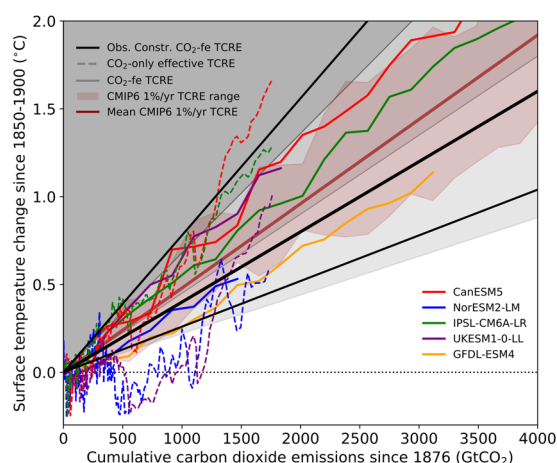
Using GMST warming of 1.23 °C in 2020 and the mid-range non-CO<sub>2</sub> forcing from Fig. 1 (130 GtCO<sub>2</sub>-fe), we find, for a 33, 50 and 66% chance of limiting warming to below 1.5 °C, indicative CO<sub>2</sub>-only budgets of 640, 545, 455 GtCO<sub>2</sub> respectively. We re-emphasise this is just one possible pathway for future non-CO<sub>2</sub> forcing, which will be determined by policy choices, some but not all of which also involve trade-offs and synergies with CO<sub>2</sub> policy. Exploring these trade-offs is a matter for policymakers. CO<sub>2</sub>-fe emissions, or warming-equivalent emissions<sup>30</sup> that are very similar and easier to calculate (see Methods), provide the necessary framework. SR1.5 gave 33rd, 50th and 66th percentile remaining carbon budgets for 1.5 °C GMST warming from 2018 of 1080, 770, 570 GtCO<sub>2</sub>, respectively. Our best-estimate remaining carbon budget for 1.5 °C from 2020, 545 GtCO<sub>2</sub>, is therefore consistent with SR1.5 having accounted for recent updates to the level of GMST and an additional 2 years of warming. SR1.5's GSAT best-estimate remaining carbon budget from 2018 is also consistent, albeit slightly more conservative (50th percentile remaining GSAT budget to 1.5 °C is 580 GtCO<sub>2</sub> from 2018) confirming that the infilled GMST products approximately correspond to GSAT remaining CO<sub>2</sub> budgets from the present-day. Our range of estimated remaining CO<sub>2</sub>-only budgets are given in Table 1, along with comparable budgets from SR1.5.

The definition of present-day anthropogenic warming plays a key role in determining the size of remaining budgets, and therefore in determining the appropriate categories for scenarios. However, re-baselining anthropogenic warming to be consistent with the assessment that 0.85 °C warming occurred up to the 2006–2015 decade relative to 1850–1900 (a statement which is used in the Structured Expert Dialogue to inform the Paris Agreement text<sup>14</sup>, and cited explicitly in discussions of 1.5 and 2.0 °C in the Paris Agreement by those familiar with the process<sup>47</sup>) results in a best-estimate remaining CO<sub>2</sub> budget from 2020 of 920 GtCO<sub>2</sub>. Figure 3d shows that, then, scenarios currently classified as 'lower-2 °C' are consistent with a peak warming of ~1.5 °C. While revised estimates of present-day GMST used in Fig. 3b mean remaining carbon budgets are consistent with those presented in SR1.5, other interpretations of temperature levels referred to in the Paris Agreement, possibly more consistent with the consensus on the current level of warming at the time the Agreement was signed, may result in significantly larger remaining budgets.

Figure 3b, c, d together show that the current classification of the IAM scenarios are much more consistent with peak warming defined by the increase in statistically infilled (i.e. GSAT-like) GMST datasets relative to pre-industrial levels. Defining temperature this way also restores consistency with most other studies of remaining budgets (see Supplementary Tables 1, 2 of ref. <sup>2</sup>), at the expense of consistency with reported present-day levels of warming associated with recent impacts<sup>14</sup>, although more closely aligning them with model-based studies of future impacts using GSAT<sup>18</sup>.

To complement the assessment of TCRES using observations of the climate system, the TCRES for a subset of CMIP6 GCMs can be calculated over history directly using CO<sub>2</sub>-fe emissions to account for the impact of non-CO<sub>2</sub> pollutants. Leach et al. (2020) demonstrate the FaIRv2.0<sup>48</sup> model can emulate the thermal and carbon cycle properties of CMIP6 GCMs, and provide fitted parameters for several CMIP6 models. RFMIP experiments<sup>49</sup> allow for the calculation of ERF time series over history (UKESM1-0-LL, NorESM2-LM, GFDL-ESM4) and extended up to 2100 where data is





**Fig. 4 TCRES calculated for a range of CMIP6 models.** FaIRv2.0 simple climate model used to emulate the carbon cycle and thermal responses of each GCM with parameters from Leach et al. (2021); forced with ERF time series diagnosed from ERF experiments completed as part of RFMIP. UKESM1-0-LL and GFDL-ESM4 calculated GCM diagnosed aerosol ERF time series over 1850–2014; NorESM2-LM, IPSL-CM6A-LR and CanESM5 calculated using transient anthropogenic ERFs from RFMIP runs. Solid lines show individual CMIP6 model TCRES calculated with CO<sub>2</sub>-fe over historical experiments (coloured by model), while dashed lines show CMIP6 models if the effective TCRE is plotted (1850–2014) from Lindicoat et al. (2021). Brown plume shows the CMIP6 TCRE range calculated with a 1%/yr concentration increase experiment (from Arora et al., 2020). Black shading shows the AR5 gaussian TCRE range, and black lines shows the observationally constrained TCRE range from Fig. 3.

available (CanESM5, IPSL-CM6A-LR). Using these, we diagnose the TCRES from estimates of the cumulative CO<sub>2</sub>-fe emissions budgets and associated warming for each GCM, plotted in Fig. 4 (coloured solid lines; the full description in SI). If total warming is instead plotted against CO<sub>2</sub> emissions alone, nonlinearities are introduced (see Fig. 4, Supplementary Fig. 11, and dotted lines in Fig. 1d). For these five models, we find a CMIP6 TCRE range of 0.35–0.68 °C/TtCO<sub>2</sub>, consistent with the range of observationally constrained GSMT TCRE from Fig. 3a (black lines in Fig. 4). CMIP6 ensemble members display TCRES which lie on average above the estimated 50th percentile of the observationally constrained distribution. Even UKESM1-0-LL and CanESM5, both of which have equilibrium climate sensitivities that are above the range consistent with historical observations<sup>13,50</sup> show high but not out-of-range TCRE estimates, lying around the 83rd percentile of the GSMT TCRE distribution. These estimated TCRES can be compared with TCRES calculated using the 1%/yr CO<sub>2</sub> concentration increase experiment (brown plume in Fig. 4), and calculated in ref.<sup>43</sup>. CMIP6 TCRES estimated with CO<sub>2</sub>-fe are near-identical to the estimates in Arora et al. (2020) using pure-CO<sub>2</sub>, indicating the CO<sub>2</sub>-fe methodology is indeed identifying the same TCRE parameter as in the 1%/yr idealised experiment. We present all calculated TCRES in supplementary table 2. The CMIP6 ensemble range appears to be consistent with the 5th–95th percentile TCRE found with historical observations, with extremes of the ensemble slightly under-sampling the observationally constrained upper and lower bounds. The mean response (0.48 °C/TtCO<sub>2</sub> in CMIP6 models assessed) is also somewhat higher than the observationally constrained result (0.40 °C/TtCO<sub>2</sub>). Simply using the CMIP6 range in isolation as an uncertainty interval, therefore, is potentially problematic, despite the range implying no significant bias. A better approach would use observations to constrain the CMIP6 ensemble TCRE range, such as the yes/no exclusion for models

based on historical temperature gradient reconstruction as suggested in Tokarska et al.<sup>24</sup>.

## DISCUSSION

Here we analyse IAM mitigation scenarios informing the IPCC's SR1.5 report, deconstructing them to highlight the relative contributions from CO<sub>2</sub> and non-CO<sub>2</sub> pollutants (Figs. 1 and 2). CO<sub>2</sub>-fe emissions provide a means to quantify non-CO<sub>2</sub> contributions to future scenarios, without relying on traditional metrics which do not translate readily into a corresponding warming response. Further, we demonstrate that a simple scaling factor, or 'effective TCRE', doesn't adequately account for the warming contribution from non-CO<sub>2</sub> drivers<sup>3,32,33</sup> as future non-CO<sub>2</sub> radiative forcing isn't tightly correlated with cumulative CO<sub>2</sub> emissions in these scenarios. We also use CO<sub>2</sub>-fe emissions to constrain the TCRE distribution based on historical temperature observations and radiative forcing estimates, and produce an observationally constrained remaining carbon budget estimate based on central non-CO<sub>2</sub> RF estimates, along with highlighting the covarying uncertainty in the physical climate response to CO<sub>2</sub> and non-CO<sub>2</sub> pollutants. We recommend that a two-dimensional presentation, which separates CO<sub>2</sub> and non-CO<sub>2</sub> contributions to warming (Fig. 3b–d) is the most transparent approach when displaying the physical constraints of remaining budgets.

A remaining carbon budget for 1.5 °C of 420 GtCO<sub>2</sub> from 2018 (the most widely quoted 66th percentile SR1.5 GSAT budget) is consistent with a current level of warming of 1.23 °C (in 2020 relative to 1850–1900)<sup>16</sup>, given an observationally constrained TCRE (0.40 °C/TtCO<sub>2</sub>; 0.26–0.78 °C/TtCO<sub>2</sub>), unless we experience a sudden increase in the TCRE or future non-CO<sub>2</sub> climate forcing above the upper end of the range in the SR1.5 1.5 °C-compatible scenarios (see Fig. 3b and Table 1; although recent updates to datasets of observed CH<sub>4</sub> and N<sub>2</sub>O mixing ratios suggest these are tracking a path higher than most future scenarios suggest<sup>51,52</sup>).

Re-baselining the current level of warming to 0.85 °C in the decade prior to 2015, a figure (based solely on GMST) that was used to contextualise the observed impacts of climate change in the Structured Expert Dialogue used to inform the Paris Agreement<sup>14,17</sup>, is inconsistent with SR1.5's remaining budget estimates, and means that scenarios conventionally referred to as 'Lower-2.0 °C-consistent' in the IIASA SR1.5 scenario database are in fact 1.5 °C-consistent (panel d). A similar misclassification occurs if CO<sub>2</sub> and non-CO<sub>2</sub> CO<sub>2</sub>-fe budgets are considered up to 2100 across the SR1.5 scenarios (panel 3c).

The decision on what index will be used to determine when 1.5 °C is reached has substantial policy implications and hence should not be determined by scientists alone. As long as observed warming continues to be reported in terms of GMST, continuing to report remaining carbon budgets in terms of GMST baselined to several periods (for example, both 0.85 °C over the decade prior to 2015; 1850–1900 pre-industrial baseline) seems the simplest and least policy-prescriptive option available. Regardless, we propose CO<sub>2</sub>-fe emissions are the most transparent method to analyse the relative contributions from individual pollutants to remaining warming, particularly in order to disentangle scenario from physical climate uncertainty.

## METHODS

### Calculating CO<sub>2</sub> forcing-equivalent emissions

CO<sub>2</sub>-fe emissions time series are computed with a four-pool carbon cycle model<sup>9,25,48</sup> based closely on the IR model used for metrics calculations in AR5<sup>8,53</sup>, but with a minor modification to allow state-dependent time-scales: for these ambitious mitigation scenarios, very similar results are obtained using the AR5 formula itself (see Supplementary Fig. 3). The similarity of the dotted and solid lines in Fig. 1c shows that, over these

scenarios and timescales, a  $1 \text{ W/m}^2$  change in ERF is approximately equivalent to  $1000 \text{ GtCO}_2\text{-fe}$ , consistent with Fig. 8.29 of ref. <sup>40</sup>.

To calculate  $\text{CO}_2\text{-fe}$  emissions we calculate the  $\text{CO}_2$  concentration associated with a given pollutant's RF scenario:

$$C_{\text{ref}+\Delta F}(t) = C_0 \exp\left(\frac{\ln(2)(F_{\text{ref}}(t)+\Delta F(t))}{F_{2x}}\right), \quad C_{\text{ref}}(t) = C_0 \exp\left(\frac{\ln(2)F_{\text{ref}}(t)}{F_{2x}}\right), \quad (1)$$

where  $F_{\text{ref}}(t)$  is the reference scenario's RF (i.e. the forcing due to all-pollutants other than the one we are considering), and  $\Delta F(t)$  are the RF of the given pollutant.  $F_{2x}$  is the RF for successive doublings in  $\text{CO}_2$  concentration.

Following this, we calculate the  $\text{CO}_2$  emissions compatible with each concentration pathway  $C_{\text{ref}+\Delta F}(t)$  and  $C_{\text{ref}}(t)$ :

$$E_{\text{ref}+\Delta F/\text{ref}}(t) = C_{\text{ref}+\Delta F/\text{ref}}(t) - C_0 - \sum_{i=0}^3 R_i(t-1)g_i; \\ \text{with } R_i(t) = a_i E(t) + R_i(t-1)g_i; \\ \text{and } g_i = \exp\left(\frac{-1}{a(t)\tau_i}\right), \quad (2)$$

$$\Delta E(t) = E_{\text{ref}+\Delta F}(t) - E_{\text{ref}}(t), \quad (3)$$

where  $E_{\text{ref}+\Delta F}(t)$  and  $E_{\text{ref}}(t)$  are the annual emissions at time  $t$  resulting in concentrations  $C_{\text{ref}+\Delta F}(t)$  and  $C_{\text{ref}}(t)$ .  $C_0$  is the pre-industrial  $\text{CO}_2$  concentration,  $a_i$  and  $\tau_i$  are coefficients defined in the AR5 IR model and  $a(t)$  is a scaling factor on response timescales to allow for a changing airborne fraction over time, as detailed in ref. <sup>3</sup>. Finally, we find the  $\text{CO}_2\text{-fe}$  emissions attributable to pollutants with RF time series  $\Delta F(t)$  by differencing the calculated annual emissions from the all forcing case, and the annual emissions for the case where we remove the RF from the pollutant:  $(\text{ref} + \Delta F) - (\text{ref})$ .

Figures 1, 2, 3 and 4 all rely on  $\text{CO}_2\text{-fe}$  emissions calculated as above by inverting the carbon cycle of FaIR. A differencing approach is taken when calculating individual pollutant  $\text{CO}_2\text{-fe}$  emissions time series, as this is suggested in Jenkins et al. (2018) to best account for nonlinearities in the carbon cycle response to under high RF perturbations<sup>25</sup>.

For ambitious mitigation scenarios, we can linearise the system to this calculation further. Now, a non- $\text{CO}_2$  ERF time series  $\Delta F(t)$  due to a particular climate forcing agent is converted to a perturbation  $\text{CO}_2$  concentration, accounting for the nonlinearity in  $\text{CO}_2$  forcing, as follows:

$$\Delta C(t) = C_0 \exp\left(\frac{\ln(2)(F_{\text{ref}}(t))}{F_{2x}}\right) \left( \exp\left(\frac{\ln(2)(\Delta F(t))}{F_{2x}}\right) - 1 \right) \approx \frac{\Delta F(t)}{RE} \quad (4)$$

where  $F_{\text{ref}}(t)$  is the forcing due to all other agents,  $F_{2x}$  is the forcing due to a  $\text{CO}_2$  doubling and  $C_0$  is the pre-industrial  $\text{CO}_2$  concentration, and  $RE$  is the radiative efficiency of  $\text{CO}_2$  given present-day concentrations. The  $\text{CO}_2\text{-fe}$  emission time series is then found using the following iterative formula:

$$\Delta E(t) = \Delta C(t) - \sum_{i=0}^3 R_i(t-1)g_i; \\ R_i(t) = a_i \Delta E(t) + R_i(t-1)g_i; \quad g_i = \exp\left(\frac{-1}{a(t)\tau_i}\right) \quad (5)$$

For ambitious mitigation scenarios, the linearization  $a(t) = 1$  and constant  $RE$  provides a very close approximation to the full carbon cycle inversion. Setting  $a(t) = 1$  in this way reproduces the linear IR model used in metric calculations of Chapter 8, AR5<sup>40</sup>.

### Approximating the $\text{CO}_2\text{-fe}$ calculation

The calculation of  $\text{CO}_2\text{-fe}$  emissions in Figs. 1 and 2 does not require a specific model. In the main text, we invert the carbon cycle in the FaIRv1.0 simple climate model to calculate compatible  $\text{CO}_2\text{-fe}$  emissions with a given forcing input. In Supplementary Figs. 3 and 4 we reproduce these figures by calculating the  $\text{CO}_2\text{-fe}$  emissions with the AR5 IR model<sup>2</sup>. This model is also employed for metric calculations in IPCC's AR5. The AR5 model is linear, meaning it can be inverted as a matrix to calculate  $\text{CO}_2\text{-fe}$  emissions<sup>54</sup>.

Converting all climate forcing agents to  $\text{CO}_2\text{-fe}$  emissions provides the most accurate and physically justified definition of an 'all-pollutants  $\text{CO}_2$  budget' but requires full forcing histories and an invertible carbon cycle model. On decade-to-century timescales, however,  $\text{CO}_2\text{-fe}$  emissions associated with any individual forcing agent may be approximated by 'warming equivalent' emissions,  $\text{CO}_2\text{-we}$ , a linear combination of the components RF level and trend over a recent time interval,  $\Delta t$ .

First, considering how  $\text{CO}_2$  emissions alone impact the global temperature anomaly. For  $\text{CO}_2$  the change in radiative forcing,  $\Delta F_{\text{CO}_2}$ ,

due to  $\text{CO}_2$  emissions over an interval  $\Delta t$  depends on both the cumulative  $\text{CO}_2$  emissions over that period,  $G$ , and the average- $\text{CO}_2$  induced forcing,  $\bar{F}_{\text{CO}_2}$ :

$$\Delta F_{\text{CO}_2} = \beta G - \rho \bar{F}_{\text{CO}_2} \Delta t \quad (6)$$

where the coefficient  $\beta$  is the additional radiative forcing per tonne  $\text{CO}_2$  emitted (around  $1 \text{ W/m}^2$  per  $1000 \text{ GtCO}_2$ ), and  $\rho$  is the rate at  $\text{CO}_2$ -induced RF declines after  $\text{CO}_2$  emissions reach zero. We can rearrange this formula to consider how to treat non- $\text{CO}_2$  radiative forcing contributions in terms of a cumulative  $\text{CO}_2\text{-we}$  budget,  $G_*$ :

$$G_* = (\Delta F + \rho \bar{F} \Delta t) / \beta \quad (7)$$

Therefore, to calculate the total human-induced warming associated with a  $\text{CO}_2$  emissions time series,  $E(t)$ , and a non- $\text{CO}_2$  forcing time series,  $F(t)$ , over a time period  $\Delta t$  we can write:

$$\Delta T = \kappa(G + G_*) = \kappa \left( G + \frac{\Delta F}{\beta} + \frac{\rho \bar{F} \Delta t}{\beta} \right) \quad (8)$$

where the first term in brackets are the cumulative  $\text{CO}_2$  emissions, the second is the  $\text{CO}_2$  budget associated with a change in non- $\text{CO}_2$  RF  $\Delta F$ , and the third is the  $\text{CO}_2$  emissions budget associated with the average global energy imbalance due to non- $\text{CO}_2$  sources,  $\bar{F}$ .  $\kappa$  is the TCRE. Values of  $\beta$  and  $\rho$  can be related back to the AGWP <sub>$\text{CO}_2$</sub> ; typical values are  $\beta = 1 \text{ W/m}^2$  per  $1000 \text{ GtCO}_2$ , and  $\rho = 0.3\%$  per year. The AR5 likely range for TCRE is  $0.45 \pm 0.23^\circ\text{C}$  per  $1000 \text{ GtCO}_2$  (and in Fig. 3 we estimate a TCRE likely range between  $0.26\text{--}0.78^\circ\text{C/TtCO}_2$ ) which far outweighs uncertainty in other coefficients. The third term is relatively small in almost all scenarios but is retained to emphasise that halting warming due to non- $\text{CO}_2$  climate drivers requires declining, not constant, non- $\text{CO}_2$  forcing, although the required rate of decline is small: of the order of  $1\text{--}3\%$  per decade. For comparison of this formula with the full  $\text{CO}_2\text{-fe}$  calculation see Supplementary Fig. 2.

These options, along with simplifications such as GWP\*, mean there are a number of alternatives to plotting the less physically representative GWP<sub>100</sub> emissions time series for non- $\text{CO}_2$  pollutants, even if in a given setting the full  $\text{CO}_2\text{-fe}$  calculation isn't appropriate.

### Observationally constrained TCRE estimate

We estimate the TCRE in Fig. 3 using an observationally constrained methodology. We first estimate the present-day temperature anomaly, using an optimal fingerprinting approach outlined in Haustein et al. (2017)<sup>38</sup>, and based on methodologies in refs. <sup>55,56</sup>.

The approach uses ordinary least-squares (OLS) regression onto observed GMST to find the residual-minimising combination of anthropogenic and natural temperature responses. For GMST we use a four-dataset-mean of HadCRUT5 (statistically infilled)<sup>57</sup>, NOAA<sup>58</sup>, Berkeley<sup>59</sup> and GISTEMP<sup>60</sup>, similar to Chapter 1, SR15<sup>17</sup>. The optimal fingerprinting methodology additionally samples uncertainty from internal variability (by sampling detrended CMIP6 PIControl experiment GSAT time series (104 members)<sup>61</sup>); along with a range of physical climate response parameters in the FaIR model when deriving temperature response shapes (18 members); uncertainty in the observed temperature anomaly using a 200-member ensemble of observational uncertainty from HadCRUT5. The derived present-day warming level ( $1.23^\circ\text{C}$  ( $1.06\text{--}1.42^\circ\text{C}$ ) in 2020;  $1.12^\circ\text{C}$  ( $0.90\text{--}1.33^\circ\text{C}$ ) average over decade 2010–2019) is in agreement with other recent assessments of the present-day warming level (e.g. Gillett et al., 2021).

With this derived warming level, we now must determine the corresponding all-pollutant cumulative  $\text{CO}_2\text{-fe}$  emissions. We do this by inverting the FaIRv1.0 carbon cycle as derived above, with carbon cycle response parameters determined by best-estimate fits the historical relationship between carbon emissions and concentrations (from Jenkins et al., 2018), using historical temperature observations to inform likely historical carbon cycle temperature feedback behaviour. A 1000-member all-pollutant total anthropogenic ERF ensemble from ref. <sup>35</sup> is used to calculate a 1000-member ensemble of cumulative  $\text{CO}_2\text{-fe}$  emissions over history, which we plot against the decadal warming levels to produce Fig. 3a. Ellipses are drawn around the central 90% of the underlying decade scatterpoint distributions, using a similar approach to that used in Fig. 1 in ref. <sup>62</sup>. TCRE estimates are found based on the decade (2011–2020). The observationally constrained TCRE distribution has a log-normal shape and is plotted in Supplementary Fig. 6.



## Defining remaining budgets to 1.5 °C

To define the remaining CO<sub>2</sub> budgets from present-day we must remove from the total CO<sub>2</sub>-fe budget the contribution from non-CO<sub>2</sub> sources of warming. Using the highlighted scenarios in Fig. 1c we find compatible non-CO<sub>2</sub> contributions of between 50–300 GtCO<sub>2</sub> to peak warming in 1.5 °C-compatible scenarios in the IIASA SR15 database, with a central estimate of 130 GtCO<sub>2</sub>.

The observationally constrained range of TCRES found in Fig. 3 of the main text is 0.26–0.78 °C/TtCO<sub>2</sub> (central 90 percent of distribution; 0.95–2.86 °C/TtC) with a best-estimate value of 0.40 °C/TtCO<sub>2</sub> (1.46 °C/TtC). Using the methodology of Haustein et al. (2017)<sup>38</sup> we find an estimated 2020 anthropogenic temperature anomaly = 1.23 °C, (5th–95th percentile = 1.06–1.42 °C) (see Supplementary Fig. 5d).

Therefore, the range of total CO<sub>2</sub>-fe remaining budgets to 1.5 °C assuming best-estimate warming to date is:

Max:  $(1.5 - 1.23) \times 1000 / 0.26 = 1040$  GtCO<sub>2</sub>

Min:  $(1.5 - 1.23) \times 1000 / 0.78 = 350$  GtCO<sub>2</sub>

Best-estimate:  $(1.5 - 1.23) \times 1000 / 0.40 = 680$  GtCO<sub>2</sub>

Assuming a central estimate of the 1.5 °C-compatible non-CO<sub>2</sub> budget remaining from 2020 to peak warming (130 GtCO<sub>2</sub>-fe in a central light blue scenario from Fig. 1, range 50–300 GtCO<sub>2</sub>-fe) we find the remaining carbon budget to 1.5 °C corresponding to different TCRES percentiles as follows:

5th percentile:  $(0.27 \times 1000 / 0.26) - 130 = 1040 - 130 = 910$  GtCO<sub>2</sub>  
(range: 740–990 GtCO<sub>2</sub>)

33rd percentile:  $(0.27 \times 1000 / 0.35) - 130 = 770 - 130 = 640$  GtCO<sub>2</sub>  
(range: 470–720 GtCO<sub>2</sub>)

50th percentile:  $(0.27 \times 1000 / 0.40) - 130 = 680 - 130 = 550$  GtCO<sub>2</sub>  
(range: 380–630 GtCO<sub>2</sub>)

66th percentile:  $(0.27 \times 1000 / 0.46) - 130 = 590 - 130 = 460$  GtCO<sub>2</sub>  
(range: 290–540 GtCO<sub>2</sub>)

95th percentile:  $(0.27 \times 1000 / 0.78) - 130 = 350 - 130 = 220$  GtCO<sub>2</sub>  
(range: 50–300 GtCO<sub>2</sub>)

This methodology is followed to find remaining CO<sub>2</sub>-fe budgets in Table 1 and to find CO<sub>2</sub>-only budgets at the 33rd, 50th and 66th percentile in the main text and for pink error bars in Fig. 3b, d.

## CO<sub>2</sub>-fe breakdown of an example 1.5 °C-compatible scenario

Figure 2 uses the same best-estimate historical ERF from ref. <sup>35</sup> which is the basis for the observationally constrained TCRES in Fig. 3. Over the remainder of the 21st century (after 2020) we use the central non-CO<sub>2</sub> forcing scenario from Fig. 1c (highlighted in light blue). Components of ERF are rescaled to match 2020 ERF in the historical ERF time series. Aerosol ERF is consistent with  $-0.9 \text{ W/m}^2$  in 2011 (the value reported in Chapter 8, AR5; refs. <sup>42,63</sup>).

Component CO<sub>2</sub>-fe budgets to peak warming are reported in the main text. Component 2100 budgets are: CO<sub>2</sub>: 140 GtCO<sub>2</sub>; methane:  $-455$  GtCO<sub>2</sub>-fe; nitrous oxide: 90 GtCO<sub>2</sub>-fe; aerosols: 500 GtCO<sub>2</sub>-fe; other forcings:  $-220$  GtCO<sub>2</sub>-fe; giving a total CO<sub>2</sub>-fe budget of 55 GtCO<sub>2</sub>-fe. Figure 2 reports a slightly different non-CO<sub>2</sub> cumulative CO<sub>2</sub>-fe budget to peak warming than is used in Fig. 3. This is a result of scalings which are used in Fig. 2 to match IAM output to historical ERF estimates (the difference is equivalent to around a year of warming).

## CMIP6 TCRES in Fig. 4

Figure 4 compares CMIP6 model TCRES to the observationally constrained distribution from Fig. 3. We use Arora et al. (2020)'s TCRES estimates using 1%/yr experiments, and compare to TCRES derived with a full CO<sub>2</sub>-fe methodology where available historical ERF data is available from RFMIP<sup>49</sup>. Parameters derived using FaIRv2.0 to reproduce carbon cycle behaviour in individual CMIP6 models are given in Leach et al.<sup>48</sup>. We use these to estimate the TCRES for the five models [CanESM5, UKESM1-0-LL, IPSL-CM6A-LR, NorESM2-LM, GFDL-ESM4] where ERF data is available. These TCRES (reproduced for individual models in Supplementary Table 2) agree well with 1%/yr concentration increase TCRES estimates in Arora et al. (2020). Historical CO<sub>2</sub> emissions from Lindicoat et al. (2020) are also used to show CO<sub>2</sub>-only effective TCRES (dashed lines).

## DATA AVAILABILITY

All data required to reproduce the figures in this paper are available freely online, and relevant databases and repositories are referenced in the text.

## CODE AVAILABILITY

All codes required to reproduce the figures in this paper are available from the corresponding author.

Received: 19 January 2021; Accepted: 13 September 2021;

Published online: 14 October 2021

## REFERENCES

- IPCC. *Summary for Policymakers of the Special Report on the Global Warming of 1.5 °C* (IPCC, 2018).
- Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférián, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335 (2019).
- Leach, N. J. et al. Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nat. Geosci.* **11**, 574 (2018).
- Millar, R. J. et al. Emission budgets and pathways consistent with limiting warming to 1.5 °C. *Nat. Geosci.* **10**, 741–747 (2017).
- Matthews, H. D., Gillett, N. P., Stott, P. A. & Zickfeld, K. The proportionality of global warming to cumulative carbon emissions. *Nature* **459**, 829–832 (2009).
- Quere, C. L. et al. Global Carbon Budget 2018. *Earth Syst. Sci. Data* **10**, 2141–2194 (2018).
- Huppmann, D. et al. *IAMC 1.5 °C Scenario Explorer and Data hosted by IIASA*. (Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis, 2018). <https://doi.org/10.22022/SR15/08-2018.15429>
- Joos, F. et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmos. Chem. Phys.* **13**, 2793–2825 (2013).
- 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. *Atmos. Chem. Phys.* **17**, 7213–7228 (2017).
- Ehlert, D. & Zickfeld, K. What determines the warming commitment after cessation of CO<sub>2</sub> emissions? *Environ. Res. Lett.* **12**, 015002 (2017).
- Allen, M. R. et al. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).
- Matthews, H. D., Zickfeld, K., Knutti, R. & Allen, M. R. Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets. *Environ. Res. Lett.* **13**, 010201 (2018).
- WMO. *WMO Provisional Statement on the State of the Global Climate in 2019* (WMO, 2019).
- UNFCCC. *Report on the Structured Expert Dialogue on the 2013–2015 Review* (UNFCCC, 2015).
- Tokarska, K. B. et al. Recommended temperature metrics for carbon budget estimates, model evaluation and climate policy. *Nat. Geosci.* **12**, 964–971 (2019).
- Gillett, N. P. et al. Constraining human contributions to observed warming since the pre-industrial period. *Nat. Clim. Change* **11**, 1–6 (2021).
- Allen, M. R. et al. Framing and Context. In: V. Masson-Delmott et al. (eds) *Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. (2018).
- Collins, M. et al. *Long-term Climate Change: Projections, Commitments and Irreversibility* (IPCC AR5, 2013).
- Matthews, H. D. & Zickfeld, K. Climate response to zeroed emissions of greenhouse gases and aerosols. *Nat. Clim. Change* **2**, 338–341 (2012).
- MacDougall, A. H. et al. Is there warming in the pipeline? A multi-model analysis of the zero emissions commitment from CO<sub>2</sub>. *Biogeosciences* **17**, 2987–3016 (2020).
- Jones, C. D. et al. The zero emissions commitment model intercomparison project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions. *Geosci. Model Dev.* **12**, 4375–4385 (2019).
- IPCC. *AR5 Synthesis Report: Climate Change 2014*. (IPCC, 2013). <https://www.ipcc.ch/report/ar5/syr/>.
- Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. A new scenario resource for integrated 1.5 °C research. *Nat. Clim. Change* **8**, 1027–1030 (2018).
- Tokarska, K. B. et al. Uncertainty in carbon budget estimates due to internal climate variability. *Environ. Res. Lett.* **15**, 104064 (2020).
- Jenkins, S., Millar, R. J., Leach, N. & Allen, M. R. Framing climate goals in terms of cumulative CO<sub>2</sub>-forcing-equivalent emissions. *Geophys. Res. Lett.* **45**, 2795–2804 (2018).

26. Mengis, N., Partanen, A.-I., Jalbert, J. & Matthews, H. D. 1.5 °C carbon budget dependent on carbon cycle uncertainty and future non-CO<sub>2</sub> forcing. *Sci. Rep.* **8**, 1–7 (2018).
27. Wigley, T. M. L. The Kyoto Protocol: CO<sub>2</sub> CH<sub>4</sub> and climate implications. *Geophys. Res. Lett.* **25**, 2285–2288 (1998).
28. Forster, P. D. et al. *IPCC Special Report on the Global Warming of 1.5°C* (IPCC, 2018).
29. Allen, M. R. et al. A solution to the misrepresentations of CO<sub>2</sub> -equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Npj Clim. Atmos. Sci.* **1**, 16 (2018).
30. Cain, M. et al. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *Npj Clim. Atmos. Sci.* **2**, 1–7 (2019).
31. Lynch, J., Cain, M., Pierrehumbert, R. & Allen, M. Demonstrating GWP<sub>ast</sub>: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. *Environ. Res. Lett.* **15**, 044023 (2020).
32. Matthews, H. D. et al. Estimating carbon budgets for ambitious climate targets. *Curr. Clim. Change Rep.* **3**, 69–77 (2017).
33. Millar, R. J. & Friedlingstein, P. The utility of the historical record for assessing the transient climate response to cumulative emissions. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **376**, 20160449 (2018).
34. Mengis, N. & Matthews, H. D. Non-CO<sub>2</sub> forcing changes will likely decrease the remaining carbon budget for 1.5 °C. *Npj Clim. Atmos. Sci.* **3**, 1–7 (2020).
35. Dessler, A. E. & Forster, P. M. An estimate of equilibrium climate sensitivity from interannual variability. *J. Geophys. Res. Atmos.* **123**, 8634–8645 (2018).
36. Allen, M., Jenkins, S., Sha, F. & Macey, A. Defining carbon neutrality, climate neutrality and net zero emissions. *Climate Policy* (2021, In Review).
37. Gillett, N. P., Arora, V. K., Matthews, D. & Allen, M. R. Constraining the ratio of global warming to cumulative CO<sub>2</sub> emissions using CMIP5 simulations. *J. Clim.* **26**, 6844–6858 (2013).
38. Hausteine, K. et al. A real-time global warming index. *Sci. Rep.* **7**, 15417 (2017).
39. Geoffroy, O. et al. Transient climate response in a two-layer energy-balance model. Part I: analytical solution and parameter calibration using CMIP5 AOGCM experiments. *J. Clim.* **26**, 1841–1857 (2012).
40. Myhre, G. et al. Anthropogenic and Natural Radiative Forcing. In: Stocker, T. F. et al. (eds) *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (2013).
41. Friedlingstein, P. et al. Global carbon budget 2019. *Earth Syst. Sci. Data* **11**, 1783–1838 (2019).
42. Bellouin, N. et al. Bounding global aerosol radiative forcing of climate change. *Rev. Geophys.* **58**, e2019RG000660 (2020).
43. Arora, V. K. et al. Carbon-concentration and carbon-climate feedbacks in CMIP6 models and their comparison to CMIP5 models. *Biogeosciences* **17**, 4173–4222 (2020).
44. Williams, R. G., Ceppi, P. & Katavouta, A. Controls of the transient climate response to emissions by physical feedbacks, heat uptake and carbon cycling. *Environ. Res. Lett.* **15**, 0940c1 (2020).
45. Damon Matthews, H. et al. An integrated approach to quantifying uncertainties in the remaining carbon budget. *Commun. Earth Environ.* **2**, 1–11 (2021).
46. United Nations Environment Programme (2019). Emissions Gap Report 2019. *UNEP, Nairobi*.
47. Mace, M. J. Mitigation commitments under the Paris Agreement and the Way Forward. *Clim. Law* **6**, 21–39 (2016).
48. Leach, N. J. et al. FalRv2.0.0: a generalised impulse-response model for climate uncertainty and future scenario exploration. *Geosci. Model Dev.* **14**, 1–29 (2020).
49. Pincus, R., Forster, P. M. & Stevens, B. The radiative forcing model intercomparison project (RFMIP): experimental protocol for CMIP6. *Geosci. Model Dev.* **9**, 3447–3460 (2016).
50. Tsutsui, J. Diagnosing transient response to CO<sub>2</sub> forcing in coupled atmosphere-ocean model experiments using a climate model emulator. *Geophys. Res. Lett.* **47**, e2019GL085844 (2020).
51. Tian, H. et al. A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* **586**, 248–256 (2020).
52. Ganesan, A. L. et al. Advancing scientific understanding of the global methane budget in support of the Paris Agreement. *Glob. Biogeochem. Cycles* **33**, 1475–1512 (2019).
53. Held, I. M. et al. Probing the fast and slow components of global warming by returning abruptly to preindustrial forcing. *J. Clim.* **23**, 2418–2427 (2010).
54. Smith, M. A., Cain, M. & Allen, M. R. Further improvement of warming-equivalent emissions calculation. *Npj Clim. Atmos. Sci.* **4**, 1–3 (2021).
55. Hegerl, G. C. et al. Detecting greenhouse-gas-induced climate change with an optimal fingerprint method. *J. Clim.* **9**, 2281–2306 (1996).
56. Hasselmann, K. Multi-pattern fingerprint method for detection and attribution of climate change. *Clim. Dyn.* **13**, 601–611 (1997).
57. Morice, C. P. et al. An updated assessment of near-surface temperature change from 1850: the HadCRUT5 data set. *J. Geophys. Res. Atmos.* **126**, e2019JD032361 (2021).
58. Smith, T. M., Reynolds, R. W., Peterson, T. C. & Lawrimore, J. Improvements to NOAA's historical merged land-ocean surface temperature analysis (1880–2006). *J. Clim.* **21**, 2283–2296 (2008).
59. Rohde, R. A. & Hausfather, Z. The Berkeley Earth land/ocean temperature record. *Earth Syst. Sci. Data* **12**, 3469–3479 (2020).
60. Lenssen, N. J. L. et al. Improvements in the GISTEMP uncertainty model. *J. Geophys. Res. Atmospheres* **124**, 6307–6326 (2019).
61. Eyring, V. et al. Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
62. Otto, A. et al. Energy budget constraints on climate response. *Nat. Geosci.* **6**, 415–416 (2013).
63. Stevens, B. Rethinking the lower bound on aerosol radiative forcing. *J. Clim.* **28**, 4794–4819 (2015).

## ACKNOWLEDGEMENTS

S.J., M.R.A., T.W. and P.F. acknowledge funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821003 (4C project). S.J. is supported by the NERC Doctoral Training Partnership NE/L002612/1. The authors thank Chris Smith for contributing transient ERF time series calculated as part of RFMIP experiments for use in the production of Fig. 4 and Spencer Lindicoat for providing CMIP6 historical CO<sub>2</sub> emissions time series in Fig. 4.

## AUTHOR CONTRIBUTIONS

S.J. and M.R.A. designed the study. M.C. and S.J. designed the simple formula approximating CO<sub>2</sub>-fe emissions in Methods. P.F. contributed CMIP6 model diagnosed CO<sub>2</sub> emissions and temperatures from 1%/yr runs for TCRE estimates and NG provided CMIP6 GSAT and GMST time series for comparisons of budgets in Fig. 3. T.W. and S.J. completed analysis of CMIP6 historical runs to estimate GCM TCRES in Fig. 4. All authors contributed to writing.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s41612-021-00203-9>.

**Correspondence** and requests for materials should be addressed to Stuart Jenkins.

**Reprints and permission information** is available at <http://www.nature.com/reprints>

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2021