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Assessing the size and uncertainty of remaining carbon budgets

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The remaining carbon budget (RCB), the net amount of CO_2 humans can still emit without exceeding a chosen global warming limit, is often used to evaluate political action against the goals of the Paris Agreement. RCB estimates for 1.5 °C are small, and minor changes in their calculation can therefore result in large relative adjustments. Here we evaluate recent RCB assessments by the IPCC and present more recent data, calculation refinements and robustness checks that increase confidence in them. We conclude that the RCB for a 50% chance of keeping warming to 1.5 °C is around 250 $GtCO_2$ as of January 2023, equal to around six years of current CO_2 emissions. For a 50% chance of 2 °C the RCB is around 1,200 $GtCO_2$. Key uncertainties affecting RCB estimates are the contribution of non-CO_2 emissions, which depends on socioeconomic projections as much as on geophysical uncertainty, and potential warming after net zero CO_2.

The remaining carbon budget (RCB) is the net amount of carbon dioxide (CO_2) humans can still emit while keeping global warming below a given limit with a given probability, taking into account the effect of other anthropogenic climate forcers[1,2]. The concept is key when considering the speed of decarbonization required to meet the goal of the Paris Agreement to keep global warming to well below 2 °C relative to pre-industrial levels and pursuing efforts to limit it to below 1.5 °C (ref. 3). Many approaches to equitable international climate action involve estimating the global RCB and dividing it among nations according to various principles of equity[4,5]. However the RCB for the Paris-relevant temperature targets (generally interpreted as a 50% chance of keeping global warming below 1.5 °C and anywhere from a 66% to 90% chance of 2.0 °C (ref. 6)) is small compared with the uncertainty in their values. This means subtle updates to the assessments can substantially affect the values, which makes their use challenging.

Previous work shows that the temperature rise is, to first order, not strongly dependent on when carbon emissions occur, only on their cumulative sum[7–13]; however, the RCB is strongly dependent on both how much and when different types of non-CO_2 emissions occur[14–19]. As a result, the RCB requires some set of scenarios describing co-evolutions of CO_2 and other emissions to estimate.

In the Working Group I (WG1) report for the IPCC Sixth Assessment Report (AR6)[1], a set of values were established using the approach presented in refs. 19,20, decomposing the RCB into CO_2 and non-CO_2 parts. The CO_2 part was assessed analytically by integrating information from multiple lines of evidence, while the non-CO_2 part was assessed using a reduced-complexity climate model (or emulator), MAGICC 7.5.1[21–23], calibrated to the IPCC AR6 assessment[24]. The impact of non-CO_2 emissions on the RCB was estimated by fitting a linear trend to the relationship between future non-CO_2 and future total warming at net zero CO_2 emissions for available scenarios in the database accompanying the IPCC Special Report on Global Warming of 1.5 °C (SR1.5)[25]. Following an update to historical data, an updated version of MAGICC (7.5.3) was available and used in the WG3 report[26,27].

The WG3 report discusses how updates to the non-CO_2 contribution at the time of net zero reduce the 1.5 °C RCB by about 100 $GtCO_2$ (about one-fifth) relative to estimates reported in WG1, although it did not tabulate values. It also makes comparisons between the RCB and the cumulative emissions until net zero of scenarios meeting a given temperature goal, which it finds approximately consistent with each other, although with less consistency for 1.5 °C of global warming than for higher levels. While this 20% change in the RCB estimate

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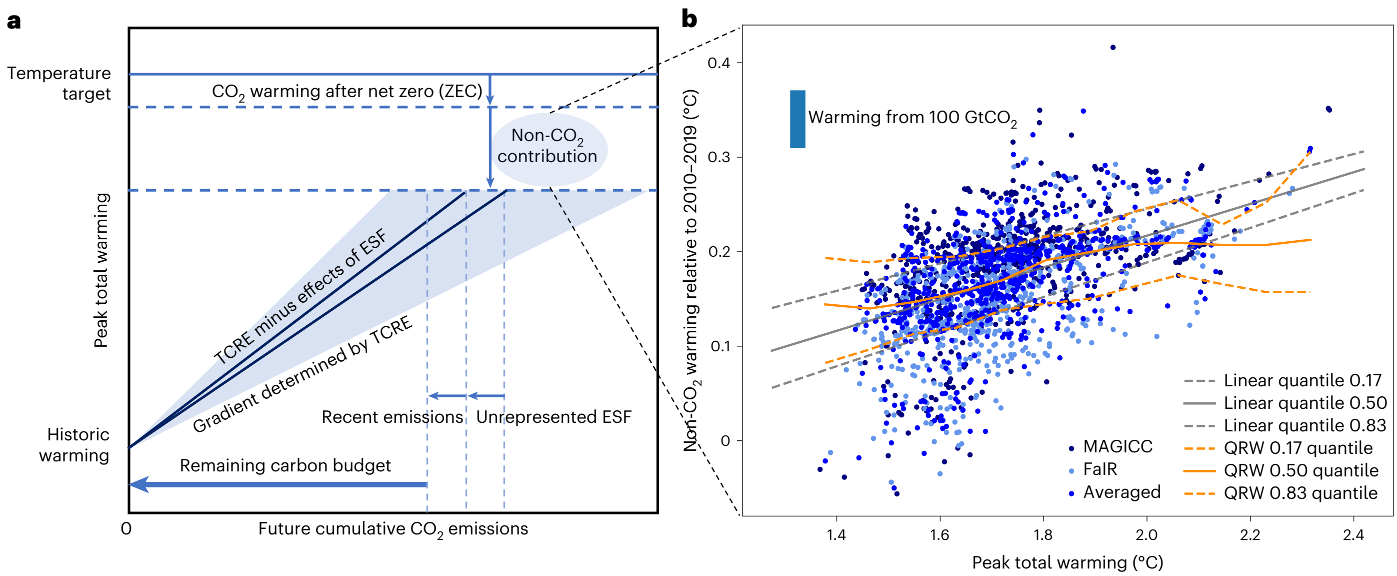

Fig. 1 | How the carbon budgets are calculated. **a**, Schematic of how different factors contribute to the remaining carbon budget, based on ref. 20. **b**, Non-CO_2 contribution to warming after 2010–2019 for updated MAGICC, FaIR and the average of these values for each scenario in the AR6 database when it reaches net zero CO_2. The bar at the top left indicates the median warming expected from 100 $GtCO_2$. We plot both the linear fit to the given quantiles and the quantiles of QRW fits to the averaged data points.

is small compared with the overall uncertainty and with past updates between the IPCC Fifth Assessment Report[8] and the SR1.5[19], it is politically important and warrants investigation.

In this Article, we update the RCB calculations fully and include results from an additional simple climate model calibrated for use in the latest IPCC report, FaIR[24,28]. We then present improvements to the calculation methodology and examine the impact of these changes. We assess the RCBs through six contributing factors following ref. 20 and present the results of various changes in calculation that lead to updated values. Where not otherwise mentioned, RCBs are listed for keeping warming to the specified warming limits with 50% probability.

Sources of uncertainty

The main contributing factors in the budget calculation assessed by WG1[1] are transient climate response to cumulative CO_2 emissions (TCRE, the temperature rise per unit carbon emitted[2,29]), historical warming (assessed human-induced global average temperature rise at present relative to pre-industrial levels), unrepresented Earth system feedbacks (ESFs), zero-emissions commitment (ZEC, the CO_2-based warming that continues after CO_2 emissions reach and are kept at net zero), warming from non-CO_2 emissions relative to the historical period and recent emissions. The equation combining these can be found in Methods, and a schematic of the equation is found in Fig. 1a. The values used for these variables can be found in Table 1.

Each of these factors comes with uncertainties, and the nature of and relationships between these uncertainties are complex. For example, while by default, uncertainty ranges are assumed to be normally distributed, other distributions for the range of TCRE are possible[30], as well as subtle nonlinearities[31]. Earth system feedbacks that are not included in the majority of Earth system models are notoriously difficult to quantify[1,20,29]. Relationships between these distributions probably exist but are under-researched; we discuss these in the Supplementary Information. Pre-industrial temperatures are also somewhat uncertain; the IPCC considers them known to only 0.2 °C accuracy, consisting of uncertainty both in the relevant period and in what historical temperatures were. However, knowing exactly what pre-industrial temperatures were is irrelevant when considering future impacts of climate change, and this uncertainty can shrink if a more recent historical benchmark is used with a predefined offset. The important point is that the same definition of historical temperature is used as in IPCC impact assessments and was intended by the Paris Agreement. In this way, we can call it a definitional uncertainty rather than uncertainty in future risk profile. This is explored further in the Supplementary Information. A similar definitional unclarity applies to the separation between CO_2 emissions from human-managed land-use changes and natural feedbacks included in the definition of TCRE. The problem can be removed by using a consistent database's definition for all terms.

In principle, ZEC can influence our calculation both when it is positive and when it is negative. In practice, a negative ZEC may be fully realized only after peak warming occurs and therefore be less relevant for limiting maximum warming. Thus, while the assessed distribution of ZEC is a Gaussian based around zero, for very delayed ZEC impacts, the effective impact of ZEC for our calculation may be defined only by the positive part of this distribution. A recent model intercomparison project on ZEC (ZEC-MIP[32]) indicates that for gradually declining emissions, some of the value identified as ZEC under the idealized conditions of an abrupt stop in emissions will be realized

Table 1 | Table of values defining CO_2 contribution to warming

Name	Value	Discussion
TCRE	0.27–0.63 °C per 1,000 $GtCO_2$ (1.0–2.3 °C per 1,000 PgC)	We investigate normal (default), positive-only normal and log-normal distributions.
Historical warming	1.07 °C 2010–2019	
ESF	26±97 $GtCO_2$	
ZEC	0±0.19 °C	Based on ref. 33. We also consider an asymmetric distribution, where negative values are set to 0, and 0±0.3, based on ref. 35.
Recent emissions	325 $GtCO_2$	Emissions from 2015 to 2021, estimated from ref. 45.

The default assumptions are all following ref. 1 except where specified.

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Table 2 | Absolute and relative changes in remaining carbon budgets at 50, 66 and 90% exceedance probabilities on changing single aspects of the calculation from the default update

Temperature (°C)	Change	Relative 50% (%)	Absolute 50% ($GtCO_2$)	Absolute 66% ($GtCO_2$)	Absolute 90% ($GtCO_2$)
1.5	Include permafrost in MAGICC results	−0.9	−3	−3	−3
1.5	Log-normal TCRE distribution	7.1	22	10	10
1.5	Positive-only normal TCRE distribution	2.0	6	6	8
1.5	Maximum non-CO_2 warming	−17.8	−56	−53	−54
1.5	Non-CO_2 warming at peak average total temperature, only NZ scenarios	−15.9	−50	−48	−48
1.5	Non-CO_2 warming at peak total temperature	−7.5	−24	−23	−23
1.5	Non-CO_2 warming at peak total temperature, only NZ scenarios	−17.4	−55	−52	−53
1.5	Non-CO_2 warming at preharmonized NZ	1.9	6	6	6
1.5	Non-CO_2 normalized 2010–2019	−1	−3	−3	−3
1.5	Recent emissions	36.8	117	117	117
1.5	Use QRW for non-CO_2 fit	−6.9	−22	−21	−21
1.5	Use SR1.5 database	−0.9	−3	−3	−3
1.5	ZEC only impacts if positive	−38.8	−123	−43	0
1.5	ZEC standard deviation 0	1.3	4	102	327
1.5	ZEC standard deviation 0.3	−0.5	−1	−93	−319
2	Include permafrost in MAGICC results	−0.6	−8	−7	−6
2	Log-normal TCRE distribution	8.5	105	62	−8
2	Positive-only normal TCRE distribution	0.9	11	9	13
2	Maximum Non-CO_2 warming	−7	−86	−77	−66
2	Non-CO_2 warming at peak average total temperature, only NZ scenarios	−2.6	−32	−29	−24
2	Non-CO_2 warming at peak total temperature	−4.8	−59	−53	−45
2	Non-CO_2 warming at peak total, only NZ scenarios	−2.7	−33	−29	−25
2	Non-CO_2 warming at preharmonized NZ	−0.6	−7	−7	−5
2	Non-CO_2 normalized 2010–2019	−0.3	−4	−4	−3
2	Recent emissions	9.5	117	117	117
2	Use QRW for non-CO_2 fit	1.5	19	16	14
2	Use SR1.5 database	−6.4	−78	−70	−60
2	ZEC only impacts if positive	−12.6	−155	−99	−19
2	ZEC standard deviation 0	0.3	4	57	172
2	ZEC standard deviation 0.3	−0.3	−4	−70	−221

NZ scenarios are scenarios reaching net zero after harmonization.

before net zero is reached[33], and this is replicated by simple climate models such as FaIR[34]. This means that a negative ZEC could result in a budget increase, but by how much is uncertain. Depending on the other characteristics of the pathway, the time taken for ZEC to materialize may also reduce its impacts; if the scenario has decreasing non-CO_2 warming, this can mask a positive ZEC, and vice versa. Typically ZEC measured until 50 years after emissions stop is used in RCB estimates[1], but the peak non-CO_2 warming in MAGICC and FaIR is typically much earlier. A pre-net zero negative ZEC may also mean that some low level of CO_2 is emitted after peak temperature has been reached and does not affect the value of the peak. To further complicate matters, ZEC-MIP suggests that the uncertainty in ZEC depends on future warming whereas the IPCC provides a ZEC assessment at only one level of cumulative carbon emissions. It reports a central value for ZEC after 1,000 PgC of cumulative carbon emissions of zero with an assessed likely range of ± 0. 3 °C in ref. 35; we include this uncertainty as a robustness case. This estimate is for 2 °C of initial warming, so it is probably a little high for the 1.5 °C budget[33].

Despite this uncertainty, we can set bounds on the impact these considerations might have. We explore the impact of ignoring negative ZEC in our calculation as an upper bound on ZEC occurring too late to prevent peak warming from exceeding the predefined global warming limit. Table 2 indicates that this would have a very substantial effect, reducing the 50% 1.5 °C budget by over a third. This is the largest single impact explored here. While this is a high estimate of the impact and indicates an impact that might materialize only in the decades after net zero CO_2 is reached, it emphasizes that an increased understanding of ZEC would be very valuable to improve the accuracy of our budgets. Symmetrically increasing the uncertainty of ZEC has only very minor impact on the median budgets but substantially reduces the budget for a 66% chance of limiting warming to 1.5 °C or 2 °C. Reducing it would increase the 66% budget.

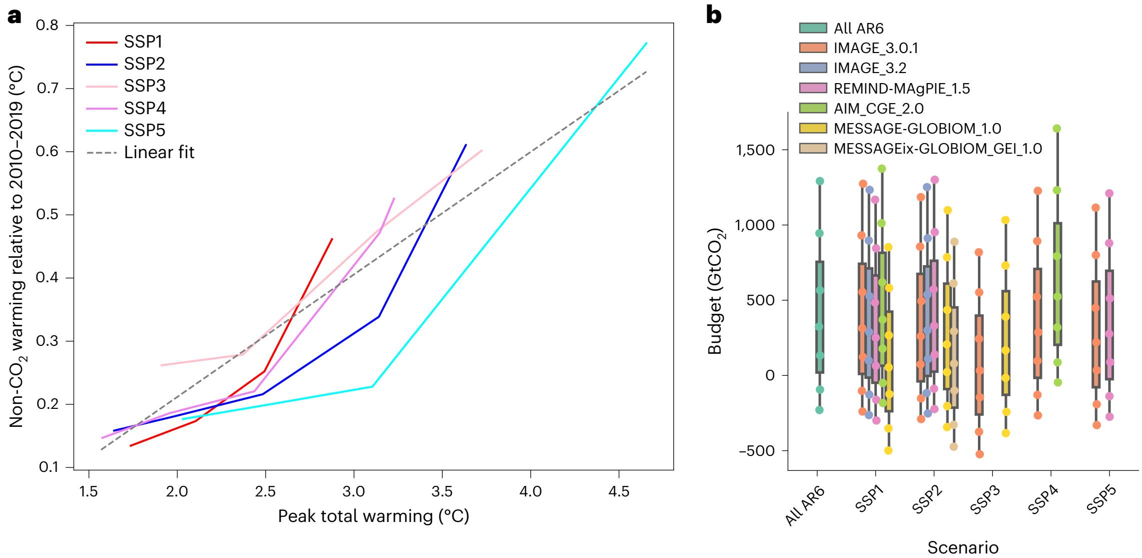

Fig. 2 | The impact of model and scenario family on carbon budgets. We use scenarios from the AR6 database to estimate non-CO_2 warming at peak warming by interpolating between scenarios from the same model with the same SSP (except for All AR6, where we interpolate between all scenarios). **a**, The impact of SSP family on non-CO_2 warming for IMAGE 3.0.1 scenarios (the only model with a complete set of SSPs). **b**, Budgets for 1.5 °C for different models and scenarios for models where there are at least three scenarios. All AR6 scenarios similarly interpolates the non-CO_2 warming between all AR6 scenarios. Box plots show median and 25th–75th percentile range; whiskers show the 10th–90th percentile values, with seven points per SSP/model group.

Non-CO_2 warming contribution

Estimating RCBs requires an estimate of how much non-CO_2 emissions will contribute to warming. This requires estimates of both how much we will emit of many different species over time and what impact they will have on the climate[36,37]. It therefore combines sociopolitical with geophysical uncertainty, which requires more complicated models than discussed so far. In an attempt to capture future socioeconomic developments, we use the AR6 scenario database[38], the most comprehensive current database of global emissions projections from different socioeconomic models. For assessing the geophysical uncertainty, we use two climate emulators. Full details of our emulator and database choices can be found in Methods. In the AR6 WG1 report, budgets were calculated with the emulator MAGICC and the SR1.5 database[25]; we explore adding FaIR and look at the impact of different versions of these models.

A version update to MAGICC (from version 7.5.1 to 7.5.3) reduced the 1.5 °C RCB by over 100 $GtCO_2$ (equivalent to roughly 0.05 °C in terms of temperature) due to a change in the historic aerosol emissions used to calibrate the model. A similar, although smaller, effect occurred when the FaIR model was updated. After combining the budgets, we find that the net effect of the updates is a 22% reduction of the 50% 1.5 °C RCB and a 13% reduction of the 66% 2 °C RCB. The budgets before and after updating are compared in Supplementary Fig. 1 and indicate uncertainties of around 100 $GtCO_2$ in the 1.5 °C budget and 200 $GtCO_2$ in the 2 °C budget from the geophysical impact of non-CO_2 emissions. This is broadly in line with the within-emulator uncertainty over non-CO_2 warming once the emulators are averaged, which gives 120 $GtCO_2$ for 1.5 °C and 210 $GtCO_2$ for 2 °C. Details of how we use these emulators to calculate non-CO_2 contributions are presented in Methods.

Previous estimates have assumed a linear relationship between additional temperature increase until peak warming and the non-CO_2 warming contribution until then. We investigate the impact of nonlinear relationships, fitting a local quantile regression function called quantile rolling windows (QRW, described in Methods) as seen in Fig. 1. While the median QRW line deviates substantially from the linear relationship for higher degrees of total warming, for the 1.5 °C and 2 °C budgets, the impact of allowing for a nonlinear relationship is less than 7% of the total budgets (Table 2).

The details of this are worth investigating. Projected non-CO_2 warming in pathways meeting 2.5 °C (at the lower end of a 'current policy' trajectory[39,40]) are 0.30 °C, compared with 0.13 °C in 1.5 °C-compliant pathways—a difference expected to be equal to the warming of over 350 $GtCO_2$. For 2 °C-compliant pathways, this non-CO_2 warming decreases to 0.22 °C, or around 190 $GtCO_2$ cooler than the 2.5 °C pathway. Subtle changes in calculation methodology or non-CO_2 mitigation effort could result in similarly large changes to the budget. The total non-CO_2 contribution is tabulated in the Supplementary Information.

Normally, RCBs are calculated using all scenarios available in a particular database because there is no particular reason to favour one model or family of scenario above another. However, it is also instructive to consider how each individual model and scenario family represents the relationship between total and non-CO_2 warming. In the AR6 database, only the IMAGE model has at least three results for all of the widely used family of scenarios known as shared socioeconomic pathways (SSPs). The SSPs, numbered one to five, represent different population, urbanization and education storylines with differing levels of challenges to mitigation of and adaptation to climate change, influencing GHG emissions and global warming projections[41]. We can estimate how the relationship between non-CO_2 warming for a given total temperature rise depends on a specific set of global socioeconomic assumptions by interpolating between individual scenarios in the same SSP group, as shown in Fig. 2a. Interestingly, Fig. 2a shows that for each SSP 'world' of scenarios, there is a highly nonlinear relationship between non-CO_2 warming and peak total warming. However, if the SSP world is unknown, the overall trend is approximately linear (dashed line). As expected from earlier literature looking at deep mitigation scenarios[42], non-CO_2 warming changes little with total warming for low total warming, but changes rapidly after some threshold. This threshold differs markedly between different SSP implementations. The different thresholds make the average fit to all SSP scenarios within the IMAGE model very linear; similar coincidences cause the linear approximation to be relatively good for the whole scenario collection.

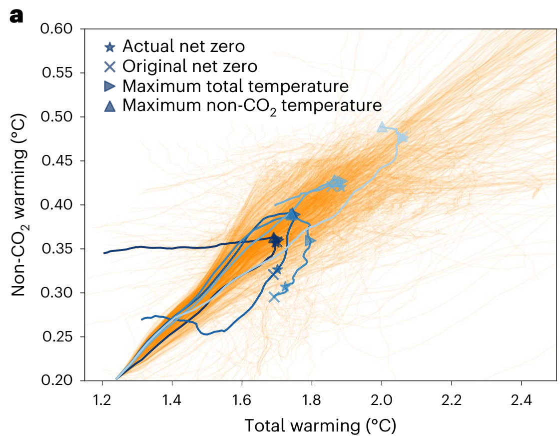

Fig. 3 | Relationship between total and non-CO_2 warming over time in each emulator. a, MAGICC. **b**, FaIR. Five pathways from different models in AR6, representative of types of scenario that reach net zero with different pathways, are highlighted, with markers indicating how different definitions of when to take non-CO_2 warming will affect the results. The same scenarios are highlighted in both plots in the same colour. Actual net zero refers to net zero in the final emissions data, whereas original net zero is for the scenario before harmonization.

In general, scenarios are designed to limit global warming to below a certain limit. Such scenarios aim to limit all GHG emissions, often modelled by applying a CO_2-equivalent price to all GHGs. Intuitively, one therefore expects a monotonic relationship between total warming and warming from non-CO_2 GHGs. However, clear limits to reducing non-CO_2 GHGs to zero have been identified, as insufficient mitigation measures have been identified to fully eliminate them for some activities such as agriculture[43]. Aerosol forcing, which cools Earth and generally reduces as CO_2 emissions do, also reduces the strength of the expected correlation. Typically, this floor of non-CO_2 warming is already achieved in pathways that limit warming below 2.0 °C and is not markedly reduced further when aiming to limit warming further to lower levels[42]. This minimum floor of non-CO_2 emissions determines to a large degree the non-CO_2 warming expected around the time CO_2 emissions reach net zero. Importantly, this minimum floor level can differ substantially both between models and between model configurations, for example, depending on assumptions about future socioeconomic development, what mitigation options are possible in a model or how land systems are treated. While the 17–83% uncertainty range in the fit to scenario data corresponds to a change in budgets of only around 100 $GtCO_2$, many individual scenarios lie several times this outside this range, as seen in Fig. 1b.

We also investigate the impact of model and SSP scenario family on RCBs (Fig. 2b). Similar plots for the SR1.5 database can be found in Supplementary Fig. 2. While results are clearly different for each combination, no clear trends emerge, assuaging concerns that over-representation of a few models or scenario families in the AR6 database might systematically bias the RCB calculations. This concern is also assuaged by the small impact of changing between the AR6 and SR1.5 databases (<1% change for the 50% 1.5 °C budget and 6% change at 2 °C; Table 2), which have very different distributions of scenarios. We find that the standard deviation between the 50% 1.5 °C budgets calculated with different single model–SSP combinations are around 120 $GtCO_2$ with scenarios from the AR6 database. The range of values across all model–SSP combinations is from 490 $GtCO_2$ to a minimum value of 80 $GtCO_2$. Carrying out the same analysis with the scenarios available in the SR1.5 database results in similar values. This emphasizes that, depending on how successfully non-CO_2 emissions are reduced, the 1.5 °C RCB can change by a factor of around two and that a more precise RCB estimate needs to be conditional on the non-CO_2 pathway to net zero. Equally, the use of RCBs to assess the global warming performance of pathways can be made more accurate if these sorts of conditional RCBs are used for comparison instead of generic central estimates.

Timing of non-CO_2 warming

The RCB is properly defined as the cumulative CO_2 emissions until annual net CO_2 emissions become zero. However, in virtually all pathways, CO_2 is the only major GHG to reach net zero. Residual emissions of other long-lived GHGs mean that Earth may continue to warm after reaching net zero. In practice, most scenarios that reach net zero CO_2 in our scenario databases then achieve net negative CO_2 emissions, and these negative emissions soon cancel out the warming from other forcers. Furthermore, both emulators used in this study have slightly negative ZECs (despite being calibrated to the IPCC AR6 assessment, which reports that the assessed value of ZEC is close to zero but with low confidence in the sign[32,33,35]). This negative ZEC in the emulators usually prevents rises in median temperature in net zero scenarios to the end of the century. These facts defang but do not resolve the question of when we should measure the non-CO_2 warming.

Our default definition of non-CO_2 warming is the non-CO_2 contribution to warming at the time CO_2 emissions become net zero, consistent with recent IPCC RCB estimates[1]. It has the benefit of decoupling the time used for determining non-CO_2 warming from the temporal evolution of the emulator's temperature response. This, for example, reduces the impact of the emulator's negative ZEC. It is, however, not the right choice of timing to ensure a given temperature is not exceeded because it does not estimate the non-CO_2 contribution at the time of peak temperature. We therefore consider variations on this assumption, described in detail in Methods and plotted for a few scenarios in Fig. 3. We find that while in some scenarios different approaches will get very similar results, in other scenarios results may differ by more than 0.1 °C. Some alternative approaches that can be considered are the non-CO_2 warming at the time of the model-reported net zero date (the date of net zero before emissions were harmonized to be consistent with recent emissions[44]), the maximum possible non-CO_2 warming at any point over the twenty-first century and the non-CO_2 warming at maximum total temperature. The impact of changing between these measures is investigated in Table 2. Most pathways do not reach net zero and therefore do not contribute to the calculation in the first two approaches. It will generally improve results to also exclude them from other approaches since these scenarios do not reach their peak temperature during the twenty-first century and so do not have well-defined RCBs.

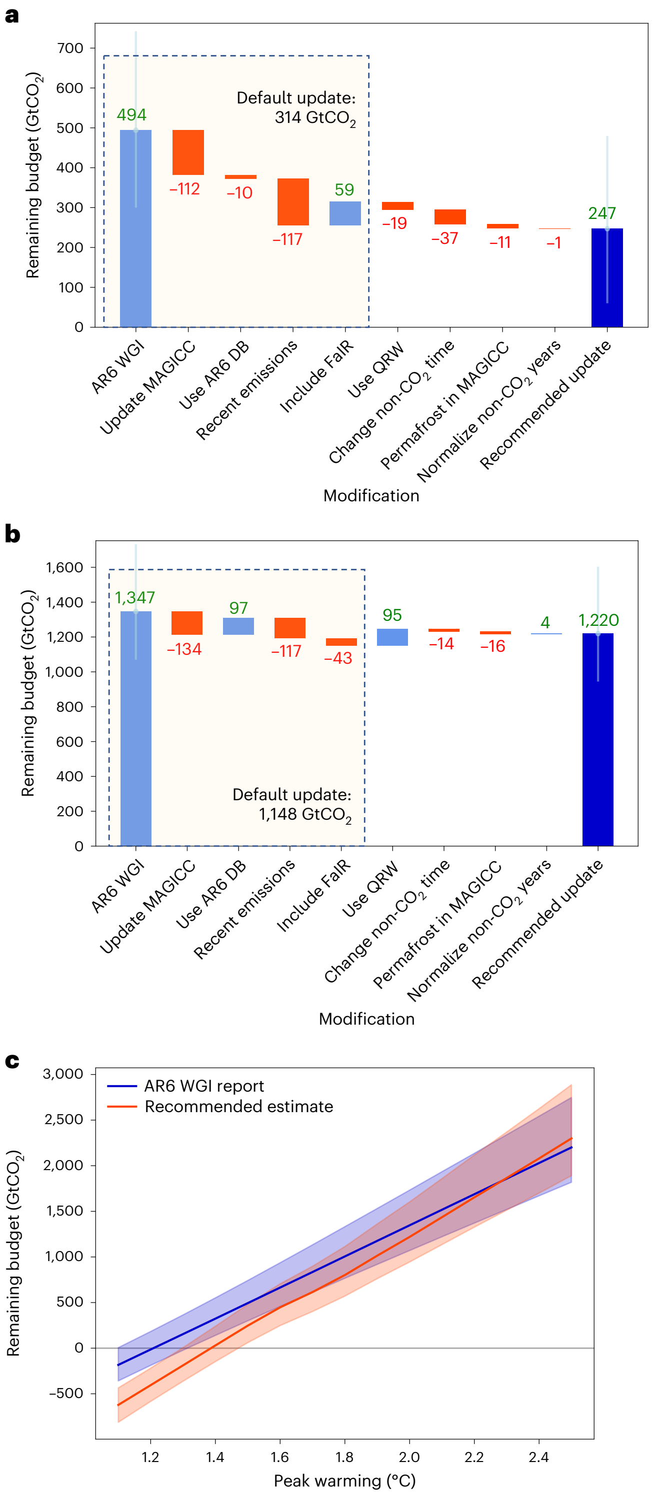

Fig. 4 | Plots of the changes to the carbon budget from each modification of the calculation. **a**, RCB for 50% chance of 1.5 °C. **b**, RCB for 50% chance of 2 °C. **c**, RCB for a range of temperatures (displaying only WG1 and updated budgets). Uncertainty intervals indicate 33rd and 66th percentile budgets considering uncertainty distribution in CO_2 warming factors. Our default update corresponds to the changes until the use of QRW. In **a** and **b**, lighter blue represents an increase and red represents a decrease in the budget with each step.

The maximum non-CO_2 warming is an upper bound on the non-CO_2 term (which is negative in the equation for the RCB) rather than a fair estimate. The original (before harmonization to recent observations) net zero test functions as a robustness check against any distorting impact of harmonization on pathways. Table 2 shows that the influence of this standard operation is minor. The most appropriate estimate of non-CO_2 warming comes from the estimates of non-CO_2 emissions at the time of peak warming since this is the deciding point for whether the scenario exceeds a particular limit. To combine the evidence that comes from the non-CO_2 warming estimates of MAGICC and FaIR, the temperature trends of the two emulators should be averaged before a maximum is found because otherwise the estimates may come from different years. Furthermore, viewing the two estimates as the true value plus an error term, averaging first and then finding the maximum allows more opportunities for error cancellation. We therefore consider average-first non-CO_2 warming at peak total temperature the best estimate of the marginal effect of non-CO_2 warming on the peak temperature. It is generally higher than the average non-CO_2 warming at net zero and hence decreases the 50% 1.5 °C RCB by 16% (Table 2). We use this technique in our 'recommended update'. The temperature limit indicated by this non-CO_2 contribution is generally temporary and before peak CO_2 warming is reached; hence, the older practice (continued in our 'default update') of taking the contribution at net zero might be justified. The default update simply incorporates new data into the pre-existing methodology; the recommended update includes calculation methodology changes.

Comparison of recommended result with AR6 WG1 results

The RCB factors updated from the AR6 WG1 report to the approach we recommend can be summarized as follows: more recent emissions were included; the version of the climate emulator MAGICC was updated and calculations from FaIR were included; the database of scenarios was changed from SR1.5 to AR6; the non-CO_2 trend was found using QRW instead of a linear trend; and the non-CO_2 warming is taken at the time of peak total warming from scenarios that reach net zero instead of at the time of net zero. As seen in Fig. 4, recent emissions, recalibrating MAGICC and the addition of FaIR had the largest impact. The difference between recommended and previous budgets is small by 2 °C, and the updated RCB for higher degrees of warming is larger for temperature rises above 2.2 °C. A diagram of budgets with different MAGICC and FaIR versions can be found in Supplementary Fig. 1. Including a variety of emulators increases the robustness of the estimate as does making non-CO_2 assumptions explicit; applying a nonlinear relationship for estimating non-CO_2 warming as a function of total warming, choice of time for non-CO_2 warming and the database of scenarios is less impactful.

After making all these changes, our best (50%) RCB estimate starting from 2022 is 250 $GtCO_2$ (17–83% range from uncertainty in the impact of CO_2: −170 to 840 $GtCO_2$) for the RCB for limiting warming to 1.5 °C. The same uncertainty in the modelled impact of non-CO_2 forcing gives a range of 160–280 $GtCO_2$. We can combine these uncertainties using a generalized extreme values functional fit to the quantiles (described in Methods), resulting in a range of −200 to 830 $GtCO_2$. Note that the skew on non-CO_2 uncertainty lowers both limits. For 2 °C, we have 1,220 $GtCO_2$ (650–2,270 $GtCO_2$ from CO_2; 600–2,240 $GtCO_2$ including non-CO_2 uncertainty). For limiting warming to 2°C with 66% or 90% probability, the RCBs are estimated at 940 and 500 $GtCO_2$, respectively. With 40 $GtCO_2$ emitted in 2022[45], this is roughly equivalent to 23 and 12 years of current CO_2 emissions for a 66% or 90% chance, respectively, of limiting warming to 2 °C and 6 years of emissions for a 50% chance of 1.5 °C. Translated into linear paths to net zero, this implies reaching global net zero CO_2 emissions around 2070, 2050 and 2035.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01848-5.

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Methods

The equation for the RCB B for a temperature T is expressed as

$$B = \left(T - \text{ZEC} - \delta T_{\text{nonCO}_2}(T) - \delta T_{\text{historic}}\right)/\text{TCRE} - \text{ESF}(T) - E_{\text{recent}}, \quad (1)$$

for $\delta T_{\text{historic}}$ the historical warming, $\delta T_{\text{nonCO}_2}$ the non-CO_2 warming, ESF the CO_2 emitted from any Earth system feedbacks otherwise not covered by the TCRE uncertainty and E_{recent} emissions that occurred too recently to be accounted for in the period of historical warming. Values for these can be found in Table 1 and a schematic is in Fig. 1a. This equation is used for all parts of this study, and we propose to modify only the distributions of individual terms. Diagrams showing the relationships between distributions of TCRE and distributions of RCB can be found in Supplementary Fig. 3. Robustness checks using emulators that would be sensitive to correlations between variables are presented in Supplementary Fig. 4.

For each temperature target, 10 million values for ESF, ZEC and TCRE are drawn from the relevant distributions (Table 1), assuming independence between each of the estimates, combined with the best estimate of non-CO_2 warming contribution for this level of peak warming and plugged into equation (1). Quantiles of the resulting budgets are then calculated. Where the normal distribution is used to capture the uncertainty in TCRE, it is possible to obtain a negative TCRE value. This would be an odd assumption that often results in a negative budget. However, this negative budget is the lower bound rather than the upper bound for emissions reaching that temperature target. The probability of a negative TCRE is less than 1% with our distribution based on the IPCC AR6 assessment[1]; for this reason and for visual clarity, graphs such as Supplementary Fig. 3 do not depict the top and bottom 1% of results for any distribution. The impact of replacing these negative TCRE draws with a very small positive value (a positive-only normal distribution) is investigated in Table 2 and found to be minor for 50%–90% budgets; it is only relevant to the extreme-probability budgets. ESF is expressed as CO_2 emitted per degree of warming and is also given by a normal distribution of values multiplied by future warming; its impact is small for budgets below 2.5 °C, so we do not consider robustness checks of this. The emissions from 2020 to 2022 were not included in the WG1 budgets and were recently evaluated as amounting to 121 $GtCO_2$ (ref. 45), although changes in the estimates of emissions in earlier years mean that our recent emissions change by 131 $GtCO_2$.

For the non-CO_2 components of projections, we default to (and recommend using) the AR6 scenario database[38] but also investigate the use of the SR1.5 database[25] for comparison with previous IPCC RCBs. The emissions scenarios in both databases are vetted to ensure that key emissions species and socioeconomic variables are within reasonable ranges in the recent past and near future, then harmonized to match historical emissions precisely and infilled with any missing emissions[44].

The emissions scenarios from the AR6 and SR1.5 databases are then run through reduced-complexity climate model emulators. For climate emulators, we use runs from both MAGICC 7.5.3[21] and FaIR 1.6.2[28]. By default, we use versions of the emulators calibrated to assessments in the AR6 WG1 report[24], but we also compare these results with runs using older model versions and pre-AR6 calibrations (MAGICC 7.5.1 and FaIR 1.3.4) for robustness checks. Both versions of MAGICC also have the option of including a module designed to mimic the effects of permafrost thawing; the impact of turning this option on is also investigated. Note that this affects only the relationship between total warming and non-CO_2 emissions as the feedback of permafrost melting on the warming per unit of CO_2 is included in the ESF.

The non-CO_2 warming contribution is calculated slightly differently in FaIR and MAGICC. In FaIR, we calculate the warming from only anthropogenic emissions and the warming from the same scenarios with only anthropogenic CO_2 emissions. We subtract the average temperatures in the period 2010–2019 from each case, and the difference between these values is then the non-CO_2 contribution to warming. In MAGICC, we do three experiments for each scenario: one with all emissions and natural climate forcers, one with anthropogenic forcers only and one with anthropogenic CO_2 emissions only. The difference between the all anthropogenic forcers and anthropogenic CO_2-only experiments is the non-CO_2 contribution to warming. We use a different approach to MAGICC when processing FaIR data because by default, FaIR includes the effects of a substantial solar cycle in future emissions, which we avoid including. Precalculated MAGICC and FaIR results for all these cases are included in the codebase for running these calculations.

In all cases, the peak temperature in the emulator until 2100 is compared with the non-CO_2 warming at various times, depending on the non-CO_2 peaking definition (see discussion in main text). The default peaking choice, in keeping with previous work, is the non-CO_2 warming at the time the scenario actually reaches net zero in the harmonized emissions, but we also consider the time it originally reached net zero CO_2 before CO_2 emissions were harmonized to recent historical data (non-CO_2 warming at original net zero CO_2); the non-CO_2 warming at peak total warming, either in all cases or restricted to scenarios that make net zero (after harmonization); the non-CO_2 warming at the time of peak total warming in MAGICC, conditional on meeting net zero (after harmonization); and, very conservatively, the maximum non-CO_2 warming experienced in the twenty-first century. While non-CO_2 warming at net zero CO_2 is defined only for emissions trajectories that reach net zero CO_2 (either before or after harmonization), it can also be calculated for scenarios that never reach net zero. These scenarios typically are either high warming, and hence less relevant for low-warming calculations, or nearly reach zero, meaning the difference between approaches is smaller.

Whichever value of non-CO_2 warming is used, the rest of the calculation is the same. If both MAGICC and FaIR are used, the peak warming and non-CO_2 warming are averaged before the fit to the relationship is made, as seen in Fig. 1b.

There are several ways of fitting a relationship of non-CO_2 warming contribution to total warming at peak. The default method is a linear trend, which fits a straight line to the points using quantile regression to find the 50th percentile. This is preferred to a least-squares fit, which would be more influenced by extreme points. Alternatively, this fit can be performed using a QRW method, which weights points according to $1/(1 + \Delta x^2)$ for Δx the distance along the x axis, normalized by a value proportional to the total range of x values. With this weighting, weighted quantiles are evaluated at ten points equally spaced across the x axis, and results for points in between are linearly interpolated. See ref. 46 for more details on this method. This technique is reasonably similar to calculating the rolling quantiles of points but with smoother behaviour and defined over a wider x-axis interval. A third technique is linear interpolation, which is appropriate only when few data points are available. We linearly interpolate between these known points to find the non-CO_2 warming corresponding to this total temperature rise, with total temperatures outside the known range assumed to have non-CO_2 warming equal to the closest point.

For runs where only a single model/scenario family is used, we filter the database for each specific model and then look for cases with at least three scenarios with names starting 'SSPn' for n between 1 and 5. We calculate the non-CO_2 component using the non-CO_2 warming at peak total warming of these cases, not filtering out scenarios that do not reach net zero to avoid a lack of data. Linear interpolation is used to make the fit.

To combine errors from CO_2 and non-CO_2 physical uncertainty, we fit a generalized extreme value distribution (GEV) to the quantiles of the data for each at each relevant temperature, following the approach of ref. 47. For the CO_2 error (the largest contribution), we fit the GEV to the 0.1, 0.17, 0.33, 0.5, 0.66, 0.83 and 0.9 quantiles of standard runs. For the non-CO_2 uncertainty, we make runs using the 0.17, 0.5 or 0.83 non-CO_2 warming temperature quantiles for each scenario. Fits to the scenario warming are made as before and budgets calculated. A GEV fit to the 50% probability budget as a function of the non-CO_2 quantile is made, and to convert this into an uncertainty, we subtract that value at 0.5 non-CO_2 warming. The combined error is then determined by adding a million draws from the two GEVs together and calculating the relevant quantiles of the result.

Data availability

The required statistics from runs of MAGICC and FaIR are available from Zenodo: https://doi.org/10.5281/ZENODO.8332951 ref. 48.

Code availability

The original code used to generate the data is available from Zenodo with the data[48]. Updates to the codebase are available from https://github.com/Rlamboll/AR6CarbonBudgetCalc.

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Author contributions

R.D.L., J.S.K. and J.R. conceived the experiments. R.D.L., Z.R.J.N. and C.J.S. wrote and executed code to collect data. R.D.L., E.B., J.S.K. and J.R. analysed the data. All authors contributed to writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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