Assessing the size and uncertainty of remaining carbon budgets

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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 carbon dioxide 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 shifts. Here we evaluate recent RCB assessments by the IPCC and explain differences between them. We present calculation refinements together with robustness checks that increase confidence in RCB estimates. We conclude that the RCB for a 50% chance of keeping warming to 1.5°C is around 300 $GtCO_2$ as of January 2022, less than 8 years of current emissions. This estimate changes to 530 and 110 $GtCO_2$ for a 33% and 66% chance, respectively. 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 the potential warming after net zero is reached.

Main

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 decarbonisation 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[3]. Many approaches to equitable international climate action involve estimating the global RCB and dividing it among nations according to various priniciples 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%-90% chance of 2.0°C[6]) are small compared to the uncertainty in their 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 (WGI) report for the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6)[2], a set of values were established using the approach presented in [19, 20], decomposing the RCB into a CO_2 and non-CO_2 part. 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 were estimated by fitting a linear trend to the relationship between future non-CO_2 and future total warming at the time net zero CO_2 emissions are reached for available scenarios in the database accompanying the IPCC Special Report on Global Warming of 1.5°C (SR15)[25]. Following an update to historical data, an updated version of MAGICC (7.5.3) was available and used in the Working Group III (WGIII) report[26, 27].

The WGIII report discusses how updates to the non-CO_2 contribution reduce the 1.5°C RCB by about 100 Gt CO_2 relative to estimates reported in WGI, i.e. by about one-fifth, though 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, though with less consistency for 1.5°C of global warming than for higher levels. While this 20% change in the RCB estimate is small compared to the overall uncertainty and to past updates between the

IPCC Fifth Assessment Report[8] and the SR1.5[19], it is politically important and warrants investigation.

Here 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 assess the RCBs through six contributing factors following[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 assessed by WGI[2] are: transient climate response to cumulative CO_2 emissions (TCRE, the temperature rise per unit carbon emitted), historic warming (assessed human-induced global average temperature rise at present relative to pre-industrial levels), unrepresented Earth system feedbacks (ESF), zero-emissions commitment (ZEC, the CO_2-based warming that continues after CO_2 emissions reach and are kept at net zero), future warming from non-CO_2 emissions, and recent emissions. The equation combining these can be found in Methods, and a schematic of the equation is found in figure 1a.

Each of these factors comes with uncertainties and the nature 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[29], and Earth system feedbacks that are not included in the majority of Earth system models are notoriously difficult to quantify[2, 20]. Preindustrial temperatures are also somewhat uncertain; the IPCC considers them known to only 0.2°C accuracy, consisting of both uncertainty in the relevant period and in what historic temperatures were. However, knowing exactly what pre-industrial temperatures were is irrelevant when considering future impacts of climate change, and this uncertainty can be rendered much smaller if a more recent historic benchmark is used with a predefined offset. In this way, we can call it a definitional uncertainty rather than uncertainty in future risk profile. In the following, we therefore do not focus on its impact.

In principle, ZEC can influence our calculation both when it is positive or negative. In practice, a negative ZEC may be realised only after peak warming is achieved and becomes irrelevant for estimating the RCB consistent with limiting maximum warming. Thus, while the assessed distribution of ZEC is a Gaussian based around zero, the effective impact of ZEC for our calculation may be only defined by the positive part of this distribution. A recent model intercomparison project on ZEC (ZEC-MIP[30]) indicates that for gradually declining emissions, some of the value identified as ZEC under the idealised conditions of an abrupt stop in emissions will be realised before net zero is reached[31]. 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 materialise 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[2], but the peak non-CO_2 warming in MAGICC and FaIR is typically much earlier. To further complicate matters, ZEC-MIP suggests that the uncertainty in ZEC depends on future warming whereas the IPCC only provides a ZEC assessment at one level of cumulative carbon emissions. It reports a central value for ZEC after 1000 PgC of cumulative carbon emissions of 0 with an assessed likely range of ±0.3 [32]. This estimate is thus for 2°C of initial warming and the range is wider than the numerical model values from ZEC-MIP (c.f., Table 1) because it accounts for structural model uncertainty.

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 occuring too late to prevent peak warming from exceeding the target global warming limit. Table 2 indicates that this would have a very substantial effect, reducing the 50% 1.5°C budget by 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 only materialize in the decades after net zero CO_2 is reached, it emphasises 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.

Non-CO_2 warming contribution

Estimating RCBs requires an estimate of how much non-CO_2 emissions will contribute to warming. This requires both an estimate of how much we will emit of many different species over time and what impact they have on the climate. It therefore combines socio-political uncertainty 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[33], the most comprehensive current database of global emissions projections from different socioeconomic models. For assessing the geophyical uncertainty, we use two climate emulators. Full details of our emulator and database choices can be found in the methods section. In the AR6 WGI 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). A similar, though smaller effect occured when the FaIR model was updated. After combining the budgets, we find that the net effect of the updates is a 19% reduction of the 50% 1.5°C RCB and a 12% reduction of the 66% 2°C RCB. The budgets before and after updating are compared in supplementary information fig. 6 and indicate an uncertainty 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. Details of how we use these emulators to calculate non-CO_2 contributions are presented in the Methods section.

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 non-linear relationships, fitting a local quantile regression function called Quantile Rolling Windows (QRW, described in Methods) as seen in figure 1. While the median QRW line deviates from the linear relationship significantly 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 4% of the total budgets (see Table 2).

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 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 and adaptation of climate change, influencing greenhouse gas emissions and global warming projections[34]. 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, figure 2a shows that for each SSP 'world' of scenarios, there is a highly nonlinear relationship between non-CO_2 warming and peak total warming. As expected from earlier literature looking at deep mitigation scenarios[35], 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.

Generally, scenarios are designed to limit global warming to below a certain limit. Such scenarios aim to limit all greenhouse gas (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 have been identified to reducing non-CO_2 GHGs to zero, as insufficient mitigation measures have been identified to fully eliminate them for some activities such as agriculture[36]. Typically, this floor of non-CO_2 emissions is already achieved in pathways that aim to limit warming to 2.0°C and is not markedly reduced further when aiming to limit warming further to lower levels[35]. 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 only corresponds to a change in budgets of around 100 $GtCO_2$, many individual scenarios lie several times this outside this range, as can be seen in figure 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 the supplementary information figure 7. While results are clearly different for each combination, no clear trends emerge, assuaging concerns that overrepresentation 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 7% at 2°C, see 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 130 $GtCO_2$ with scenarios from the AR6 database. The ranges of values across all model-SSP combinations are 490 $GtCO_2$ and the minimum values are 80 $GtCO_2$. Carrying out the same analysis with the scenarios available in the SR1.5 database results in similar values. This emphasises that with depending on how succesfull non-CO_2 emissions are reduced, the 1.5°C RCB can change by around a factor of 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 only until net CO_2 emissions become zero. However in virtually all pathways CO_2 is the only significant GHG to reach net zero. Residual emissions of other long-lived GHGs mean that the 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 that reports that the assessed value of ZEC is close to zero but with low confidence in the sign[30–32]). This negative ZEC in the emulators usually prevents temperature rises in net zero scenarios through to the end of the century. These facts defang but do not resolve the question: when should we 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[2]. 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 instance, reduces the impact of the emulator's negative ZEC. It is, however, not necessarily 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 figure 3. We find that while in some scenarios different approaches will get very similar results, in other scenarios results may differ by over 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 harmonised to be consistent with recent emissions[37]); 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 too, since these scenarios do not reach their peak temperature during the twenty-first century and so do not have well-defined RCBs.

The maximum non-CO_2 warming is designed as an upper bound on the non-CO_2 term (which is negative in the equation for the RCB) rather than a fair estimate. The preharmonised net zero test functions as a robustness check against any distorting impact of harmonisation on pathways. Table 2 shows that the influence of this standard operation is minor. The best estimate of non-CO_2 warming in principle 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 opportunies for error cancellation. We therefore consider average-first peak non-CO_2 warming 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 14%, as seen in 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.

Comparison of recommended result to AR6 WGI results

The RCB factors updated from the AR6 WGI report to the approach we recommend can be summarised as follows: more recent emissions were included; the version of the climate emulator MAGICC was updated and calculations from FaIR were also 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 emissions in MAGICC from scenarios which reach net zero instead of at the time of net zero. As seen in figure 4, recent emissions, recalibrating MAGICC and the addition of FaIR had the largest impact. The difference between current 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 information figure 6. Including a variety of emulators increases the robustness of the estimate as does making non-CO_2 assumptions explicit; applying a non-linear relationship for estimating non-CO_2 warming as function of total warming, choice of time for non-CO_2 warming and the database of scenarios are less impactful.

After making all these changes, our best (50%) RCB estimate starting from 2022 is 300 (17-83% range from uncertainty in the impact of CO_2: -120–890) $GtCO_2$ for the RCB for limiting warming to 1.5°C and 1260 (700–2310) $GtCO_2$ for 2°C. For limiting warming to 2°C with 66% or 90% probability, the RCBs are estimated at 990 and 550 $GtCO_2$, respectively. With 39 $GtCO_2$ emitted in 2021[38], this is roughly equivalent to 25 and 14 years of current emissions for a 66% or 90% chance, respectively, of limiting warming to 2°C, and 8 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 before 2040.

Methods

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

$$B = (T - \mathrm{ZEC} - \delta T_{\mathrm{nonCO_2}}(T) - \delta T_{\mathrm{historic}})/\mathrm{TCRE} - \mathrm{ESF}(T) - E_{\mathrm{recent}}, \quad (1)$$

for $\delta T_{\mathrm{historic}}$ the historic warming, $\delta T_{\mathrm{nonCO_2}}$ 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 historic warming. Values for these can be found in table 1 and a schematic in figure 1a.

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 unphysical assumption and 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[2]; for this reason and for visual clarity, graphs such as figure 5b do not depict the top and bottom 1% of results for any distribution. 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 in 2020 and 2021 were not included in the WGI budgets and were recently evaluated as amounting to 77 $GtCO_2$[38]. Reductions in the estimates of emissions in earlier years means that our total update to recent emissions only change by 68 $GtCO_2$.

For the non-CO_2 components of projections, we default to (and recommend using) the AR6 scenario database[33], 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 harmonised to match historic emissions precisely and infilled with any missing emissions[37].

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 WGI report[24], but also we compare these results to 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 also 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 up until 2100 is compared to 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 harmonised emissions, but we also consider: the time it originally reached net zero CO_2 before CO_2 emissions were harmonised to recent historic data (non-CO_2 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 harmonisation); the non-CO_2 warming at the time of peak total warming in MAGICC, conditional on meeting net zero (after harmonisation); 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 only defined for emissions trajectories that reach net zero CO_2 (either before or afer harmonisation), 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 figure 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 quantile rolling windows method (QRW), which weights points according to $1/(1+\Delta x^2)$ for Δx the distance along the x-axis, normalised by a value proportional to the total range of x values. With this weighting, weighted quantiles are evaluated at 10 points equally spaced across the x-axis and results for points in between are linearly interpolated. See [39] 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 only appropriate 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-non-CO_2 warming at peak total warming of these cases, not filtering out scenarios which do not reach net zero to avoid a lack of data. Linear interpolation is used to make the fit.

Data availability

The code to generate this analysis and statistics from runs of MAGICC and FaIR that it requires are available from https://github.com/Rlamboll/AR6CarbonBudgetCalc.

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Figures and tables

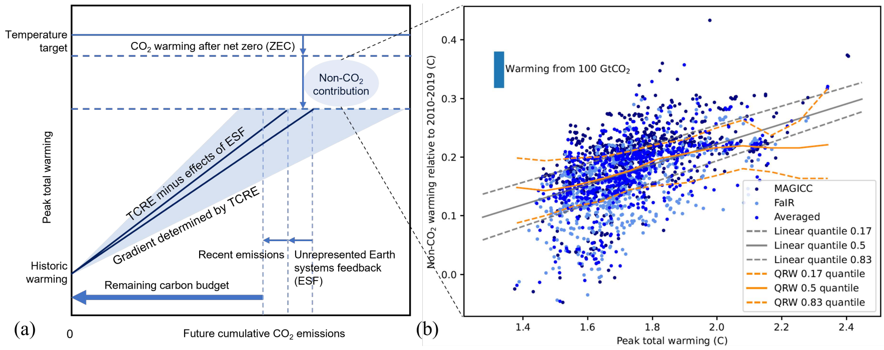
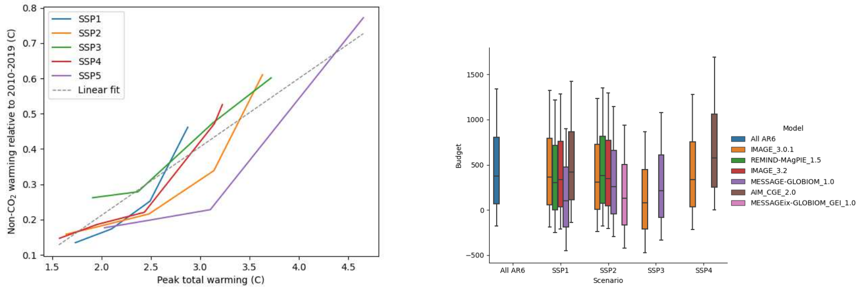


Figure 1: a) Schematic of how different factors contribute to the remaining carbon budget. b)Non-CO_2 contribution to warming after 2010-2019 for updated MAGICC, FaIR and the average of these values for each scenario in the AR6 database that reaches net zero CO_2. The bar at the top left indicates the median warming expected from 100 $GtCO_2$. We plot both the linear fit to the given quantiles and the quantile rolling windows (QRW) fits to the averaged datapoints.

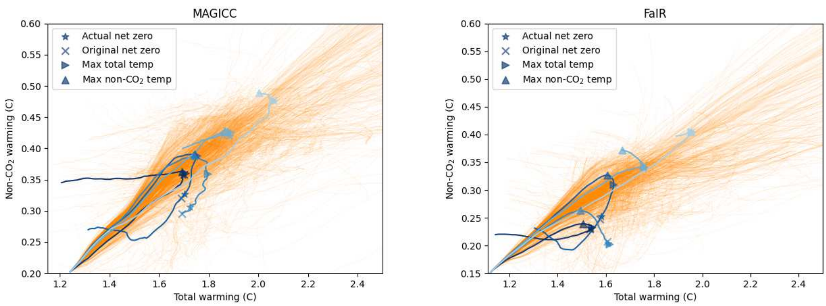
Name	Value	Discussion
TCRE	0.27-0.63°C per $GtCO_2$ (1.0–2.3°C per 1000 PgC)	We investigate normal (default) and lognormal distributions
Historical Warming	1.07°C 2010-2019	
ESF	26 ± 97 $GtCO_2$	
ZEC	0 ± 0.19°C	Based on [31]. We also consider an asymmetric distribution, where negative values are set to 0, and 0 ± 0.3, based on [32].
Recent emissions	277	Emissions from 2015-2021, estimated from [38].

Table 1: Table of values defining CO_2 contribution to warming. The default assumptions are all following [2] except where specified.



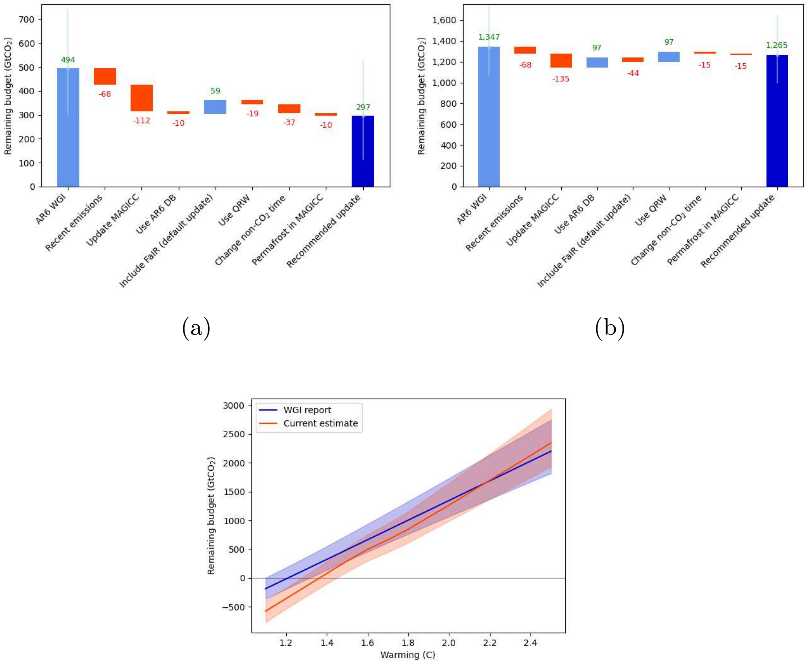
(a) (b)

Figure 2: The impact of model and scenario family on carbon budgets, using scenarios from the AR6 database, infilled with non-CO_2 warming at peak warming interpolated from 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 b) Budgets for 1.5°C for different models and scenarios for models where there are at least 3 scenarios



(a) (b)

Figure 3: Relationship between total and non-CO_2 warming over time in a) MAGICC and b) FaIR models. Five pathways from different models, representative of scenarios that reach net zero are shown, 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.



(c)

Figure 4: Plots of the impacts of changes to the carbon budget from each modification of the calculation, for a 50% chance of a) 1.5°C b) 2°C c) a range of temperatures (only displaying WGI and updated budgets). Error bars/ranges indicate 33rd and 66th percentile budgets considering uncertainty in CO_2 warming factors. Our "default update" corresponds to the changes up until the use of QRW.

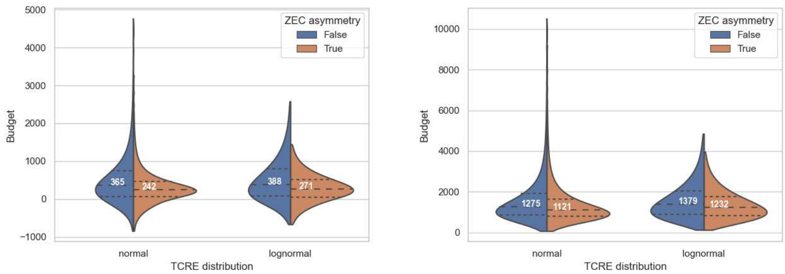
Warming (°C)	**Change**	**Rel. 50% (%)**	**Abs 50% (Gt CO2)**	**Abs 66% (Gt CO2)**	**Abs 90% (Gt CO2)**
1.5	Include permafrost in MAGICC	-1.8	-6	-6	-6
1.5	Lognormal TCRE distribution	6.2	23	10	11
1.5	Maximum Non-CO_2 warming	-15.4	-56	-53	-54
1.5	Non-CO_2 warming at peak average total, only NZ scenarios	-13.7	-50	-47	-49
1.5	Non-CO_2 warming at peak total temp	-6.5	-24	-22	-23
1.5	Non-CO_2 warming at peak total, only NZ scenarios	-15	-55	-51	-53
1.5	Non-CO_2 warming at preharmonised NZ	1.8	7	6	6
1.5	Recent emissions	18.6	68	68	67
1.5	Use QRW for non-CO_2 fit	-5.8	-21	-20	-21
1.5	Use SR1.5 database	-0.6	-2	-2	-2
1.5	ZEC only impacts if positive	-33.6	-123	-43	0
1.5	ZEC standard deviation 0	1.3	5	102	327
1.5	ZEC standard deviation 0.3	-0.4	-1	-93	-319
2	Include permafrost in MAGICC	-0.9	-11	-10	-9
2	Lognormal TCRE distribution	8.2	104	62	-7
2	Maximum Non-CO_2 warming	-6.7	-86	-77	-66
2	Non-CO_2 warming at peak average total, only NZ scenarios	-2.5	-31	-28	-24
2	Non-CO_2 warming at peak total temp	-4.6	-58	-52	-45
2	Non-CO_2 warming at peak total, only NZ scenarios	-2.5	-32	-28	-25
2	Non-CO_2 warming at preharmonised NZ	-0.6	-7	-7	-6
2	Recent emissions	5.3	68	68	68
2	Use QRW for non-CO_2 fit	1.5	19	17	14
2	Use SR1.5 database	-6.1	-78	-69	-59
2	ZEC only impacts if positive	-12.1	-154	-98	-19
2	ZEC standard deviation 0	0.2	2	56	171
2	ZEC standard deviation 0.3	-0.3	-4	-70	-221

Table 2: Absolute and relative changes in remaining carbon budgets at 50, 66 and 90% exceedance probabilities upon changing single aspects of the calculation from the default. NZ scenarios are scenarios reaching net zero after harmonisation.

Supplementary Information

Non-normal distributions

The impact of using non-normal distributions for the TCRE on the 50% estimates of carbon budget are substantial, since the means of these distributions are different when they are defined to meet the same limits of likelihood. The impacts of this combined with different treatment of ZEC values is shown in figure 5 - in the asymmetric case, values of ZEC below zero are treated as zero.



(a) (b)

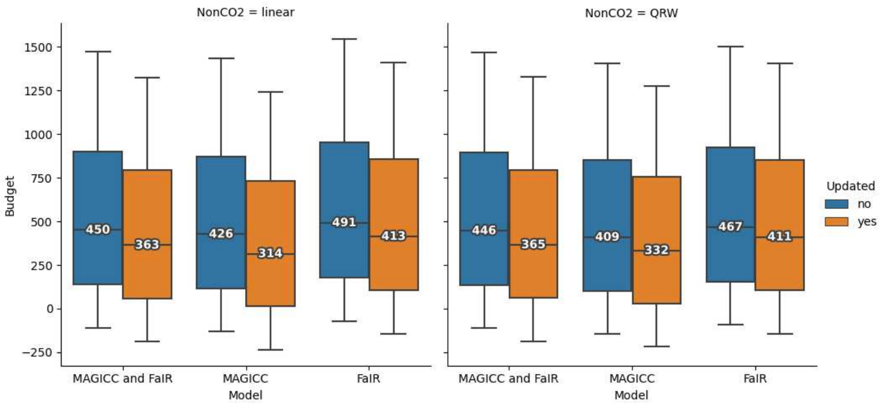
Figure 5: The impact of distribution of ZEC and TCRE on default-values budgets for (a) 1.5°C and (b) 2°C, extending to the 1st/99th percentiles. Dashed lines are drawn at 25%, 50% and 75% percentiles. ZEC is given by a normal distribution, but values below 0 are set to 0 in the asymmetric case.

Updating MAGICC and FaIR

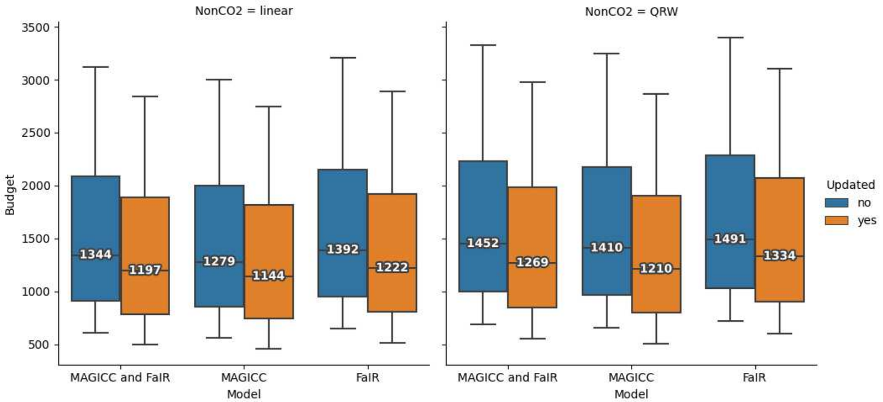
Budgets were calculated both with the versions of MAGICC and FaIR available at the time of writing the AR6 WGI report and the versions available at the end of this period. Alterations of around 60-110 $GtCO_2$ are found between versions and between FaIR and MAGICC for the 1.5°C budget and 150-200 $GtCO_2$ for the 2°C budget, indicating that this is a reasonable ballpark for the uncertainty in the physics-based model uncertainty in non-CO_2 warming. Since the updates do not affect the structure of the models and both MAGICC and FaIR are trained on similar sets of data, this is expected to be an underestimate of the non-CO_2 physics based uncertainty.

Impacts of individual models and scenarios

For the sake of convenience, we replot the figure of model-and-SSP specific budgets found in the main text figure 2b in figure 7, clustered by models then by SSP rather than the reverse. We also plot with both clusterings the values from the SR1.5 database, which contains many more examples of these



(a)

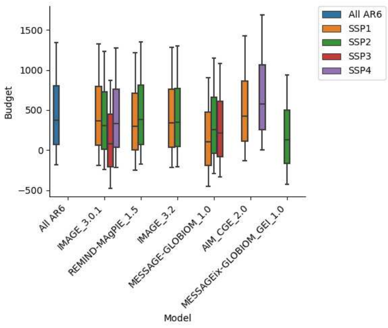


(b)

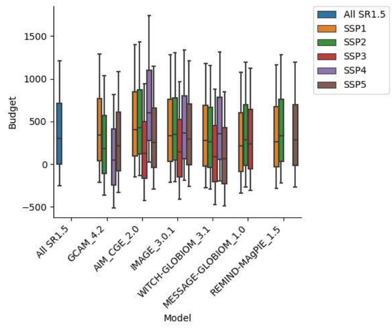
Figure 6: The impact of updates to the simple climate models FaIR, MAGICC and the average warming found in both together on carbon budgets calculated from the SR1.5 database for non-CO_2 factors. (a) is for 1.5°C, (b) for 2°C. They are subdivided by whether they fit a the linear trend for non-CO_2 or use the QRW local quantile regression to the non-CO_2 data. These budgets are calculated using the SR1.5 database of scenarios.

scenarios as more groups submitted more than three valid scenarios for each SSP.

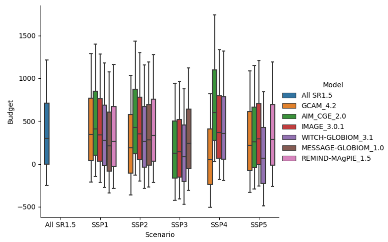
Tables of remaining budgets



(a)



(b)



(c)

Figure 7: Plots of budgets arising from interpolating only scenarios from a particular model and SSP combination. a) From the AR6 database b) From the SR1.5 database c) From the SR1.5 database, the same data as in (b) but clustered by SSP first.

Warming (C)		**Quantile**						
Future	**Total**	**0.1**	**0.17**	**0.33**	**0.5**	**0.66**	**0.83**	**0.9**
0.03	1.1	244	66	-170	-357	-535	-803	-1007
0.13	1.2	483	275	16	-177	-351	-596	-772
0.23	1.3	744	498	207	3	-172	-404	-559
0.33	1.4	1027	735	404	184	3	-223	-365
0.43	1.5	1330	985	607	366	175	-52	-187
0.53	1.6	1644	1242	812	547	343	110	-23
0.63	1.7	1972	1508	1022	729	510	266	132
0.73	1.8	2306	1778	1233	911	674	418	279
0.83	1.9	2645	2052	1446	1093	837	565	421
0.93	2	2987	2327	1660	1275	999	709	558
1.03	2.1	3335	2608	1875	1457	1160	851	692
1.13	2.2	3688	2889	2091	1639	1320	991	823
1.23	2.3	4035	3171	2308	1821	1480	1130	952
1.33	2.4	4391	3453	2525	2003	1638	1267	1080
1.43	2.5	4749	3741	2743	2185	1797	1404	1206

Table 3: Budgets for various temperatures and probability quantiles under the default update (including both updated emulators applied to AR6 with recent emissions).

Warming (C)		**Quantile**						
Future	**Total**	**0.1**	**0.17**	**0.33**	**0.5**	**0.66**	**0.83**	**0.9**
0.03	1.1	-13	-167	-387	-574	-764	-1070	-1318
0.13	1.2	246	67	-170	-357	-535	-803	-1006
0.23	1.3	537	321	55	-140	-314	-556	-726
0.33	1.4	862	598	290	79	-98	-327	-476
0.43	1.5	1214	889	530	297	110	-116	-254
0.53	1.6	1558	1172	757	498	298	67	-67
0.63	1.7	1852	1411	946	663	449	210	76
0.73	1.8	2188	1683	1159	847	616	364	227
0.83	1.9	2581	1999	1405	1058	806	537	394
0.93	2	2970	2313	1648	1265	990	701	550
1.03	2.1	3379	2642	1902	1480	1180	869	709
1.13	2.2	3801	2980	2161	1698	1372	1037	866
1.23	2.3	4211	3311	2414	1911	1558	1200	1018
1.33	2.4	4626	3645	2672	2127	1747	1362	1169
1.43	2.5	5056	3989	2934	2346	1937	1526	1321

Table 4: Budgets for various temperatures and probability quantiles under the recommended update (including both updated emulators applied to AR6 with recent emissions, permafrost included, QRW and non-CO_2 warming at the time of average peak warming).