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Assessing the size and uncertainty of remaining carbon budgets

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SI for "Assessing the size and uncertainty of remaining carbon budgets"

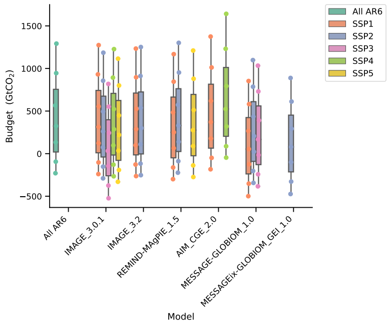
Impacts of individual models and scenarios

For the sake of convenience, we replot the figure of model-and-SSP specific budgets found in the main text figure 2b, 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 scenarios as more groups submitted more than three valid scenarios for each SSP.

Updating MAGICC and FaIR

In WG1, MAGICC was used with two different sets of historical input emissions files. As a result of the short timelines, for the remaining carbon budget estimates in WG1, MAGICC was used in line with the historical input emissions used for CMIP6 GHG concentration projections [1]. For WG3's scenario assessment and WG1 Cross Chapter Box 7.1, MAGICC was used with historical input emissions that matched the harmonisation assumptions used in WG3, which had much lower levels of aerosol emissions in particular. This increases the estimate of the aerosol unmasking effect[2]. This increased the estimated non-CO_2 contribution (between the WG1 carbon budget approach and the approach used in WG1) on the order of a few hundredths of a degree. While this amount is small in the context of the uncertainty in non-CO_2 warming, it is nonetheless the dominant contributor (translating to roughly 100 $GtCO_2$) to the change in budget.

FaIR was used to provide budgets for the SR1.5 assessment of emissions scenarios, using v1.3.4 and v1.6.2 used in parts of AR6, though not for the budget calculation. Alongside the update to the model version, there were updates to the climate assessment and calibration methods between the two assessments. The key differences in the climate assessment between SR1.5 and AR6 were the equilibrium climate sensitivity distribution was higher (2–5°C very likely range versus 1.5–4.5°C likely range), effective radiative forcing from CO_2 doubling had increased (3.93 W m^{-2} versus 3.71 W m^{-2}), and effective radiative forcing from aerosols in the present day had been evaluated to be stronger (-1.3 W m^{-2} versus -0.9 W m^{-2}). The AR6 ensemble was also constrained differently, by considering several variables (historical surface temperature, historical ocean heat uptake, present-day CO_2 concentrations,



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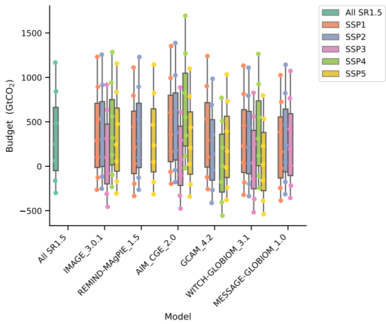

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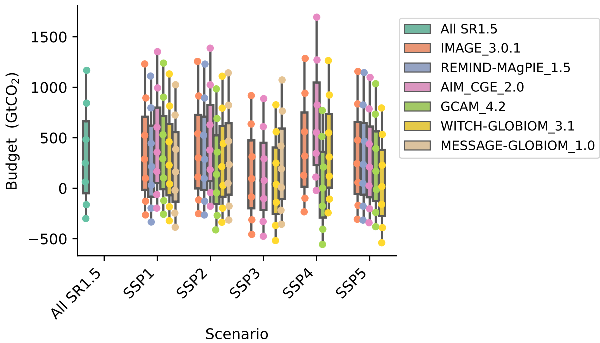
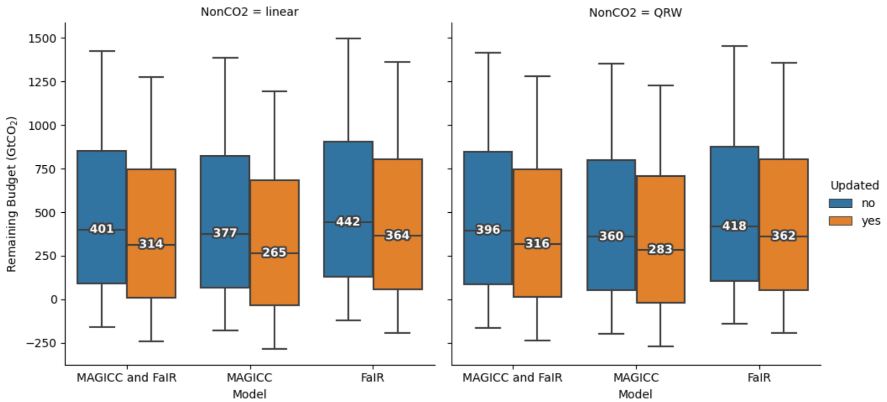


(c)

Figure 1: 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. Box plots show median and 25-75th percentile range, whiskers show the 10-90th percentile values of the 10 000 000 runs.

and assessed ranges of ECS, TCR, TCRE and aerosol forcing), compared to a simple historical warming metric in SR1.5.

In this report, budgets were calculated both with the versions of MAGICC and FaIR available at the time of writing the AR6 WG1 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.



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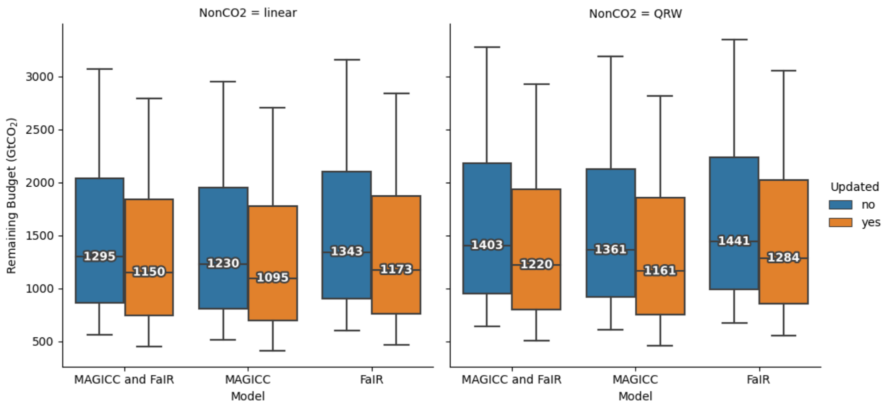
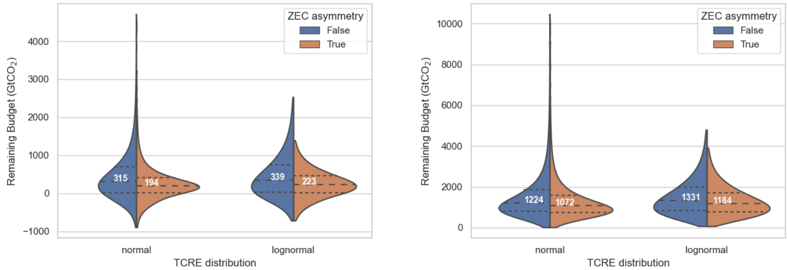


(b)

Figure 2: 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. Box plots show median and 25-75th percentile range, whiskers show the 10-90th percentile values

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 3 - in the asymmetric case, values of ZEC below zero are treated as zero.



(a) (b)

Figure 3: 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.

Purely emulated results

A rival approach is assessing budgets using only emulator results. This incorporates some relationships between distributions of variables, as discussed above, but is more reliant on the specific model structure of the emulators. In this section, we provide a sanity check on our results using this method. For this exercise, we compare the peak warming with the cumulative CO_2 emissions after 2022 in the actual scenarios. Since the estimates must be based on the full set of emissions, our results necessarily revolve around a subset of scenarios reaching the appropriate peak temperature, plus or minus some tolerance limit. Since the number of scenarios above and below this temperature is not equal, a linear correction to each value may be applied. We use the effective TCRE to construct this correction - the TCRE after taking account of the derivative in ESF:

$$\mathrm{TCRE}_E = \frac{1}{(1/\mathrm{TCRE} - d\mathrm{ESF}/dT)}. \tag{1}$$

We can then express the budget as the average of these corrected values: $B = \langle E - (T - T_{peak})\mathrm{TCRE}_E \rangle$.

It may be observed from figure 4a that random variation dominates tolerance values below 0.03°C. Without the $TCRE_E$ correction, the estimates for 1.5°C rapidly ascend due to the presence of many more scenarios narrowly missing the target than acheiving it. The corrected values show significant drift over the range of tolerance values explored, but remain reasonable compared to the expected values.

In principle it is possible to sanity check these estimates by using the effective TCRE using a linear trend fit to the relationship between cumulative CO_2 and warming within the tolerance. However in practice this produces bad results for 1.5°C in particular, as shown in figure 4c. MAGICC does not find many scenarios compatible with 1.5^{o}C and therefore struggles to estimate the effective TCRE over the relevant range. The gradient estimates are also systematically biased, as the tolerance limits depresses the range of temperatures; this means the estimate of the gradient between temperature and cumulative emissions is underestimated. Results are much more stable for the 2C budget, as it has a better number of scenarios and the influence of the correction is reduced by the symmetry of the scenarios around the center point.

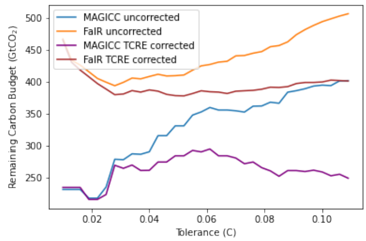
Relationships between distributions

In this paper we present each variable as independently distributed, however there are in practice some constraints on relationships between variables; for instance, if TCRE is low, non-CO_2 warming must be higher to generate the same observed recent warming. In general we don't expect these to change the median warming estimates, but it is likely to narrow the uncertainty in budgets. One exception to this would be aerosol cooling. A highest estimate of aerosol cooling implies a larger future warming as aerosol levels decrease in pathways that reach net zero this century, therefore future non-CO_2 warming is higher but CO_2 warming is also higher to counteract the present aerosol cooling. This effect would therefore result in higher uncertainty than considering each distribution independently.

There are also likely more subtle factors - for instance, in constrained FaIR ensembles we see that having a very negative ZEC results in low peak warming not being a possible outcome [3], whereas a naive model would indicate that this made low peak warming more likely. This would be a case where a constraint could affect the median carbon budget as well as the uncertainty. The impact of this would be structurally different to, but similar in effect, to the robustness exercise where only a positive ZEC influenced the calculation. However the nature of the constraint and to what extent it depends on the particular structure of FaIR is currently unclear - another instance of the importance of an increased understanding of ZEC.

Historical uncertainty

As mentioned in the main text, the pre-industrial average temperature is poorly defined and not known to a high degree of accuracy. The IPCC assessed



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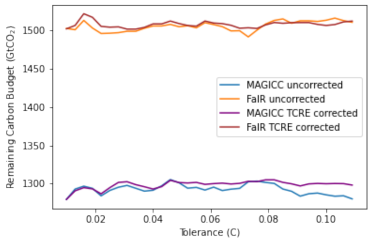

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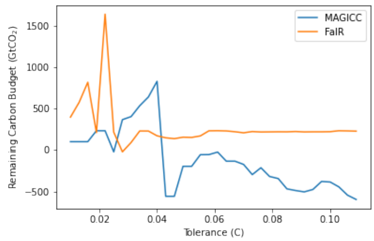

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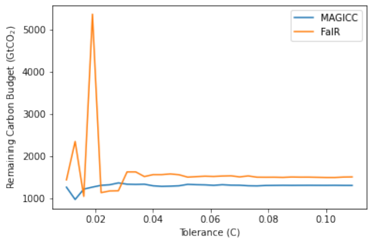

(d)

Figure 4: Comparison of the results of calculating the carbon budget using only scenarios with a temperature peak within some tolerance of the required temperature target. a, c) for 1.5^{o}C; b, d) for 2^{o}C. a, b) illustrations of using average of all scenarios in a tolerance band, with or without correcting for effective TCRE. c, d) The estimated carbon budget as a function of the tolerance in peak CO_2 emissions temperatures around the required budget, with a linear fit to the scenarios within the trend.

the uncertainty in a particular definition of it (the average temperature during 1850-1900) as being 0.2°C. The impact of this may be included in the model, and has the same impact as an increase in ZEC. Adding a 0.2°C uncertainty to the existing 0.19°C uncertainty in quadrature produces 0.28°C effective uncertainty, the results of which are very similar to the 0.3°C ZEC case considered in table 2 of the main document.

Tables of remaining budgets and non-CO_2 contributions

Warming (C)		**Quantile**						
Future	**Total**	**0.1**	**0.17**	**0.33**	**0.5**	**0.66**	**0.83**	**0.9**
0.23	1.3	694	449	158	-46	-221	-453	-608
0.33	1.4	978	686	355	135	-46	-272	-414
0.43	1.5	1280	935	557	317	126	-101	-236
0.53	1.6	1596	1193	764	498	295	62	-72
0.63	1.7	1922	1459	973	680	461	217	83
0.73	1.8	2258	1730	1184	862	625	369	231
0.83	1.9	2598	2003	1397	1044	788	516	372
0.93	2	2940	2280	1611	1226	950	660	509
1.03	2.1	3287	2557	1826	1408	1110	802	643
1.13	2.2	3637	2840	2042	1590	1271	942	774
1.23	2.3	3988	3121	2259	1772	1430	1080	904
1.33	2.4	4340	3405	2476	1954	1589	1218	1031
1.43	2.5	4695	3689	2693	2135	1747	1355	1157

Table 1: 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**
0.23	1.3	488	272	6	-189	-363	-605	-775
0.33	1.4	812	547	240	30	-147	-376	-525
0.43	1.5	1163	838	480	247	60	-166	-304
0.53	1.6	1507	1121	706	447	248	17	-117
0.63	1.7	1803	1363	898	615	401	161	28
0.73	1.8	2146	1639	1114	802	571	319	182
0.83	1.9	2542	1958	1362	1014	762	492	349
0.93	2	2927	2269	1603	1219	944	655	504
1.03	2.1	3338	2599	1859	1436	1135	824	663
1.13	2.2	3757	2936	2117	1653	1326	991	820
1.23	2.3	4168	3266	2370	1866	1512	1153	972
1.33	2.4	4585	3601	2626	2080	1700	1315	1122
1.43	2.5	5006	3940	2887	2298	1890	1479	1273

Table 2: 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).

Warming (C)	Total temp (C)	Non-CO_2 warming (C)	CO_2-equiv ($GtCO_2$)
0.03	1.1	0.066	147
0.13	1.2	0.083	184
0.23	1.3	0.1	221
0.33	1.4	0.116	258
0.43	1.5	0.133	296
0.53	1.6	0.15	333
0.63	1.7	0.167	370
0.73	1.8	0.183	407
0.83	1.9	0.2	445
0.93	2	0.217	482
1.03	2.1	0.234	519
1.13	2.2	0.251	556
1.23	2.3	0.267	594
1.33	2.4	0.284	631
1.43	2.5	0.301	668

Table 3: Non-CO_2 warming in the default update (linear trend at time of net zero, averaged across MAGICC and FaIR).

Warming (C)	Total temp (C)	Non-CO_2 warming (C)	CO_2-equiv ($GtCO_2$)
0.03	1.1	0.165	365
0.13	1.2	0.165	365
0.23	1.3	0.165	365
0.33	1.4	0.164	364
0.43	1.5	0.165	366
0.53	1.6	0.173	384
0.63	1.7	0.196	436
0.73	1.8	0.211	468
0.83	1.9	0.214	475
0.93	2	0.22	488
1.03	2.1	0.221	491
1.13	2.2	0.222	493
1.23	2.3	0.225	499
1.33	2.4	0.227	504
1.43	2.5	0.227	504

Table 4: Non-CO_2 warming in the recommened update (QRW across the average of the temperature pathways calculated by MAGICC and FaIR at the time of peak warming in the average). Note that QRW infills ranges outside the limits of known scenarios with the value calculated at the edges (conservative extrapolation).

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