An integrated approach to quantifying uncertainties in the remaining carbon budget

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Supplementary Material

Parameter (and its full name)	Input distribution in the "Main case"	Sensitivity analysis	Distribution details
f_{nc} Ratio of non-CO_2 to total anthropogenic radiative forcing	Empirical distribution (Fig. S1 a) with median value of 0.14, mean of 0.13, and 5-95% range of -0.11 to 0.33.	Gaussian distribution fitted to the empirical distribution (mu = 0.14 and σ = 0.17 for the 1σ case. For the '2 std Gaussian fit case', the value of σ was doubled, see Fig. S1 a)	Forcing ratios calculated from the updated radiative forcing database that will be used for AR6 (mean for 2010-2019), using the FaIR model emulator (Smith et al. 2018)
E Cumulative CO_2 emissions	640 PgC ± 65 PgC (as 1 σ range) from 1870 to the end of 2019	Gaussian distribution fitted to: mu= 640 PgC σ = 65 PgC draw random samples from (Fig. S1 b)	Based on Global Carbon Project estimates (Friedlingstein et al. 2019)
ΔT_{anth} Anthropogenic warming in the year 2019 (with respect to the 1850-1900 baseline)	Empirical distribution (Fig. S1b) with median value of 1.18 °C	Gaussian distribution fitted to the empirical distribution (mu = 1.17 and σ = 0.138 for the 1σ case. For the '2 std Gaussian fit' case, the value of σ was doubled) (Fig. S1 b)	3-dataset average of observed temperature change (HadCRUT-CW, GISTEMP and Berkeley Earth), with natural forced and internal variability removed using the method of Haustein et al. 2017.

Supplementary Table S1. Range of parameters used in sampling to generate distributions of TCRE and Remaining carbon budgets (based on Eq.1 and Eq.3, respectively).

Parameter (and its full name)	Input values "Main case"	Comments
ΔT_{anth} Anthropogenic warming in the year 2019 (with respect to the 1850-1900 baseline)	Same as in Table S1.	
E Cumulative CO_2 emissions from 1870 to the end of 2019	Same as in Table S1.	
f_{nc} Ratio of non-CO_2 to total anthropogenic radiative forcing	Same as in Table S1	
f_{nc}^* Future ratio of non-CO_2 to total anthropogenic radiative forcing (at the time when emissions reach net zero).	Linearly related to f_{nc} f_{nc}^* = 0.3081 f_{nc}+ 0.1400+ offset; in the 'Main case' the offset is zero, and two sensitivity cases have an offset values of ± 0.05.	The linear fit based by fitting a first order polynomial using the linear least squares regression. The fit to the distribution of grey points is shown in Fig.3b (based on the SR1.5 scenario database and the FaIR model, similarly as f_{nc}). $f_{nc}^*$is treated as a constant function of f_{nc} (since it reflects socioeconomic rather than geophysical uncertainty)
ΔT_{ZEC} Zero Emission Commitment	0 °C (mean value) -0.3 to 0.3 °C (5-95%; Supplementary Fig. S4)	fitted Gaussian to 5-95% range, centered on zero based on ZECMIP (MacDougall et al. 2020)
ΔT_{lim} Global mean warming target	1.5 °C (also 1.75 °C and 2.0 °C in the supplementary Fig. S4 and table S4).	treated as a constant

Supplementary Table S2. Range of parameters used in sampling to generate distributions of remaining carbon budgets (based on Eq.3).

TCRE	Median	33%	67%	5%	95%
'Main case'	**0.439**	**0.402**	**0.480**	**0.317**	**0.618**
'No uncertainty in any parameters'	0.431	0.431	0.431	0.431	0.431
'No uncertainty in T_{anth}'	0.434	0.402	0.470	0.323	0.588
'Gaussian fit T_{anth}'	0.429	0.390	0.472	0.299	0.612
'2 std Gaussian fit T_{anth}'	0.427	0.373	0.486	0.243	0.674
'No uncertainty in E'	0.437	0.406	0.472	0.330	0.587
'Gaussian fit E'	0.439	0.402	0.480	0.317	0.618
'2 std Gaussian fit E'	0.442	0.393	0.499	0.292	0.722
'No uncertainty in f_{nc}'	0.436	0.411	0.464	0.355	0.557
'Gaussian fit f_{nc}'	0.435	0.389	0.483	0.276	0.636
'2 std Gaussian fit f_{nc}'	0.434	0.353	0.518	0.141	0.771

Supplementary Table S3. Resulting TCRE ranges in °C / 1000$GtCO_2$

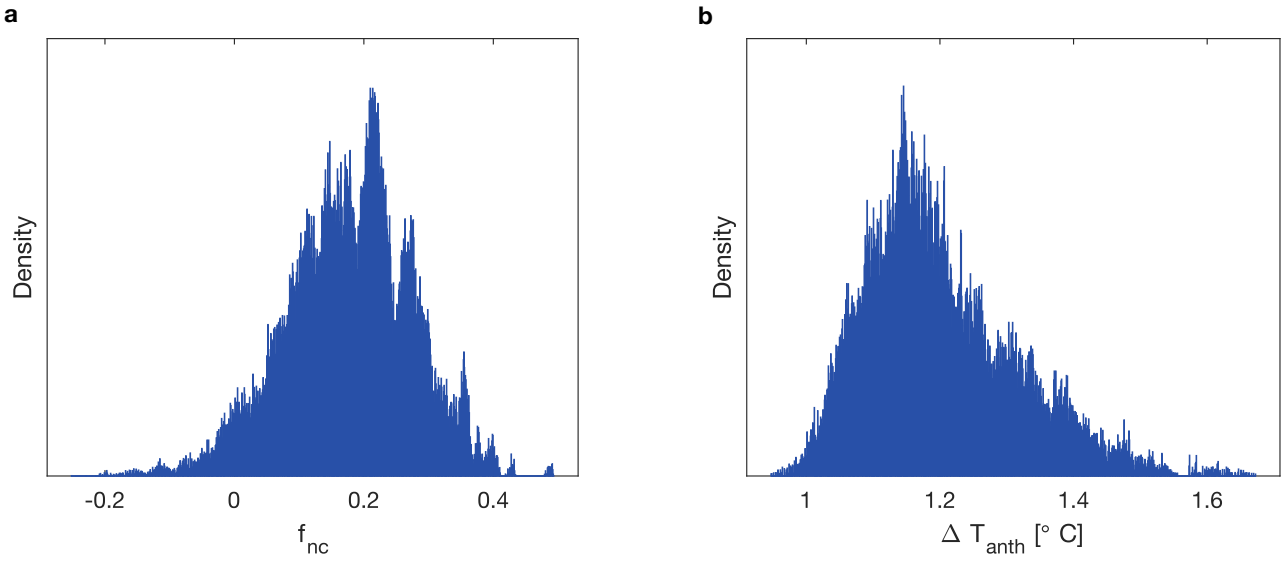
1.5 °C budgets (in $GtCO_2$)	Median	33%	67%	5%	95%
'Main case'	443	227	673	-307	1398
'No uncertainty in any parameters'	491	491	491	491	491
'No uncertainty in ZEC (ZEC = 0)'	459	296	629	-116	1155
'2 std in ZEC'	433	102	783	-743	1868
'No uncertainty in T_{anth}'	476	286	678	-191	1310
'Gaussian fit \Delta T_{anth}'	507	271	767	-285	1643
'2 std Gaussian fit \Delta T_{anth}'	513	188	909	-487	2612
'No uncertainty in E'	447	230	678	-308	1385
'Gaussian fit E (same as main case)'	443	227	673	-307	1398
'2 std Gaussian fit E'	429	218	662	-303	1439
'No uncertainty in f_{nc}'	451	265	641	-215	1195
'Gaussian fit \sigma f_{nc}'	475	233	746	-329	1737
'2 std Gaussian fit f_{nc}'	473	133	926	-538	4080
Socio-economic uncertainty					
'high f_{nc}* (intercept + 0.05)'	274	74	487	-427	1155
'low f_{nc}* (intercept -0.05)'	612	381	860	-187	1642

Supplementary Table S4. Resulting remaining carbon budget ranges for 1.5 °C target.

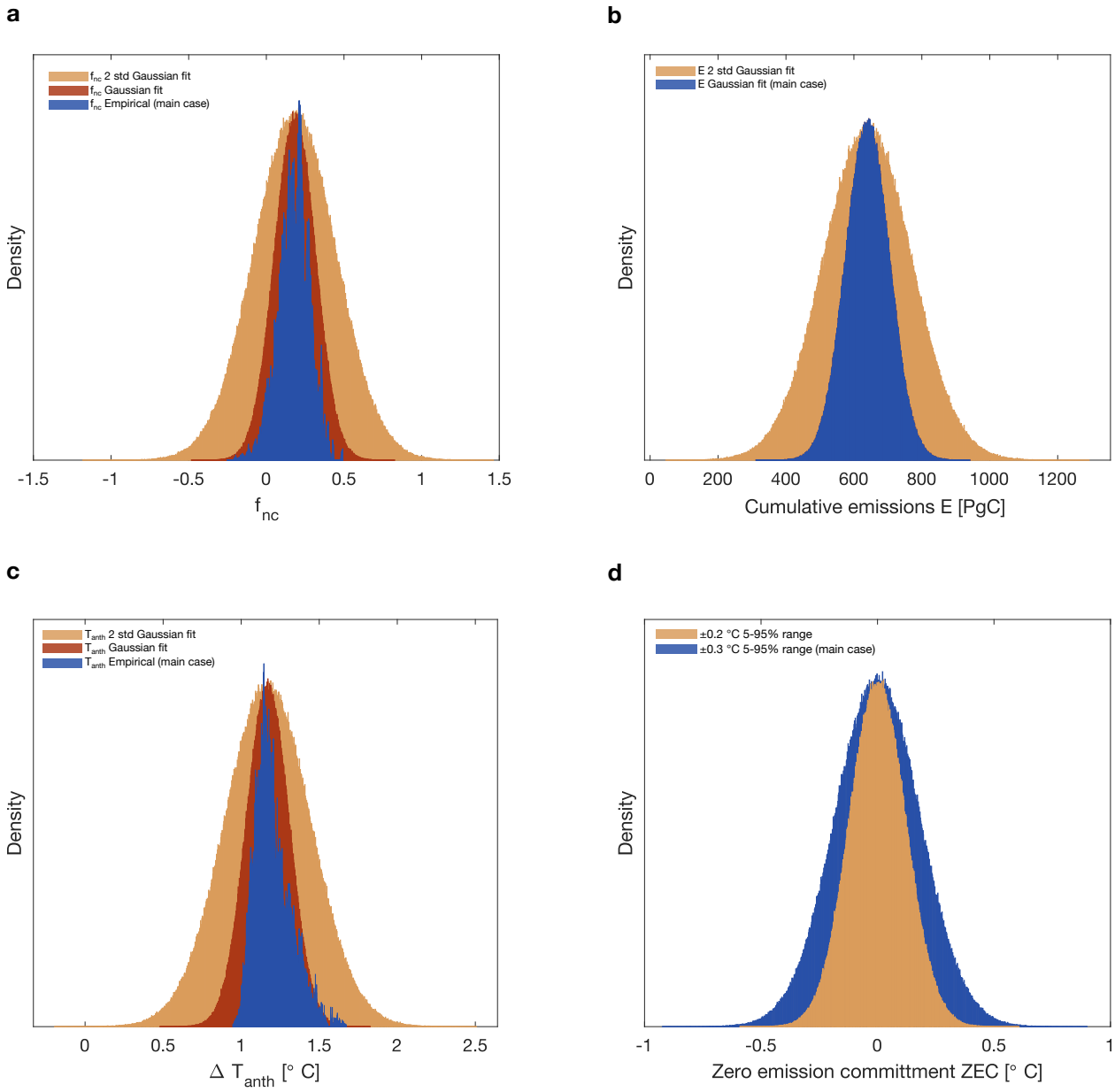
1.75 °C budgets (in $GtCO_2$)	Median	33%	67%	5%	95%
'Main case'	908	670	1'164	86	1'970
'No uncertainty in any parameters'	964	964	964	964	964
'No uncertainty in ZEC (ZEC = 0)'	924	731	1'126	251	1'755
'2 std in ZEC'	896	549	1'263	-314	2'415
'No uncertainty in T_{anth}'	944	739	1'165	234	1'862
'Gaussian fit \Delta T_{anth}'	982	718	1'273	109	2'262
'2 std Gaussian fit \Delta T_{anth}'	989	617	1'443	-141	3'408
'No uncertainty in E'	916	678	1'169	87	1'942
'Gaussian fit E (same as main case)'	908	670	1'164	86	1'970
'2 std Gaussian fit E'	885	643	1'154	83	2'054
'No uncertainty in f_{nc}'	918	717	1'123	204	1'722
'Gaussian fit \sigma f_{nc}'	943	673	1'248	58	2'375
'2 std Gaussian fit f_{nc}'	939	552	1'461	-196	5'131

2.0 °C budgets (in $GtCO_2$)	Median	33%	67%	5%	95%
'Main case'	1374	1110	1656	469	2550
'No uncertainty in any parameters'	1437	1437	1437	1437	1437
'No uncertainty in ZEC (ZEC = 0)'	1389	1166	1624	612	2358
'2 std in ZEC'	1359	995	1747	103	2970
'No uncertainty in T_{anth}'	1414	1190	1655	647	2422
'Gaussian fit \Delta T_{anth}'	1457	1164	1781	495	2887
'2 std Gaussian fit \Delta T_{anth}'	1465	1046	1979	199	4207
'No uncertainty in E'	1386	1125	1661	478	2502
'Gaussian fit E (same as main case)'	1374	1110	1656	469	2550
'2 std Gaussian fit E'	1344	1066	1654	438	2683
'No uncertainty in f_{nc}'	1385	1167	1609	611	2259
'Gaussian fit \sigma f_{nc}'	1412	1112	1753	434	3021
'2 std Gaussian fit f_{nc}'	1406	969	1999	138	6181

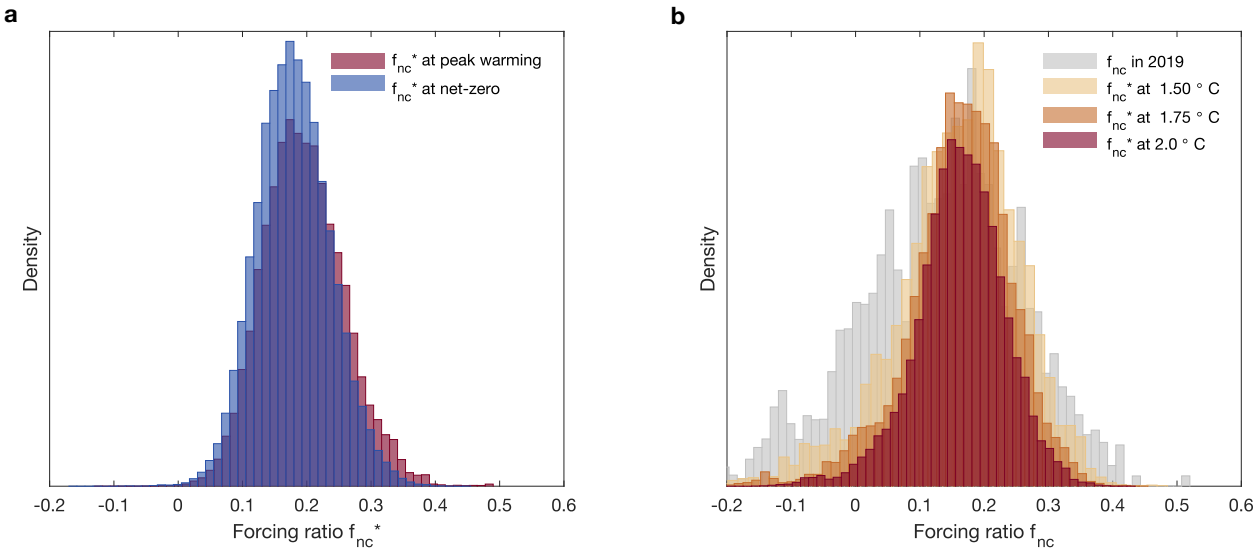
Supplementary Table S5. Resulting remaining carbon budget ranges for 1.75 and 2.0 °C targets.



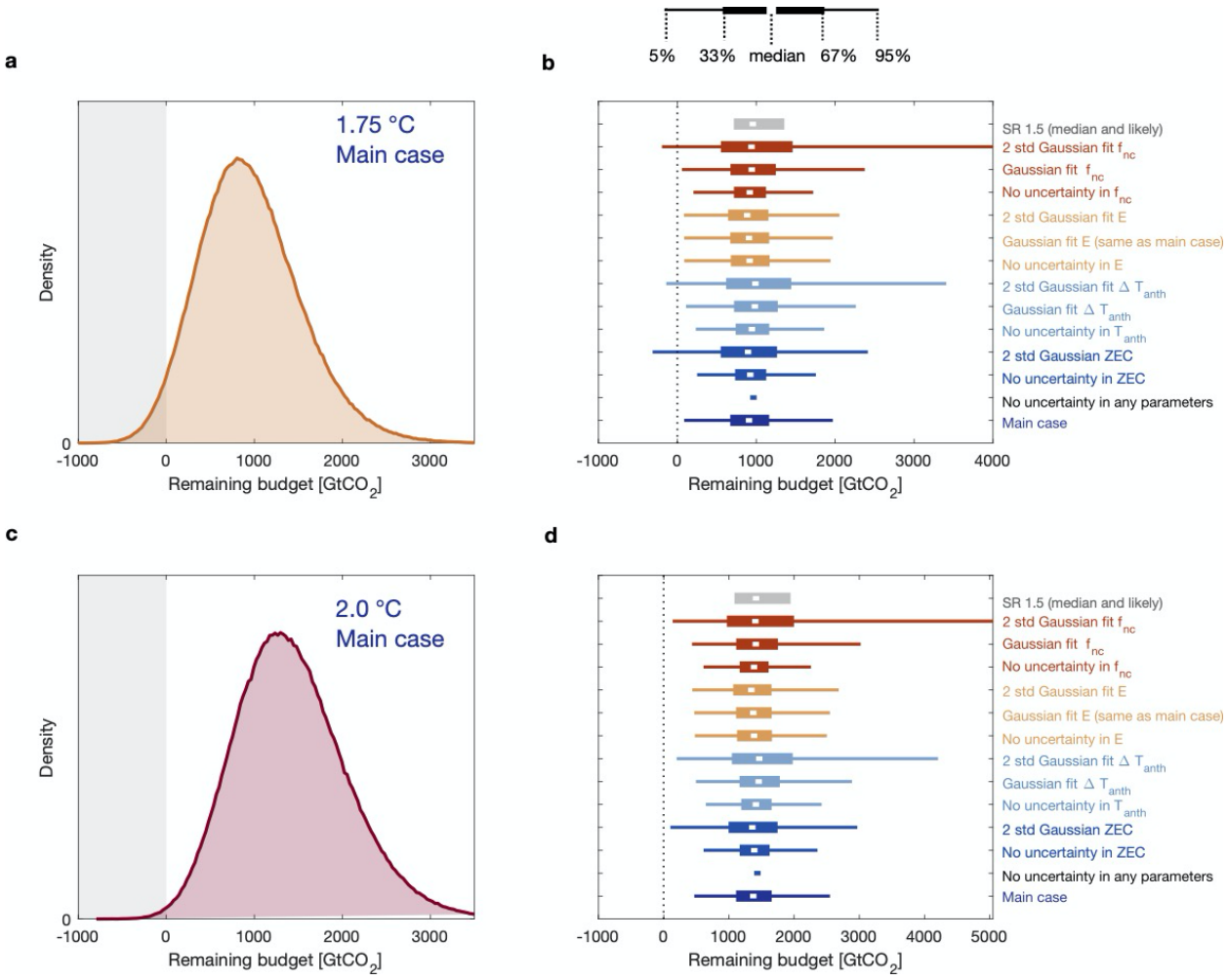
Supplementary Figure S1. Empirical distributions used to draw random samples for f_{nc} and ΔT_{anth} in Eq.1 and Eq.3 labelled as the 'Main case'. (see Supplementary Table S1 and Methods for details).



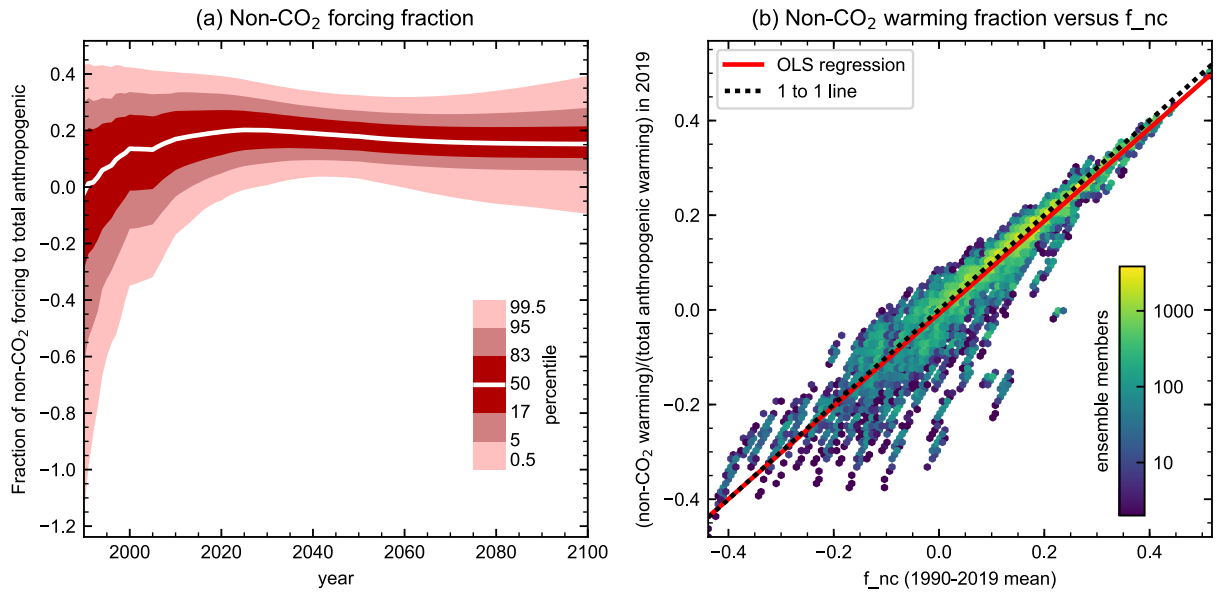
Supplementary Figure S2. Distributions used for sampling in Eq.1 and Eq.3, including additional distributions for sensitivity analysis. The red and orange distributions show Gaussian approximation of the empirical distributions. Distributions used for sampling in the main case are indicated by blue, as labelled. Panels (b) and (d) are based on Normal distributions, in which the blue distributions case is the same as the distribution used to sample in 'Main case' (see Supplementary Table S1 and S2). Orange distributions in panels a-c have the same mean as the red distributions, but inflated the variance (to twice the standard deviation, prior to sampling), in order to account for a wider spread in the uncertainty in each input parameter, in sensitivity analysis in Fig.1 and Fig.2.



Supplementary Figure S3. Radiative forcing ratio of non-CO_2 to total forcing for scenarios in the 1.5 °C scenario database. (**a**) at the time of peak warming and at the time of net-zero emissions; (**b**) in the year 2019 (mean 1990-2019 value), and at the time when each temperature target is reached (1.5 °C, 1.75 °C, and 2.0 °C, respectively). For all warming targets, we use a linear approximation of f_{nc}^{*} as a function of f_{nc} (Supplementary Table S2). f_{nc} at peak warming and at net-zero are calculated for the 30-year mean prior to reaching net-zero emissions or peak warming.



Supplementary Figure S4. Distribution of the remaining carbon budget for 1.75 and 2.0 °C temperature targets, with cumulative CO_2 emissions from the beginning of the year 2020 onwards (left panels), and the effect of related geophysical uncertainties (right panels). (**a,c**) Distribution of the remaining carbon budget for the "Main case" for 1.75 °C and 2.0 °C targets, respectively; (**b,d**) Sensitivity of the 1.75 °C and 2.0 °C remaining budgets, respectively, and their range to increased or decreased uncertainty in the input distributions of individual parameters (coloured bars as labelled on vertical axis) and comparison to the SR1.5 estimates (grey bars, where the upper grey bar represents the total range spanned by additional uncertainties that were not included in the median and 33-67th TCRE percentile range shown in the lower grey bar). SR1.5 numbers illustrated here adjusted downwards (based on Ref.[19]), to represent remaining budgets from the beginning of the year 2020, rather than 2018 as originally reported. The box plots indicate the median value, the 33-67% range, and the 5-95% range, as labelled.



Supplementary Fig. S5. (**a**) Time series of non-CO_2 forcing fraction; (**b**) and non-CO_2 warming fraction as a function of the 30-year average (1990-2019) average of f_{nc}, with an ordinary least squares (OLS) regression line shown in red, and a reference 1:1 line shown by a black dashed line. The colour bar in panel (**b**) is logarithmic and indicates sample density (expressed as a number of ensemble members).

Supplementary References:

Friedlingstein, P. *et al.* Global Carbon Budget 2019. *Earth System Science Data* **11**, 1783–1838 (2019).

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