Estimating remaining carbon budgets using emulators of CMIP6 models

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Supplementary material

1 Parameters in carbon model impulse-response function

Estimated parameters in the impulse response function for CO_2,

$$G_{\mathrm{CO_2}}(t) = c_0 + \sum_{i=1}^{4} c_i e^{-t/\tau_i} \,,$$

are for the multi-model mean of the CO_2-impulse experiments[1]:

$$(c_0, c_1, c_2, c_3, c_4) = (0.128, 0.019, 0.032, 0.035, 0.025) \text{ (Gt CO}_2 \text{ per yr)}. \tag{1}$$

The fit to the multi-model mean plus one standard deviation gives parameters

$$(c_0, c_1, c_2, c_3, c_4) = (0.128, 0.014, 0.0271, 0.0397, 0.033)\,(\text{Gt CO}_2\text{ per yr}), \tag{2}$$

and the multi-model mean minus one standard deviation gives parameters

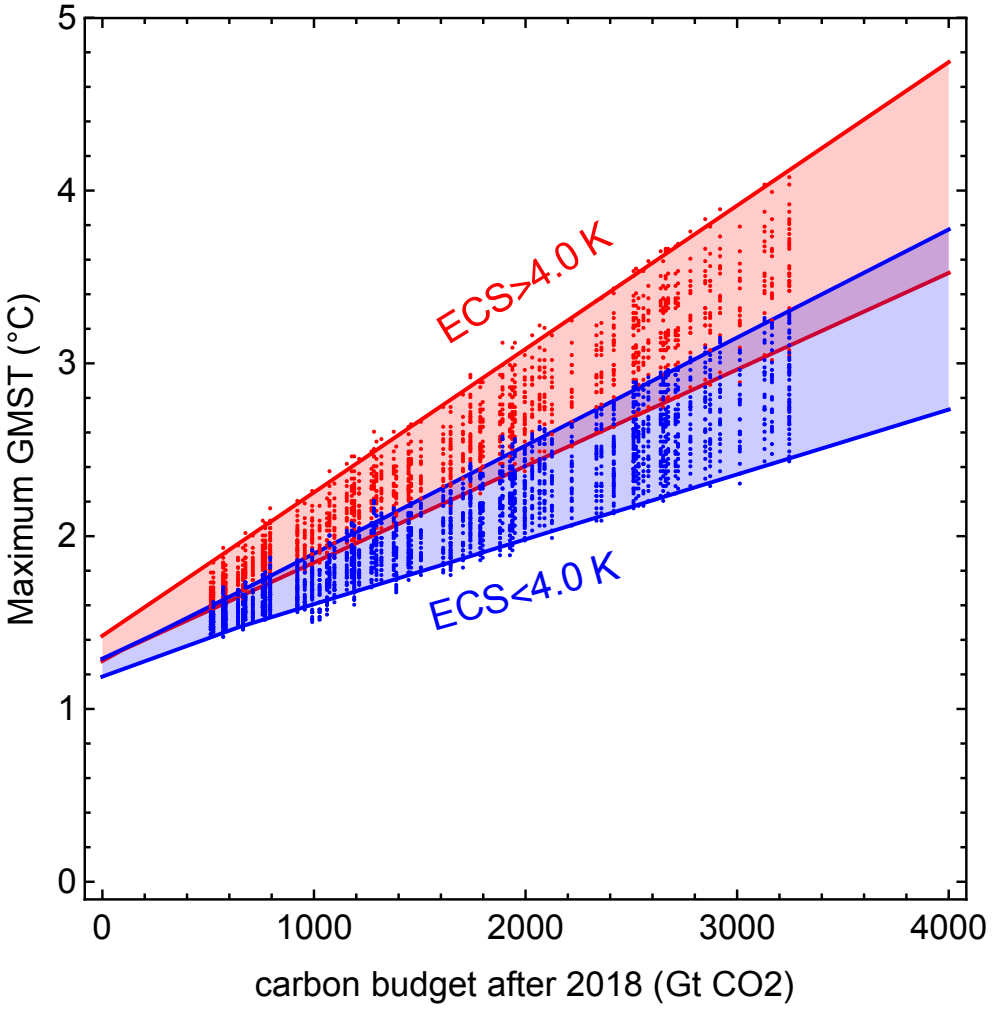
$$(c_0, c_1, c_2, c_3, c_4) = (0.128, 0.023, 0.038, 0.033, 0.019)\,\text{ppm/(Gt CO}_2\text{ per yr)}. \tag{3}$$

2 Parameters in climate model emulators

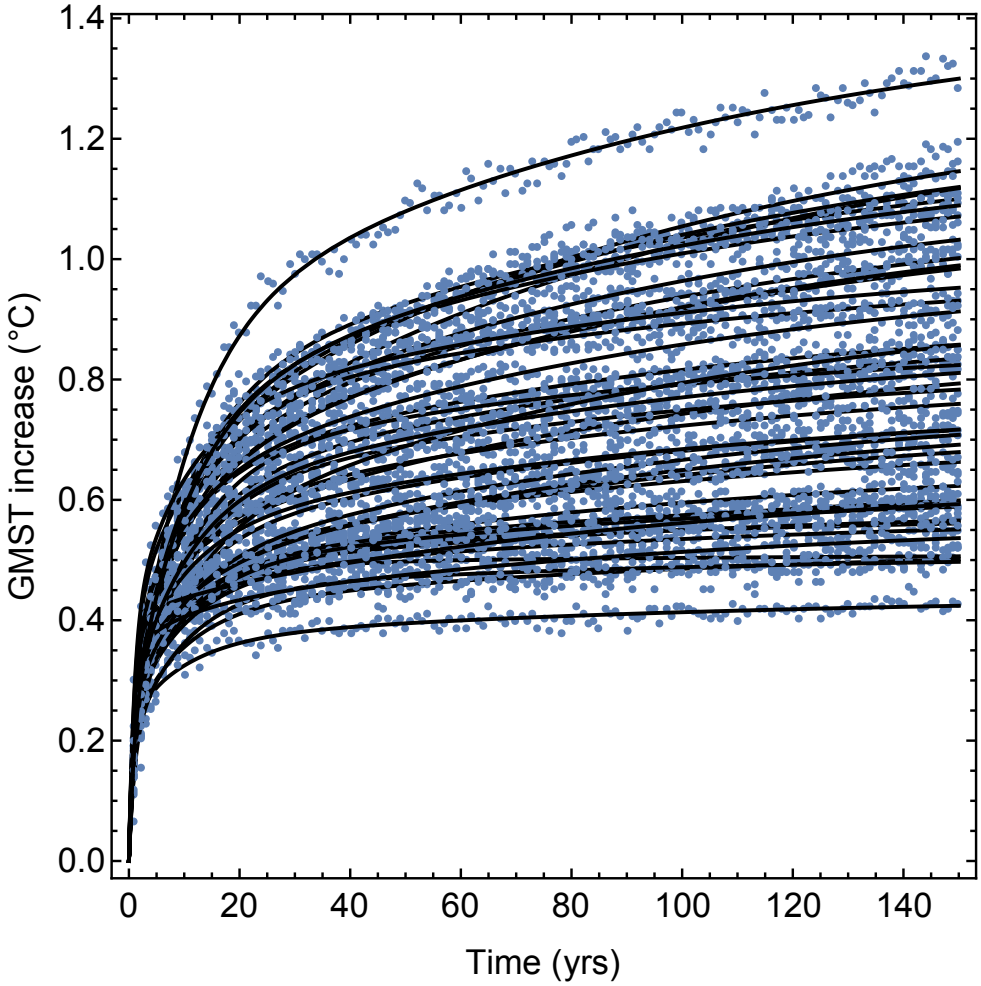
Supplementary Table 1 shows the estimated parameters d_1, d_2, and d_3 for the 41 models in the CMIP6 ensemble. The table also shows the ECS and $F_{2\times\text{CO}_2}$ of each climate model, estimated using the standard Gregory-plot technique[2].

1. Joos, F. *et al.* Global warming feedbacks on terrestrial carbon uptake under the intergovernmental panel on climate change (ipcc) emission scenarios. *Global Biogeochemical Cycles* **15**, 891–907 (2001).

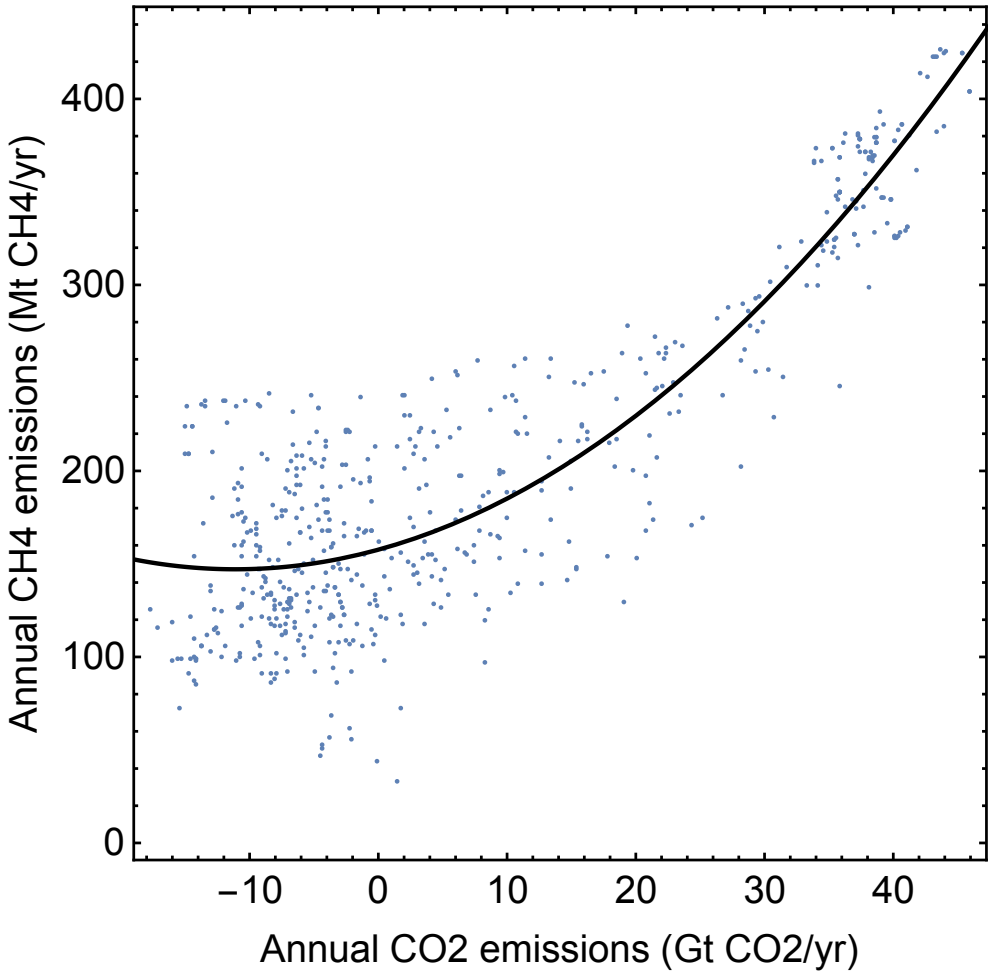
2. Gregory, J. M. *et al.* A new method for diagnosing radiative forcing and climate sensitivity. *Geophysical Research Letters* **31** (2004).



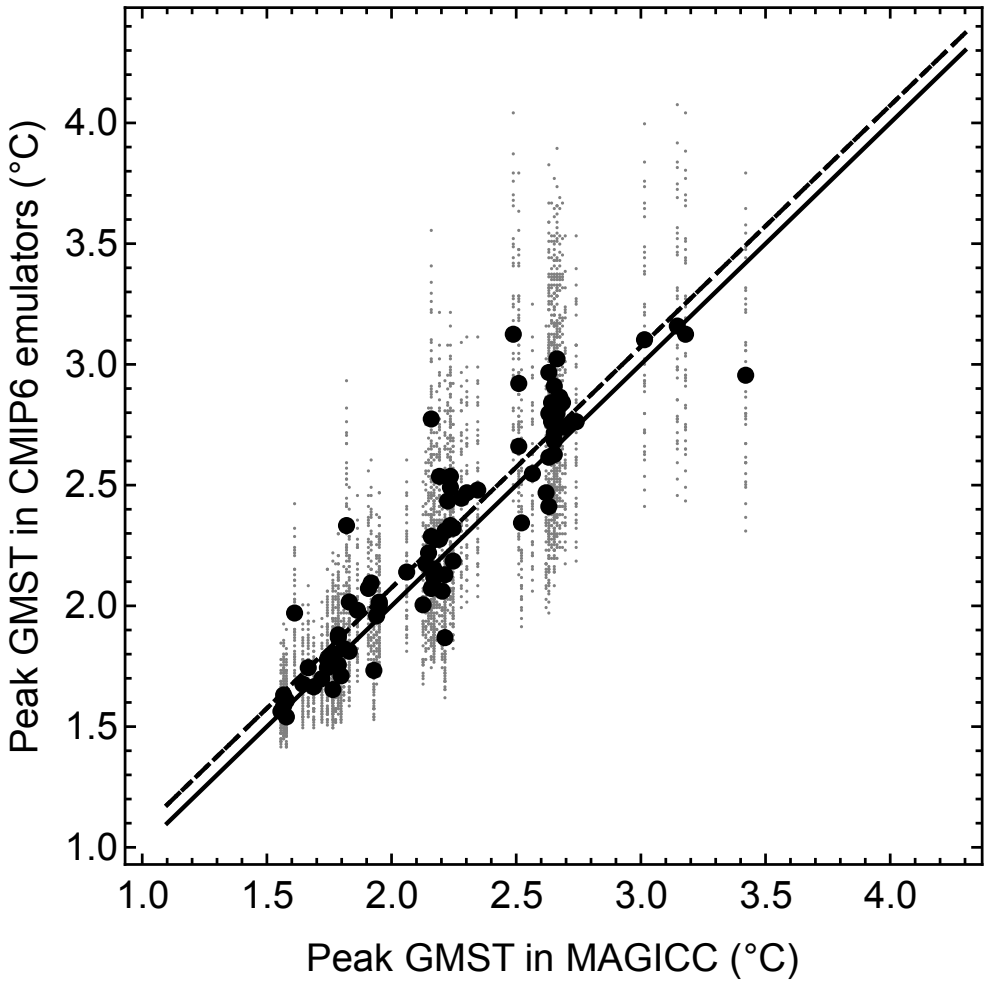
Supplementary Fig. 1 Linear relationships between total positive CO_2 emissions and peak GMST for models with high- and low ECS. Shows the same data as in Fig. 2a, but colored so that models with ECS>4.0 K are in red and models with ECS<4.0 K are in blue. The lines show the minimum and maximum TCRE for the two ranges of ECS.



Supplementary Fig. 2 ESM emulators in the CMIP6 ensemble fitted to 4×CO_2 runs. The points show the temperature increase over the first 150 yrs after an abrupt quadrupling of CO_2 normalized by dividing by the Gregory-estimate of the forcing. The black curves are the fitted temperature responses as described in the Methods section.



Supplementary Fig. 3 The dependence between CO_2 and methane emissions in the scenario database. The points show the annual methane emissions versus the annual CO_2 emissions for each emission scenario and each year from 2018 to 2100. The curve show a quadratic fit to the points.



Supplementary Fig. 4 Peak temperatures in MAGICC compared to in CMIP6 ESM emulators. Each small point shows the peak GMST estimated from a ESM emulator and in the MAGICC model for a given emission scenario. The large black points show the average values over each ESM emulator for each scenario. The black dotted line has unit slope and zero intercept and the dashed line is a linear fit to the data.

Earth System Model	d_1 (K m^2/W yrs)	d_2 (K m^2/W yrs)	d_3 (K m^2/W yrs)	ECS (K)	$F_{2\times CO_2}$ (W m^{-2})
ACCESS-CM2	0.25	0.041	0.004	4.7	3.4
ACCESS-ESM1-5	0.28	0.034	0.005	3.9	2.8
AWI-CM-1-1-MR	0.28	0.028	0.003	3.2	3.6
BCC-CSM2-MR	0.36	0.016	0.003	3.0	3.1
BCC-ESM1	0.24	0.037	0.003	3.3	3.0
CAMS-CSM1-0	0.22	0.020	0.001	2.3	4.2
CanESM5	0.20	0.055	0.004	5.6	3.7
CAS-ESM2-0	0.34	0.029	0.003	3.5	3.3
CESM2	0.34	0.028	0.006	5.2	3.3
CESM2-FV2	0.38	0.027	0.006	5.2	2.9
CESM2-WACCM	0.30	0.031	0.005	4.7	3.3
CESM2-WACCM-FV2	0.30	0.036	0.005	4.8	2.9
CMCC-CM2-SR5	0.22	0.038	0.002	3.5	3.8
CNRM-CM6-1	0.23	0.050	0.003	4.9	3.6
CNRM-CM6-1-HR	0.19	0.046	0.002	4.3	4.0
E3SM-1-0	0.18	0.068	0.006	5.3	3.3
EC-Earth3-Veg	0.24	0.045	0.005	4.3	3.4
FGOALS-f3-L	0.28	0.019	0.002	3.0	4.1
FGOALS-g3	0.29	0.017	0.002	2.8	3.7
GFDL-CM4	0.35	0.027	0.004	3.9	3.2
GFDL-ESM4	0.25	0.025	0.001	2.6	3.8
GISS-E2-1-G	0.31	0.017	0.001	2.8	3.6
GISS-E2-1-H	0.25	0.028	0.002	3.1	3.5
GISS-E2-2-G	0.23	0.026	0.000	2.4	3.7
IITM-ESM	0.23	0.013	0.001	2.4	4.6
INM-CM4-8	0.30	0.019	0.002	1.8	2.7
INM-CM5	0.23	0.026	0.001	1.9	2.9
IPSL-CM6A-LR	0.23	0.051	0.004	4.6	3.4
KACE-1-0-G	0.19	0.033	0.004	4.4	3.3
MIROC-ES2L	0.20	0.025	0.001	2.7	4.1
MIROC6	0.24	0.023	0.001	2.6	3.7
MPI-ESM1-2-HR	0.29	0.018	0.003	3.0	3.6
MPI-ESM1-2-LR	0.23	0.025	0.001	3.0	4.2
MRI-ESM2-0	0.30	0.017	0.003	3.1	3.5
NESM3	0.40	0.033	0.003	4.8	3.7
NorCPM1	0.25	0.023	0.003	3.0	3.3
NorESM2-LM	0.40	0.002	0.002	2.6	3.4
NorESM2-MM	0.35	0.006	0.002	2.5	3.8
SAM0-UNICON	0.30	0.024	0.002	3.7	3.9
TaiESM1	0.26	0.034	0.003	4.3	4.0
UKESM1-0-LL	0.22	0.052	0.005	5.4	3.6

Supplementary Table 1 Estimates of ECS, forcing and linear-response parameters in CMIP6 models for each emission scenario.