Supplementary Information for

Emulating absent land processes reduces carbon budgets in CMIP6 models

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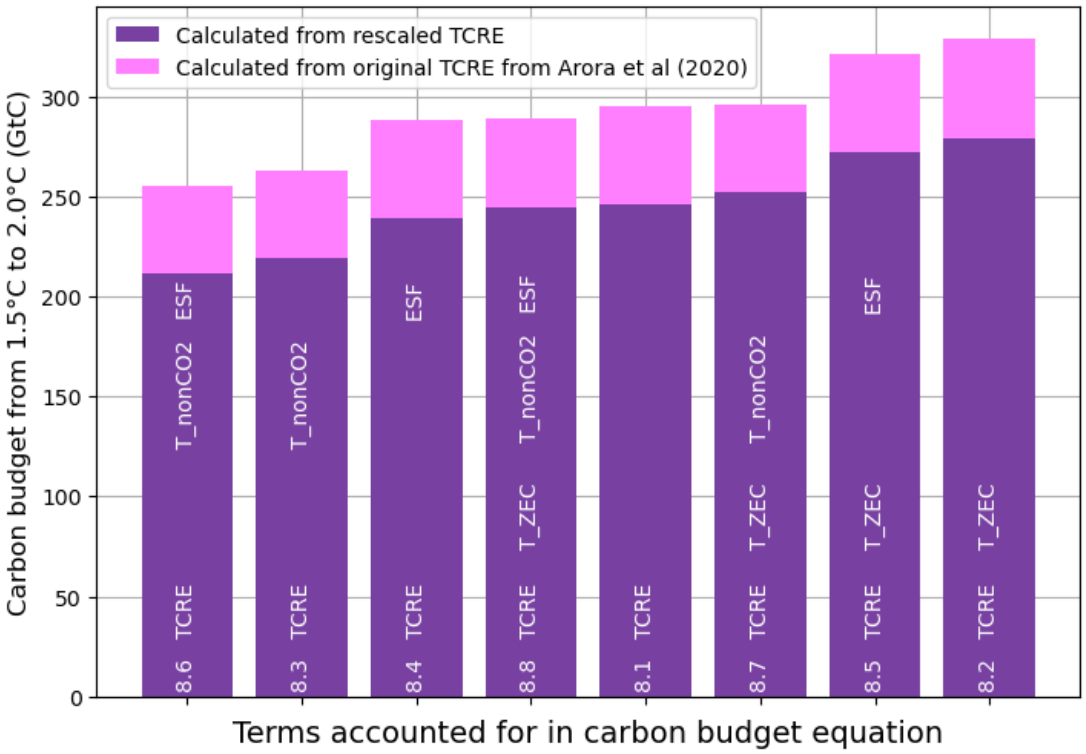

Supplementary Figure 1: Bar chart showing the average carbon budget from 1.5°C to 2°C of 11 CMIP6 ESMs. Calculated from Equations 8.1 to 8.8, using the original TCRE from Arora et al (2020)[1] (lilac bars) and the TCRE rescaled to account for absent processes (purple bars). Bar labels show equation number and the adjustment terms included in the calculation of the carbon budget: T_nonCO2 = warming due to non-CO_2 forcing, T_ZEC is zero emissions commitment (ZEC25) from MacDougall et al (2020)[2] where available; ESF is emissions due to Earth system feedbacks not accounted for in the calculation of TCRE.

	Nitrogen limitation	Dynamic vegetation	Fire-vegetation interactions	Interactive BVOC emissions	Interactive CH_4 cycle and emissions from wetlands	Spatially varying diffuse fraction of photo-synthetically active radiation	Overall scaling factor for each ESM	
							TCRE	CE
ACCESS-ESM1.5	Yes	No	No	No	No	No	1.251	0.939
BCC-CSM2-MR	No	No	No	No	No	No	1.348	0.853
CanESM5	No	No	No	No	No	No	1.348	0.853
CESM2	Yes	No	Yes	No	No	Yes	1.021	1.062
CNRM-ESM2-1	No	No	Yes	No	No	No	1.203	0.959
GFDL-ESM4	No	Yes	Yes	Yes	No	Yes	1.148	0.912
IPSL-CM6A-LR	No	No	No	No	No	No	1.348	0.853
MIROC-ES2L	Yes	No	No	No	No	No	1.251	0.939
MPI-ESM1.2-LR	Yes	Yes	Yes	No	No	No	1.121	0.991
NorESM2-LM	Yes	No	Yes	Yes	No	Yes	1.035	1.054
UKESM1-0-LL	Yes	Yes	No	Yes	No	No	1.281	0.876
ukesm-ctrl	Yes	Yes	No	No	No	No	1.267	0.884

Supplementary Table 1: ESM-specific scaling factors and the processes included or not (Yes/No) in each model. The final two columns contain the scaling factors by which the original TCRE and Cumulative Emissions from Arora et al (2020)[1] are multiplied to account for the processes not represented in each model, as shown in columns 2 to 7. Included are 11 CMIP6 models, and the control configuration of the UKESM process ensemble, *ukesm-ctrl.*

Earth System Model	TCRE (°C/EgC)	Rescaled TCRE (°C/EgC)		Cumulative Emissions (GtC)	Rescaled Cumulative Emissions (GtC)	
BCC-CSM2-MR	1.32	1.78	+34.8%	1291	1101	-14.7%
NorESM2-LM	1.32	1.37	+3.5%	1075	1133	+5.4%
MIROC-ES2L	1.39	1.74	+25.1%	1135	1066	-6.1%
GFDL4-ESM4	1.45	1.66	+14.8%	1066	972	-8.8%
CNRM-ESM2-1	1.63	1.96	+20.3%	1124	1078	-4.1%
MPI-ESM1.2-LR	1.65	1.85	+12.1%	1127	1117	-0.9%
ACCESS-ESM1.5	2.02	2.53	+25.1%	1064	1000	-6.0%
CanESM5	2.09	2.82	+34.8%	1214	1035	-14.7%
CESM2	2.13	2.17	+2.1%	1073	1139	+6.2%
IPSL-CM6A-LR	2.13	2.87	+34.8%	1107	944	-14.7%
UKESM1-0-LL	2.30	2.95	+28.1%	1054	924	-12.3%
CMIP6 Mean ± Std Dev	1.77 ± 0.36	2.15 ± 0.52	+21.4% ± 11.4%	1121 ± 70	1046 ± 73	-6.7% ± 7.3%
ukesm-allprocs, this study	**3.13**	**-**		**952**	**-**	
ukesm-ctrl, this study	2.48	**3.14**		1077	**952**	

Supplementary Table 2: Table of original and rescaled TCRE and cumulative emissions to 2xCO_2 for 11 CMIP6 ESMs. The last two rows show the same figures, where applicable, for the control (*ukesm-ctrl*) and 'all processes' (*ukesm-allprocs*) configurations of UKESM. The rescaled *ukesm-ctrl* entries, and those from *ukesm-allprocs* they are intended to reconstruct, are both highlighted in bold. Percentages are the percentage change after rescaling.

Equation used to calculate carbon budget from 1.5°C to 2°C	$CB_{1.5\_2.0}$ using original[9] TCRE (GtC)	$CB_{1.5\_2.0}$ using rescaled TCRE (GtC)	Reduction in $CB_{1.5\_2.0}$ after rescaling TCRE (%)
8.1: $CB_{1.5\_2.0} = (2.0°C - 1.5°C)/TCRE$	295	246	16.5
8.2: $CB_{1.5\_2.0} = (2.0°C - 1.5°C - T_{ZEC})/TCRE$	329	279	14.7
8.3: $CB_{1.5\_2.0} = (2.0°C - 1.5°C - T_{nonCO2})/TCRE$	263	219	16.5
8.4: $CB_{1.5\_2.0} = (2.0°C - 1.5°C)/TCRE - ESF$	288	239	16.9
8.5: $CB_{1.5\_2.0} = (2.0°C - 1.5°C - T_{ZEC})/TCRE - ESF$	321	272	15.0
8.6: $CB_{1.5\_2.0} = (2.0°C - 1.5°C - T_{nonCO2})/TCRE - ESF$	255	212	17.0
8.7: $CB_{1.5\_2.0} = (2.0°C - 1.5°C - T_{nonCO2} - T_{ZEC})/TCRE$	296	252	14.6
8.8: $CB_{1.5\_2.0} = (2.0°C - 1.5°C - T_{nonCO2} - T_{ZEC})/TCRE - ESF$	289	245	14.9
Mean and standard deviation	292±24	245±21	16.0±0.8

Supplementary Table 3: Carbon emissions budget from 1.5°C to 2°C, $CB_{1.5\_2.0}$. Columns 2 and 3 show $CB_{1.5\_2.0}$ calculated from the CMIP6 ESMs' original (Arora et al (2020))[1] and rescaled TCRE respectively, for each of Equations 8.1 to 8.8, as shown in the first column. $CB_{1.5\_2.0}$ is the carbon budget from 1.5°C to 2°C, T_{ZEC} is the committed warming evaluated 25 years after the cessation of CO_2 emissions, T_{nonCO2} is the estimated warming due to non-CO_2 forcing, and *ESF* is an estimate of the CO_2 released due to feedbacks unaccounted for in the calculation of TCRE. See Methods for details.

Nitrogen limitation in CMIP7 ESMs

CMIP7 participating models CanESM6, EC-Earth-4, GISS-E3 and ICON-ESM[3] are expected to include nitrogen limitation of land carbon uptake, replacing 'carbon only' models CanESM5, EC-Earth-3, GISS-E2 and MPI-ESM1.2-LR respectively.

References

1. Arora, V. K., Katavouta, A., Williams, R. G. *et al.* Carbon–concentration and carbon–climate feedbacks in CMIP6 models, and their comparison to CMIP5 models. *Biogeosciences* **17**, 4173–4222 (2020).

2. MacDougall, A. H., Frölicher, T. L., Jones, C. D. *et al.* Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences* **17**, 2987–3016 (2020).

3. Jungclaus, J. H., Lorenz, S. J., Schmidt, H. *et al.* The ICON-Earth System Model version 1.0. *J. Adv. Model. Earth Syst.* **14**, e2021MS002813 (2022).