



Supplement of

fair-calibrate v1.4.1: calibration, constraining, and validation of the FaIR simple climate model for reliable future climate projections

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Model	κ_1	κ_2	κ_3	C_1	C_2	C_3	ϵ	γ	σ_ξ	σ_η	$F_{4\times\text{CO}_2}$	ECS	TCR
ACCESS-CM2	0.67	2.81	0.68	3.73	11.6	86	1.35	1.62	0.53	0.45	7.19	5.36	2.48
ACCESS-ESM1-5	0.70	3.58	0.84	3.77	8.9	87	1.56	2.74	0.60	0.64	6.56	4.69	2.00
AWI-CM-1-1-MR	1.22	1.79	0.66	4.14	11.0	47	1.32	3.97	0.65	0.94	8.02	3.28	2.17
BCC-CSM2-MR	1.06	2.13	0.85	4.16	11.8	63	1.25	2.30	0.34	0.54	6.71	3.15	1.87
BCC-ESM1	0.88	1.48	0.91	5.35	15.8	77	1.29	1.88	0.31	0.39	6.25	3.53	1.91
CAMS-CSM1-0	1.88	5.32	0.65	2.61	9.1	52	1.25	27.69	0.45	2.66	8.86	2.35	1.73
CAS-ESM2-0	0.93	2.50	0.67	3.56	8.6	55	1.33	1.89	0.41	0.52	6.97	3.74	2.18
CESM2	0.65	3.88	0.90	4.83	6.4	71	1.68	2.80	0.49	0.71	8.18	6.29	2.49
CESM2-FV2	0.54	4.01	1.01	3.86	7.0	86	1.75	2.71	0.61	0.88	7.36	6.84	2.24
CESM2-WACCM	0.72	7.33	0.84	3.82	6.2	85	1.59	2.98	0.51	0.70	8.07	5.60	2.31
CESM2-WACCM-FV2	0.56	3.52	0.94	3.39	9.5	107	1.50	2.89	0.53	0.94	6.73	5.98	2.16
CIESM	0.68	2.65	1.00	5.28	11.6	69	1.35	0.81	0.55	0.36	8.48	6.26	2.69
CMCC-CM2-SR5	1.08	2.15	0.72	3.48	11.5	53	1.29	25.58	0.80	2.69	8.08	3.74	2.30
CNRM-CM6-1	0.78	1.56	0.67	3.22	16.1	116	0.91	24.01	0.47	1.67	7.32	4.70	2.66
CNRM-CM6-1-HR	0.94	1.99	0.65	4.16	11.8	90	0.80	7.10	0.48	0.69	7.70	4.10	2.57
CNRM-ESM2-1	0.68	2.62	0.69	3.53	7.6	104	0.83	4.67	0.50	0.89	5.90	4.35	2.39
CanESM5	0.62	2.48	0.61	3.63	10.6	73	1.12	2.62	0.48	0.42	7.33	5.93	2.92
E3SM-1-0	0.58	2.37	0.37	3.65	9.6	42	1.49	3.07	0.60	0.91	7.05	6.03	3.10
EC-Earth3	0.82	2.65	0.56	3.24	10.5	34	1.25	25.38	0.74	2.26	7.12	4.33	2.53
EC-Earth3-Veg	0.84	2.32	0.60	3.24	10.3	31	1.26	25.91	0.69	2.68	7.48	4.46	2.65
FGOALS-f3-L	1.44	5.65	0.71	1.97	10.4	71	1.52	29.14	0.63	2.75	9.33	3.25	2.02
FGOALS-g3	1.26	2.84	0.91	4.07	7.8	91	1.26	1.20	0.44	0.24	7.65	3.04	1.86
FIO-ESM-2-0	0.87	4.67	0.87	3.02	8.4	91	1.32	25.96	0.60	1.62	8.13	4.67	2.31
GFDL-CM4	1.00	2.79	1.25	5.31	0.2	81	1.81	2.72	0.71	0.95	9.02	4.50	2.19
GFDL-ESM4	1.38	1.92	0.84	4.32	10.6	124	1.02	4.32	0.49	1.07	7.36	2.66	1.79
GISS-E2-1-G	1.44	2.09	1.20	3.59	10.6	163	1.09	2.89	0.66	0.53	8.02	2.78	1.76
GISS-E2-1-H	1.11	4.31	0.78	2.24	9.7	78	1.19	3.62	0.59	0.55	7.20	3.25	1.93
GISS-E2-2-G	1.97	1.92	0.63	3.60	11.3	314	0.44	2.39	0.54	0.54	8.04	2.04	1.68
HadGEM3-GC31-LL	0.61	2.85	0.64	3.87	9.3	66	1.17	3.13	0.61	0.46	7.22	5.91	2.83
HadGEM3-GC31-MM	0.65	2.01	0.69	3.40	14.1	65	1.04	3.13	0.43	0.50	7.16	5.54	2.77
IITM-ESM	1.99	2.80	1.00	3.76	12.0	150	1.06	2.95	0.54	1.15	9.43	2.37	1.67
INM-CM4-8	1.58	1.90	0.55	4.35	9.8	22	1.45	2.51	0.26	0.44	5.94	1.88	1.41
INM-CM5-0	1.54	1.90	0.58	4.58	11.4	49	1.45	1.92	0.32	0.44	6.23	2.02	1.42
IPSL-CM6A-LR	0.72	1.76	0.48	3.40	13.2	62	1.28	3.22	0.49	0.90	7.05	4.90	2.70
KACE-1-0-G	0.73	3.63	0.87	2.54	8.7	101	1.25	2.08	0.35	0.36	7.80	5.36	2.50
KIOST-ESM	0.93	3.05	0.95	2.15	9.6	95	1.41	2.35	0.32	0.61	7.22	3.87	1.99
MIROC-ES2L	1.95	1.71	0.70	4.56	16.6	204	0.45	1.95	0.95	0.71	8.81	2.25	1.78
MIROC6	2.00	1.20	0.60	4.27	22.9	350	0.38	1.86	0.89	0.71	8.57	2.15	1.71
MPI-ESM-1-2-HAM	1.30	2.14	0.97	4.93	14.6	105	1.38	2.54	0.49	0.55	8.48	3.27	1.94
MPI-ESM1-2-HR	1.17	1.59	1.11	5.12	23.6	73	1.56	3.49	0.44	0.57	7.82	3.34	1.89
MPI-ESM1-2-LR	1.40	1.95	1.07	5.15	10.7	95	1.26	2.40	0.71	0.47	8.93	3.19	2.01
MRI-ESM2-0	1.11	2.85	1.25	4.24	10.5	94	1.33	2.99	0.52	0.98	7.56	3.41	1.80
NESM3	0.96	1.05	0.48	2.49	19.2	126	0.72	2.80	0.27	0.55	8.15	4.23	2.85
NorCPM1	1.03	2.07	1.33	5.72	17.6	92	1.51	1.81	0.50	0.49	7.26	3.52	1.75
NorESM2-LM	1.70	1.56	7.21	4.56	0.4	120	1.61	1.68	0.74	1.30	9.40	2.76	1.64
NorESM2-MM	1.96	0.79	7.23	4.12	121.5	0	1.20	1.49	0.66	1.31	9.10	2.32	1.71

SAM0-UNICON	1.04	2.69	1.03	4.63	6.3	111	1.25	2.44	0.64	0.80	8.36	4.01	2.20
TaiESM1	0.87	2.31	0.92	5.06	9.0	91	1.23	2.04	0.69	0.46	8.15	4.67	2.44
UKESM1-0-LL	0.66	2.60	0.61	2.92	11.3	73	1.13	3.55	0.44	0.50	7.38	5.63	2.84

Table S1: Parameters of the three-layer stochastic energy balance model for 49 CMIP6 $4\times\text{CO}_2$ forcing experiments. The ECS and TCR are calculated from the eigenvalue decomposition (see Leach et al. (2021)).

PRIMAP-Hist category	Gas	Lifetime (yr) (AR6)	GWP ₁₀₀ (AR6)	Emissions scaling factor
N ₂ O	N ₂ O	109	273	1.08
NF ₃	NF ₃	569	17400	7.45
SF ₆	SF ₆	3200	25200	1.05
HFCs	HFC-23	228	14600	1.14
	HFC-32	5.4	771	1.90
	HFC-125	30	3740	0.85
	HFC-134a	14	5810	1.07
	HFC-143a	51	5810	0.91
	HFC-152a	1.6	164	1.10
	HFC-227ea	36	3600	1.07
	HFC-236fa	213	8690	1.09
	HFC-245fa	7.9	962	0.97
	HFC-365mfc	8.9	914	0.96
	HFC-4310mee	17	1600	1.03
PFCs	CF ₄	50000	7380	1.34
	C ₂ F ₆	10000	12400	1.51
	C ₃ F ₈	2600	9290	1.72
	c-C ₄ F ₈	3200	10200	1.68
	C ₄ F ₁₀	2600	10000	1.71
	C ₅ F ₁₂	4100	9220	1.75
	C ₆ F ₁₄	3100	8620	1.21
	C ₇ F ₁₆	3000	8410	1.37
C ₈ F ₁₈	3000	8260	1.54	

Table S2. Data relating to the non-CO₂, non-CH₄ greenhouse gas emissions scalings used in `fair-calibrate v1.4.1`. The GWP₁₀₀ values are used for the HFC and PFC disaggregations. Note this is not an exhaustive list of minor greenhouse gases in FaIR (refer to Leach et al. (2021) for the default species used in the model).

Parameter name	Domain	Description
cc_co2_concentration_1750	Carbon cycle	CO ₂ concentration in 1750 (section 3.2.4)
cc_rA	Carbon cycle	r_A in eq. (7)
cc_rU	Carbon cycle	r_A in eq. (7)
cc_rT	Carbon cycle	r_T in eq. (7)
cc_r0	Carbon cycle	r_0 in eq. (7)
ari_BC	Aerosol-radiation	ERFari contribution from BC emissions (table 3)
ari_OC	Aerosol-radiation	ERFari from OC emissions (table 3)

ari_Sulfur	Aerosol-radiation	ERFari from SO ₂ emissions (table 3)
ari_NH3	Aerosol-radiation	ERFari from NH ₃ emissions (table 3)
ari_NOx	Aerosol-radiation	ERFari from NO _x emissions (table 3)
ari_VOC	Aerosol-radiation	ERFari from VOC emissions (table 3)
ari_CH4	Aerosol-radiation	ERFari from CH ₄ concentration (table 3)
ari_N2O	Aerosol-radiation	ERFari from N ₂ O concentration (table 3)
ari_EESC	Aerosol-radiation	ERFari from EESC (table 3)
aci_shape_so2	Aerosol-cloud	s_{SO_2} in eq. (8)
aci_shape_bc	Aerosol-cloud	s_{BC} in eq. (8)
aci_shape_oc	Aerosol-cloud	s_{OC} in eq. (8)
aci_beta	Aerosol-cloud	β in eq. (8)
clim_F_4xCO2	Climate response	Effective radiative forcing for quadrupled CO ₂
clim_c1	Climate response	C_1 in eq. (1)
clim_c2	Climate response	C_2 in eq. (2)
clim_c3	Climate response	C_3 in eq. (3)
clim_kappa1	Climate response	κ_1 in eq. (1)
clim_kappa2	Climate response	κ_2 in eqs. (1) and (2)
clim_kappa3	Climate response	κ_2 in eqs. (2) and (3)
clim_epsilon	Climate response	ε in eq. (3)
clim_gamma	Climate response	γ in eq. (4)
clim_sigma_eta	Climate response	Standard deviation of ξ in eq. (1)
clim_sigma_xi	Climate response	Standard deviation of η in eq. (4)
o3_CH4	Ozone	Contribution to O ₃ from CH ₄ (table 4)
o3_N2O	Ozone	Contribution to O ₃ from N ₂ O (table 4)
o3_EESC	Ozone	Contribution to O ₃ from EESC concentration (table 4)
o3_VOC	Ozone	Contribution to O ₃ from VOC (table 4)
o3_CO	Ozone	Contribution to O ₃ from CO (table 4)
o3_NOx	Ozone	Contribution to O ₃ from NO _x (table 4)
fscale_CO2	Forcing	Scale factor for CO ₂ forcing (table 5)
fscale_CH4	Forcing	Scale factor for CH ₄ forcing (table 5)
fscale_N2O	Forcing	Scale factor for N ₂ O forcing (table 5)
fscale_minorGHG	Forcing	Scale factor for other GHG forcing (table 5)
fscale_stratH2O	Forcing	Scale factor for H ₂ O from CH ₄ forcing (table 5)
fscale_LAPSI	Forcing	Scale factor for BC on snow forcing (table 5)
fscale_landuse	Forcing	Scale factor for land use forcing (table 5)
fscale_volcanic	Forcing	Scale factor for volcanic forcing (table 5)
fscale_solar_trend	Forcing	linear trend in solar forcing (table 5)
fscale_solar_amplitude	Forcing	Scale factor for amplitude of solar cycle (table 5)

Table S3: The 45 parameters or inputs to FaIR that are probabilistically sampled in `fair-calibrate v1.4.1` and `v1.4.0`. Table or section numbers refer to the main text and indicate prior distributions for `fair-calibrate v1.4.1`. Where no table or section number is given, the prior distribution is a kernel density estimate from CMIP6 model calibrations. Horizontal lines delimitate components of the Earth system that are calibrated together, and for kernel density estimates describe those components where the prior distributions are correlated.

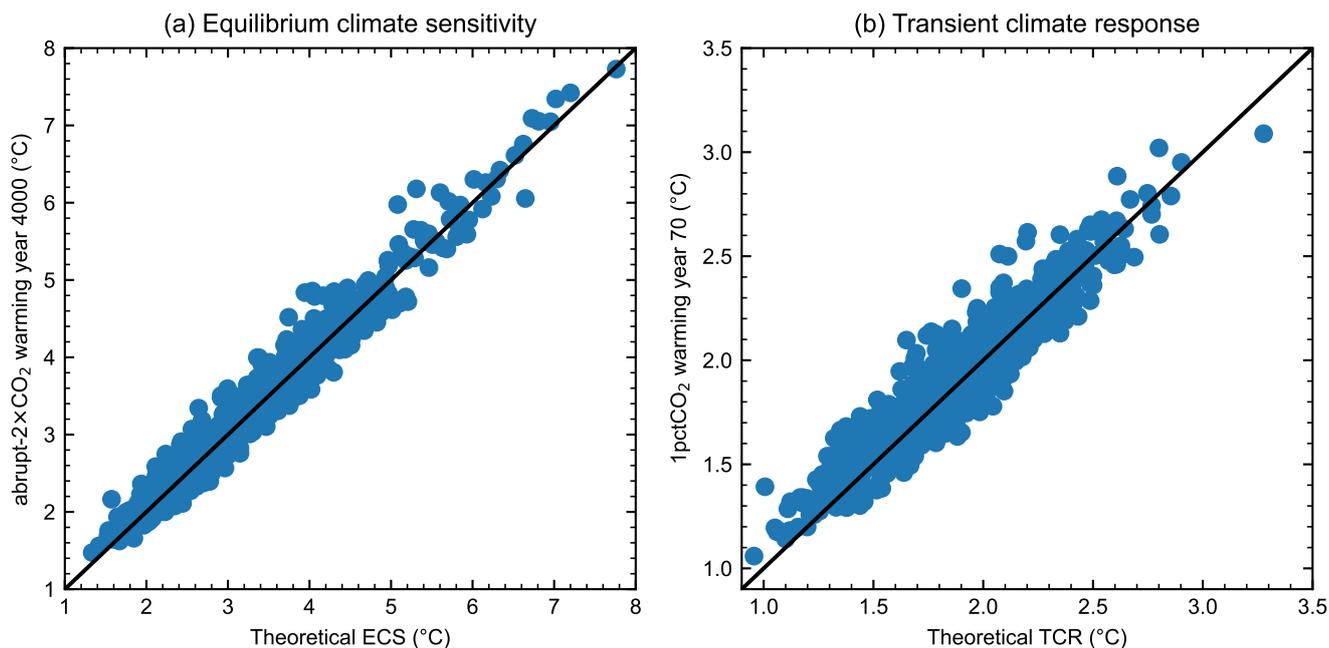


Figure S1. Comparisons of the theoretical (a) ECS and (b) TCR derived from the impulse-response formulation of the energy balance model (Leach et al., 2021) with the model-calculated values from abrupt-2×CO₂ and 1pctCO₂ simulations in FaIR.

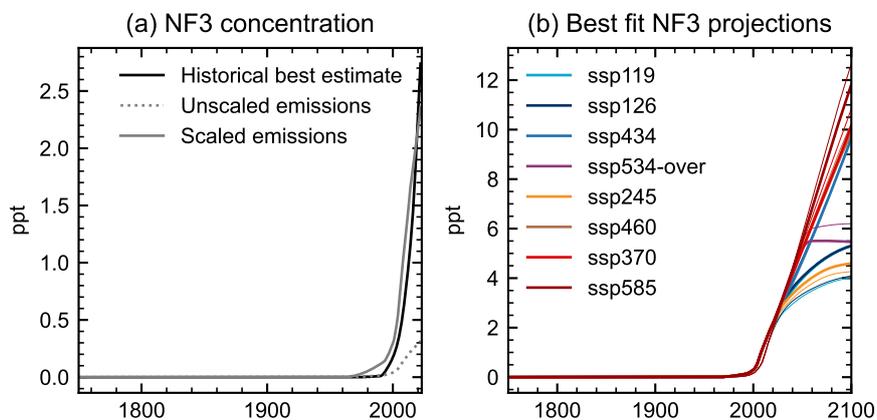


Figure S2. As for fig. 2, showing NF₃ as an example where (a) a large scaling factor applied to the historical emissions better reproduces concentrations, and (b) when applied, future concentration projections are in line with the CMIP6 SSPs (Meinshausen et al., 2020).

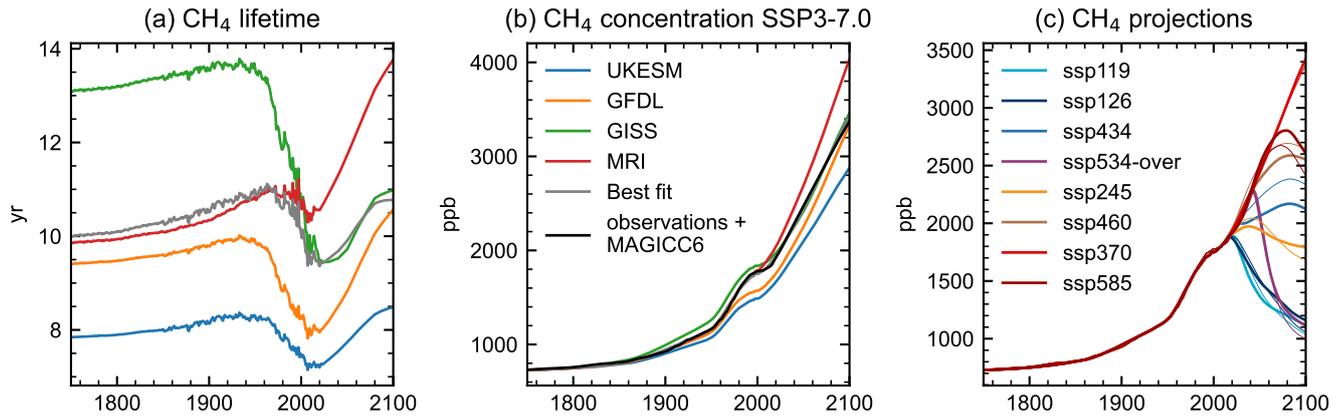


Figure S3. As for fig. 3, for *fair-calibrate* v1.4.0. Subplot (b) shows projected concentrations under SSP3-7.0 with each AerChemMIP model's estimates lifetimes from (a).

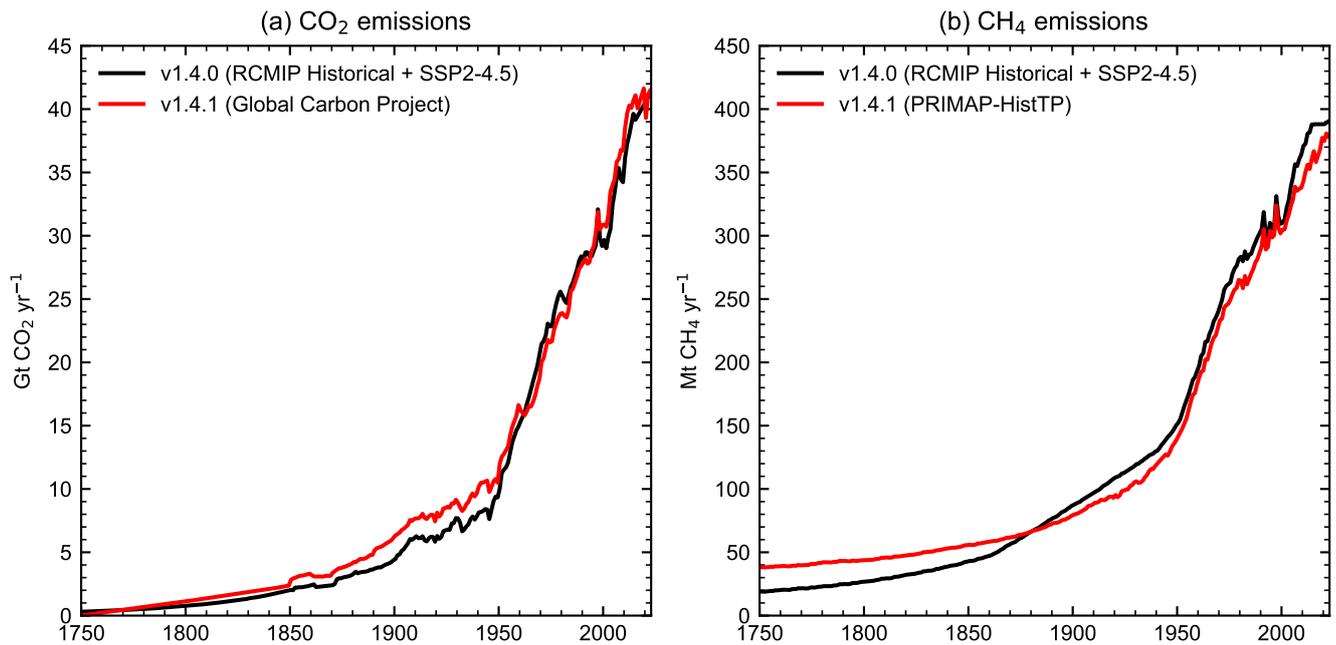


Figure S4. Comparison of (a) CO₂ emissions and (b) CH₄ emissions used in *fair-calibrate* v1.4.0 (black) and v1.4.1 (red).

Distributions and correlations of CMIP6 calibrations

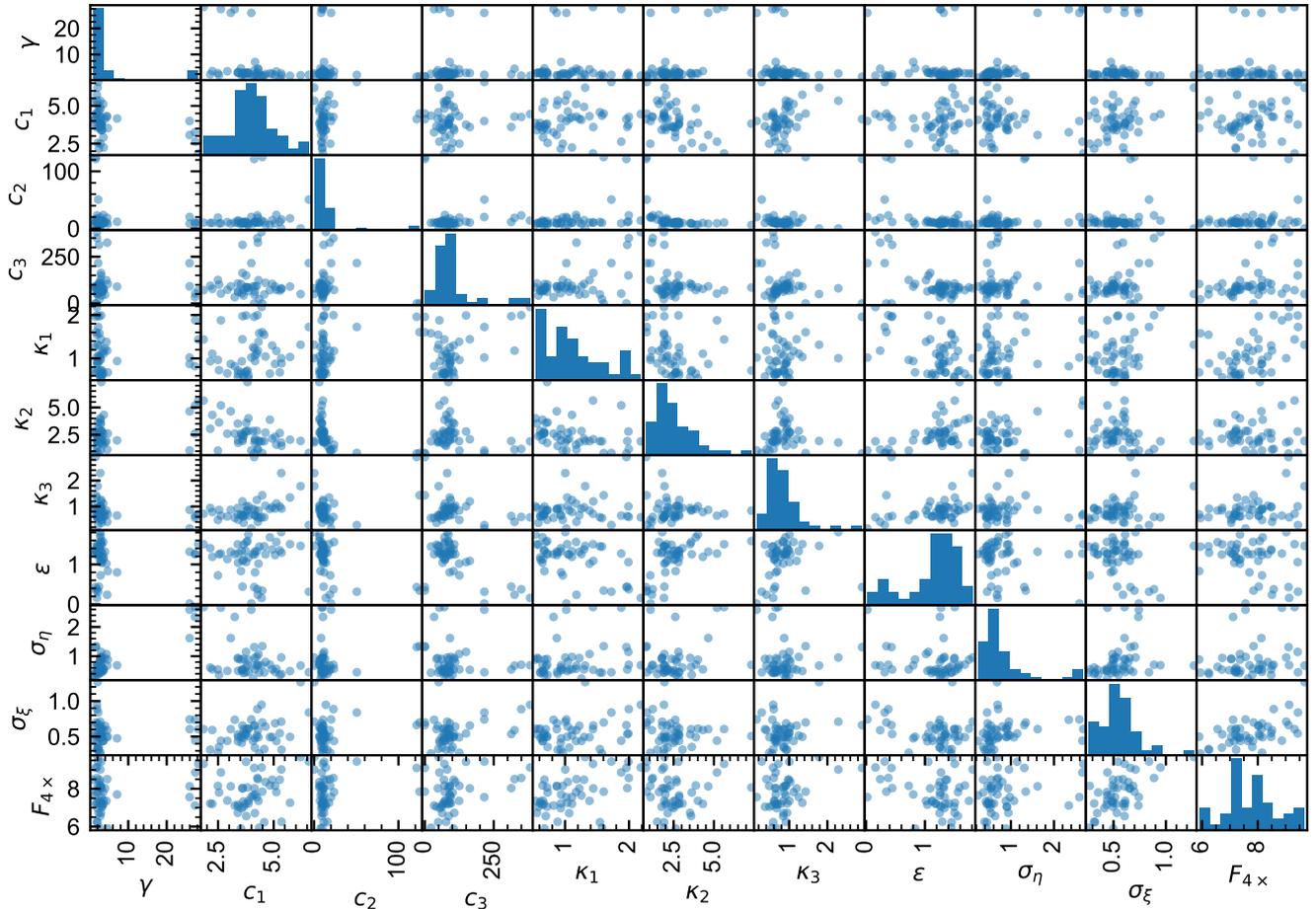


Figure S5. Matrix plot showing the calibrated parameters from the three-layer energy balance model, their distributions (on the diagonal) and correlations between parameters (off diagonal). These model-fitted parameters are used to draw an 11-dimensional kernel density estimate that is sampled from to inform the climate response.

Metric	Target			Reweighted posterior			Relative difference			Fit?
	lower	central	upper	lower	central	upper	lower	central	upper	
ECS (K)	2.00	3.00	5.00	2.01	2.99	4.94	0%	0%	-1%	Yes
TCR (K)	1.20	1.80	2.40	1.30	1.81	2.38	+9%	0%	-1%	Yes
GMST 2003–2022 rel. 1850–1900 (K)	0.87	1.03	1.13	0.88	1.03	1.14	+1%	0%	+1%	Yes
EEU 2020 rel. 1971 (ZJ)	356.8	465.3	573.8	350.5	467.9	569.4	-2%	+1%	-1%	Yes
Aerosol ERF 2005–2014 rel. 1750 ($W m^{-2}$)	-2.0	-1.3	-0.6	-1.98	-1.30	-0.58	-1%	0%	-4%	Yes
ERFari 2005–2014 rel. 1750 ($W m^{-2}$)	-0.6	-0.3	0.0	-0.58	-0.29	+0.01	-4%	-4%		Yes
ERFaci 2005–2014 rel. 1750 ($W m^{-2}$)	-1.7	-1.0	-0.3	-1.68	-0.98	-0.34	-1%	-2%	+12%	Yes
CO ₂ concentration 2022 (ppm)	416.2	417.0	417.8	416.2	417.0	417.9	0%	0%	0%	Yes
WMGHG ERF 2019 rel. 1750 ($W m^{-2}$)	3.03	3.32	3.61	3.01	3.28	3.57	-1%	-1%	-1%	
CH ₄ ERF 2019 rel. 1750 ($W m^{-2}$)	0.43	0.54	0.65	0.44	0.56	0.67	+3%	+3%	+2%	
Airborne fraction at $2 \times CO_2^*$	0.43	0.53	0.63	0.50	0.51	0.52	+16%	-4%	-18%	
Airborne fraction at $4 \times CO_2^*$	0.44	0.60	0.76	0.53	0.58	0.62	+21%	-3%	-19%	
TCRE* ($K (1000 GtC)^{-1}$)	0.58	1.65	2.72	1.16	1.57	2.07	+99%	-5%	-24%	
SSP1-1.9 2021–2040 rel. 1995–2014 (K)	0.38	0.61	0.85	0.35	0.59	0.91	-9%	-4%	+8%	
SSP1-1.9 2041–2060 rel. 1995–2014 (K)	0.40	0.71	1.07	0.33	0.71	1.26	-18%	-1%	+18%	
SSP1-1.9 2081–2100 rel. 1995–2014 (K)	0.24	0.56	0.96	0.14	0.58	1.35	-40%	+4%	+41%	
SSP1-2.6 2021–2040 rel. 1995–2014 (K)	0.41	0.63	0.89	0.37	0.61	0.92	-10%	-4%	+3%	
SSP1-2.6 2041–2060 rel. 1995–2014 (K)	0.54	0.88	1.32	0.48	0.87	1.44	-11%	-2%	+9%	
SSP1-2.6 2081–2100 rel. 1995–2014 (K)	0.51	0.90	1.48	0.39	0.89	1.73	-23%	-1%	+17%	
SSP2-4.5 2021–2040 rel. 1995–2014 (K)	0.44	0.66	0.90	0.40	0.60	0.86	-8%	-8%	-4%	
SSP2-4.5 2041–2060 rel. 1995–2014 (K)	0.78	1.12	1.57	0.71	1.06	1.54	-9%	-6%	-2%	
SSP2-4.5 2081–2100 rel. 1995–2014 (K)	1.24	1.81	2.59	1.06	1.71	2.68	-14%	-6%	+3%	
SSP3-7.0 2021–2040 rel. 1995–2014 (K)	0.45	0.67	0.92	0.41	0.59	0.83	-8%	-13%	-9%	
SSP3-7.0 2041–2060 rel. 1995–2014 (K)	0.92	1.28	1.75	0.86	1.15	1.56	-7%	-10%	-11%	
SSP3-7.0 2081–2100 rel. 1995–2014 (K)	2.00	2.76	3.75	1.85	2.53	3.52	-8%	-8%	-6%	
SSP5-8.5 2021–2040 rel. 1995–2014 (K)	0.51	0.76	1.04	0.48	0.69	1.02	-7%	-9%	-2%	
SSP5-8.5 2041–2060 rel. 1995–2014 (K)	1.08	1.54	2.08	1.01	1.45	2.06	-6%	-6%	-1%	
SSP5-8.5 2081–2100 rel. 1995–2014 (K)	2.44	3.50	4.82	2.32	3.35	4.78	-5%	-4%	-1%	

Table S4. As for table 5 for `fair-calibrate v1.4.0`. Dark shading is more than 20% from the target for upper and lower ranges and 10% for the central. Paler shading is more than 10% from the target for upper and lower ranges and 5% for the central.

References

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- 5 Meinshausen, M., Nicholls, Z. R. J., Lewis, J., Gidden, M. J., Vogel, E., Freund, M., Beyerle, U., Gessner, C., Nauels, A., Bauer, N., Canadell, J. G., Daniel, J. S., John, A., Krummel, P. B., Luderer, G., Meinshausen, N., Montzka, S. A., Rayner, P. J., Reimann, S., Smith, S. J., van den Berg, M., Velders, G. J. M., Vollmer, M. K., and Wang, R. H. J.: The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500, *Geoscientific Model Development*, 13, 3571–3605, <https://doi.org/10.5194/gmd-13-3571-2020>, <https://gmd.copernicus.org/articles/13/3571/2020/>, 2020.