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Supplement of

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

Chris Smith et al.

Correspondence to: Chris Smith (chris.smith@vub.be)

Model	κ_1	κ_2	κ_3	C_1	C_2	C_3	ϵ	γ	σ_ξ	σ_η	$F_{4\times CO_2}$	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$\times CO_2$ 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_2O	N_2O	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_2F_6	10000	12400	1.51
	C_3F_8	2600	9290	1.72
	c-C_4F_8	3200	10200	1.68
	C_4F_{10}	2600	10000	1.71
	C_5F_{12}	4100	9220	1.75
	C_6F_{14}	3100	8620	1.21
	C_7F_{16}	3000	8410	1.37
	C_8F_{18}	3000	8260	1.54

Table S2. Data relating to the non-CO_2, non-CH_4 greenhouse gas emissions scalings used in `fair-calibrate` v1.4.1. The GWP_{100} 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 NOx 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_2O concentration (table 3)
ari_EESC	Aerosol-radiation	ERFari from EESC (table 3)
aci_shape_so2	Aerosol-cloud	s_{SO2} 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_2O (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 NOx (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_2O forcing (table 5)
fscale_minorGHG	Forcing	Scale factor for other GHG forcing (table 5)
fscale_stratH2O	Forcing	Scale factor for H_2O 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 deliminate components of the Earth system that are calibrated together, and for kernel density estimates describe those components where the prior distributions are correlated.

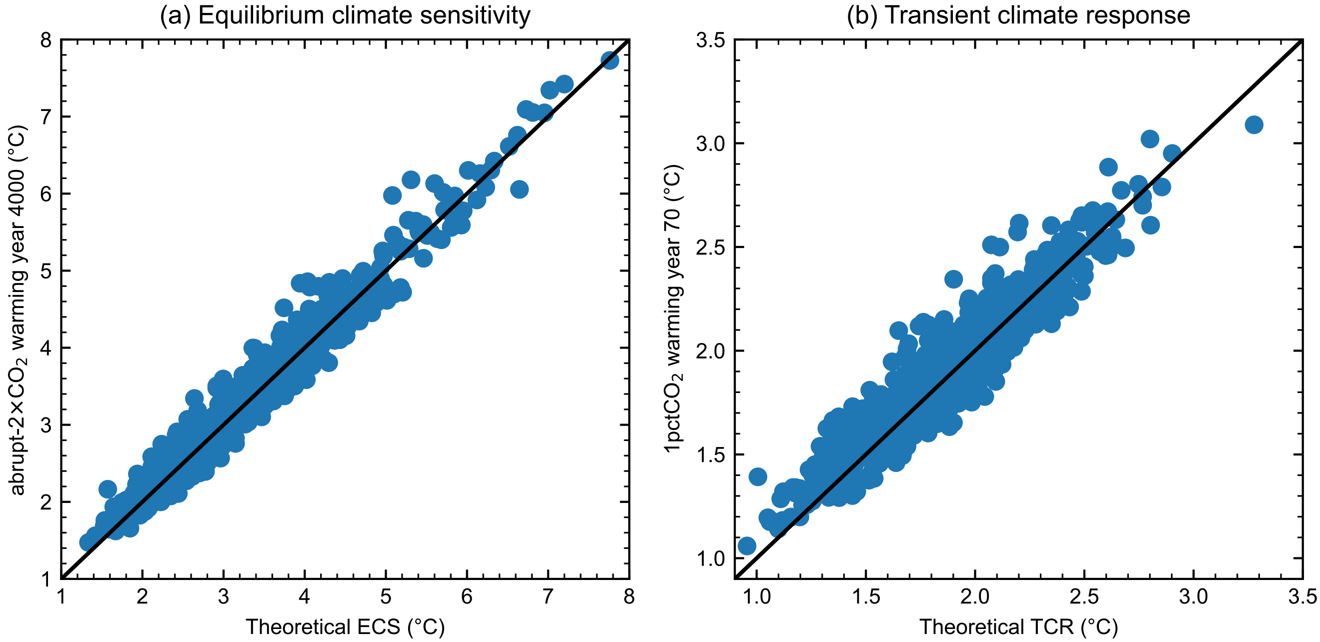

Figure S1. Comparisons of the theoretical (a) ECS and (b) TCR derived from the impulse-response formulation of the energy balance model (Leach et al., 2021) with the model-calculated values from abrupt-2$\times CO_2$ and 1pctCO_2 simulations in FaIR.

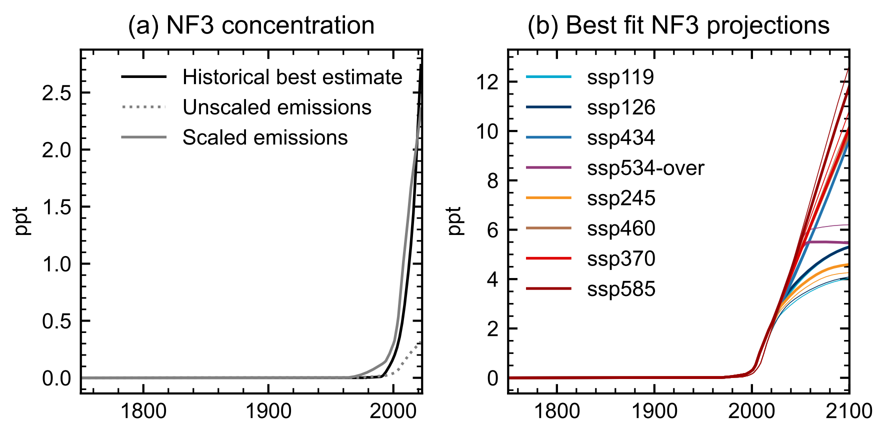

Figure S2. As for fig. 2, showing NF_3 as an example where (a) a large scaling factor applied to the historical emissions better reproduces concentrations, and (b) when applied, future concentration projections are in line with the CMIP6 SSPs (Meinshausen et al., 2020).

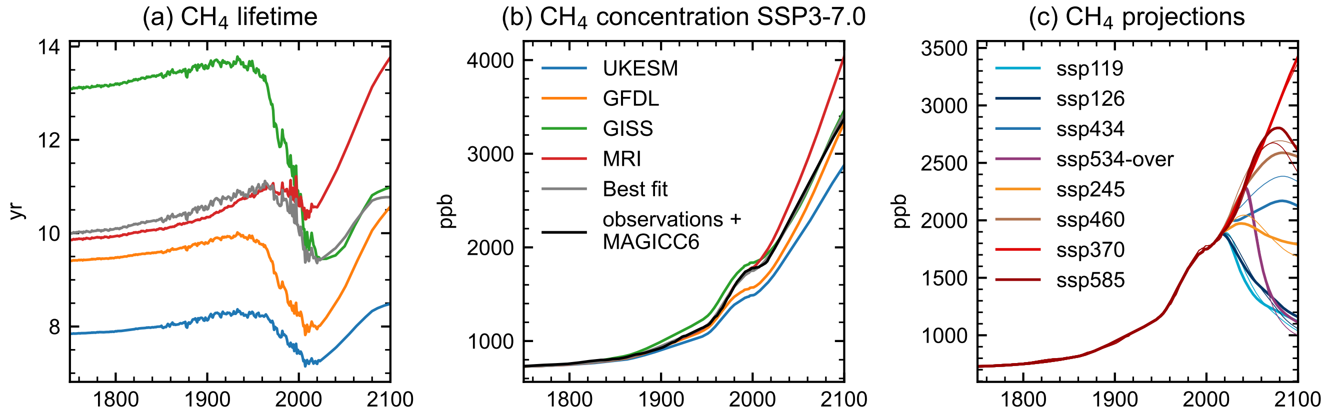

Figure S3. As for fig. 3, for `fair-calibrate` v1.4.0. Subplot (b) shows projected concentrations under SSP3-7.0 with each AerChemMIP model's estimates lifetimes from (a).

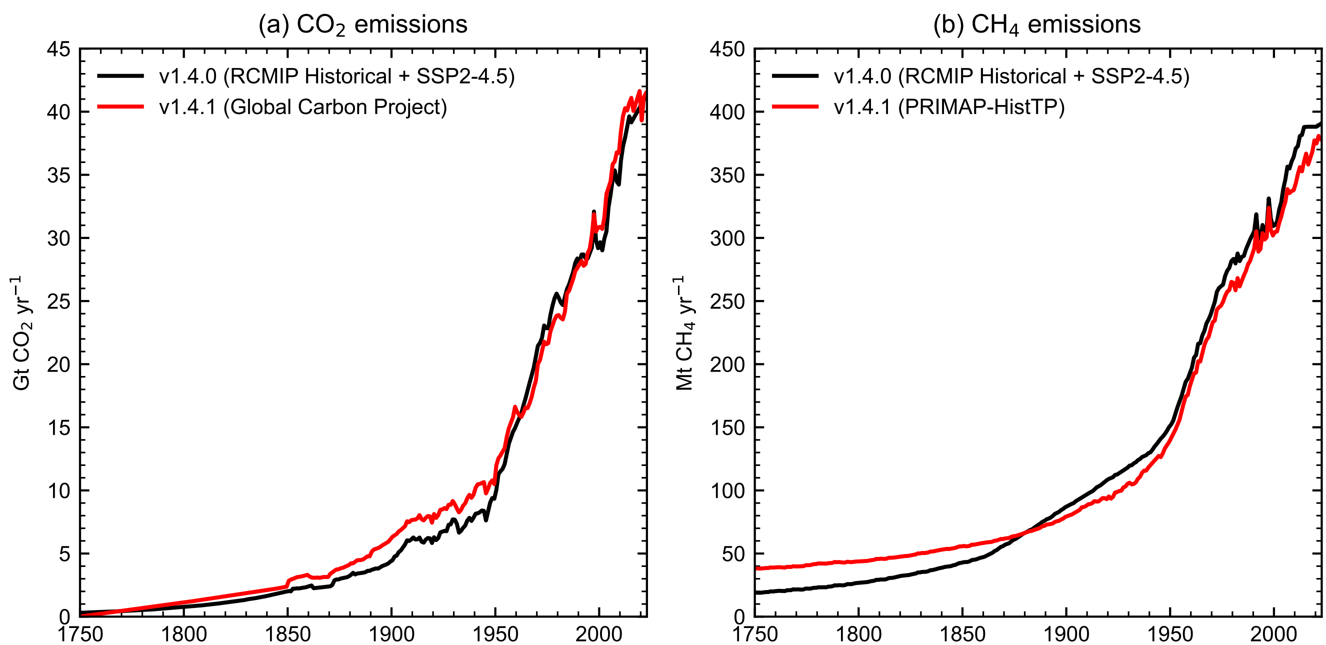

Figure S4. Comparison of (a) CO_2 emissions and (b) CH_4 emissions used in `fair-calibrate` v1.4.0 (black) and v1.4.1 (red).

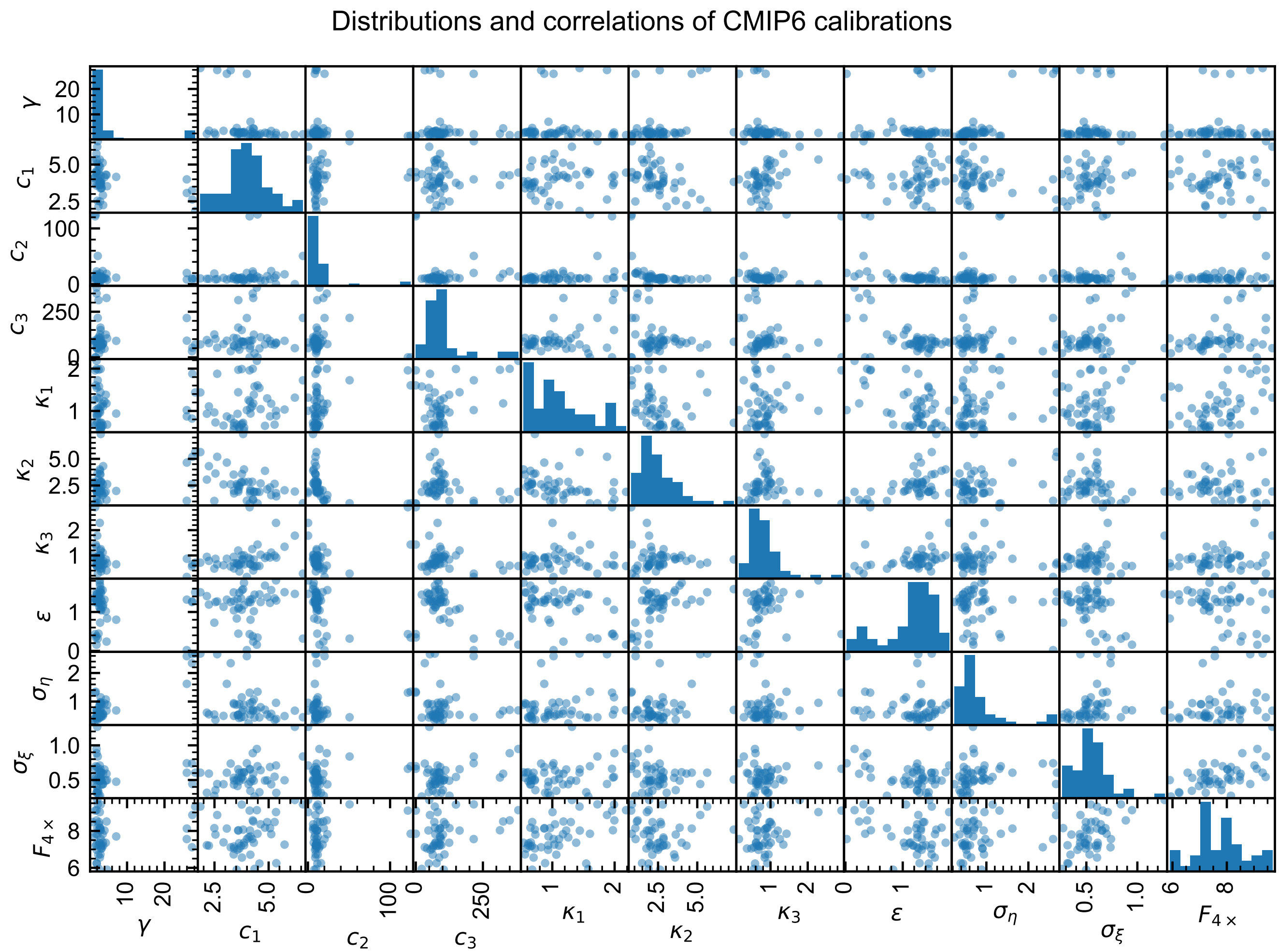

Figure S5. Matrix plot showing the calibrated parameters from the three-layer energy balance model, their distributions (on the diagonal) and correlations between parameters (off diagonal). These model-fitted parameters are used to draw an 11-dimensional kernel density estimate that is sampled from to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

Metric	Target lower	Target central	Target upper	Reweighted posterior lower	Reweighted posterior central	Reweighted posterior upper	Relative difference lower	Relative difference central	Relative difference upper	Fit?
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×CO_2*	0.43	0.53	0.63	0.50	0.51	0.52	+16%	−4%	−18%	
Airborne fraction at 4×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

Leach, N. J., Jenkins, S., Nicholls, Z., Smith, C. J., Lynch, J., Cain, M., Walsh, T., Wu, B., Tsutsui, J., and Allen, M. R.: FaIRv2.0.0: a generalized impulse response model for climate uncertainty and future scenario exploration, Geoscientific Model Development, 14, 3007–3036, https://doi.org/10.5194/gmd-14-3007-2021, 2021.

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.