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Effective radiative forcing and adjustments in CMIP6 models

Christopher J. Smith et al.

Correspondence to: C. J. Smith (c.j.smith1@leeds.ac.uk)

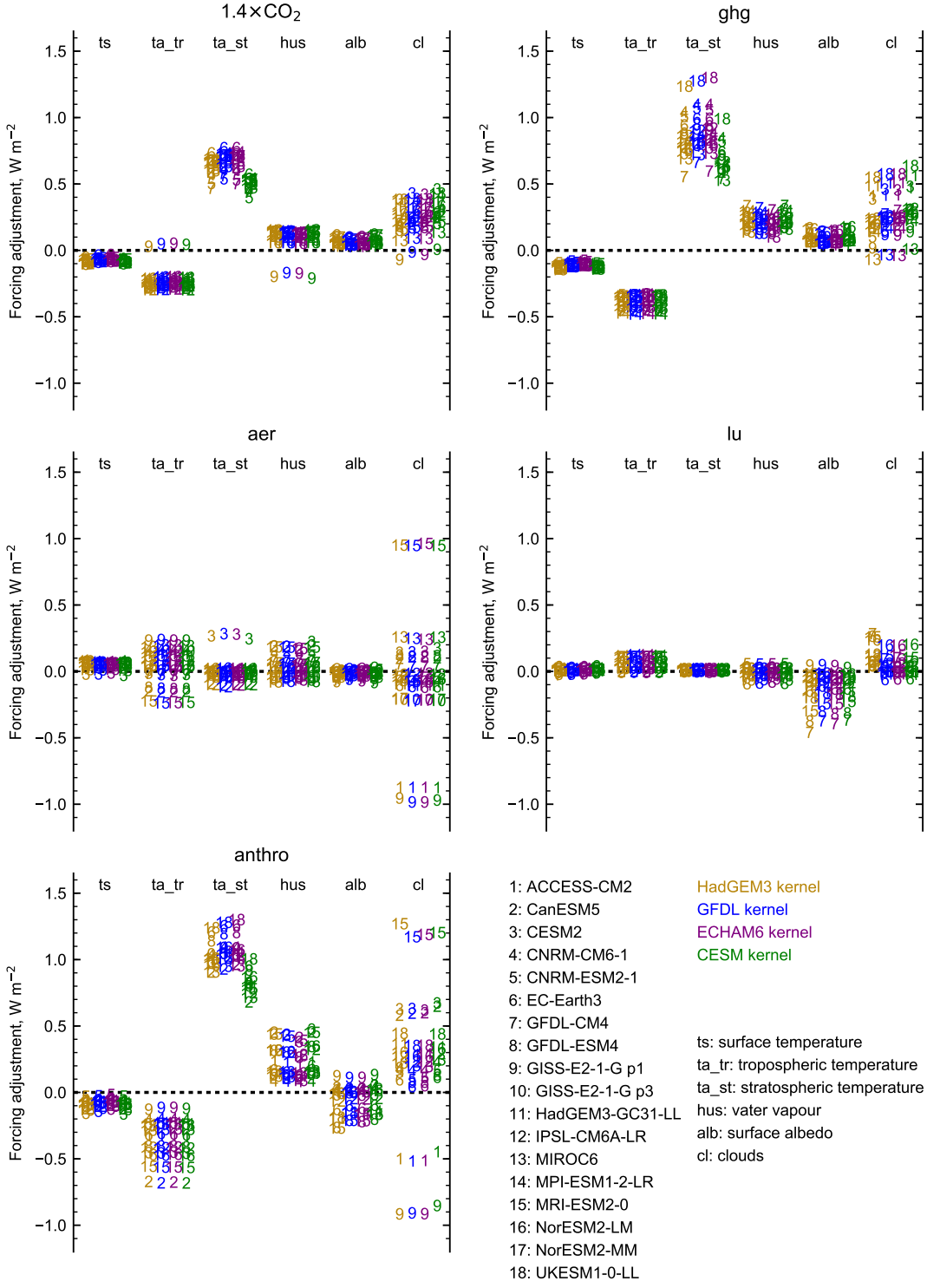

Figure S1. Forcing adjustments from four radiative kernels for each model and adjustment. Clouds adjustments are calculated according to the cloud masking method described in Soden et al. (2008) and do not necessarily correspond to values in the main text.

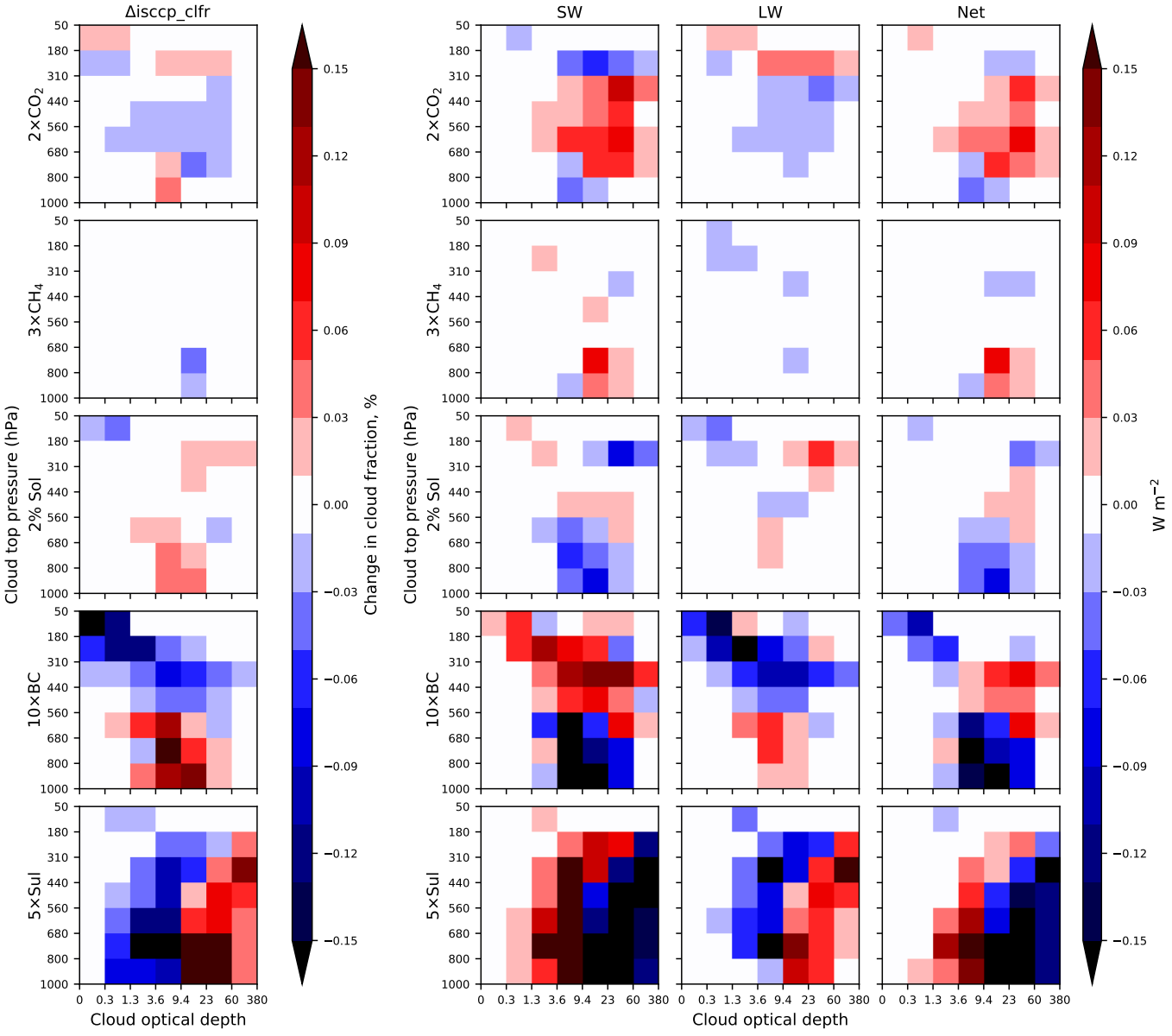

Figure S2. ISCCP cloud radiative effect from idealised single forcing experiments in the HadGEM2-ES model as part of PDRMIP.

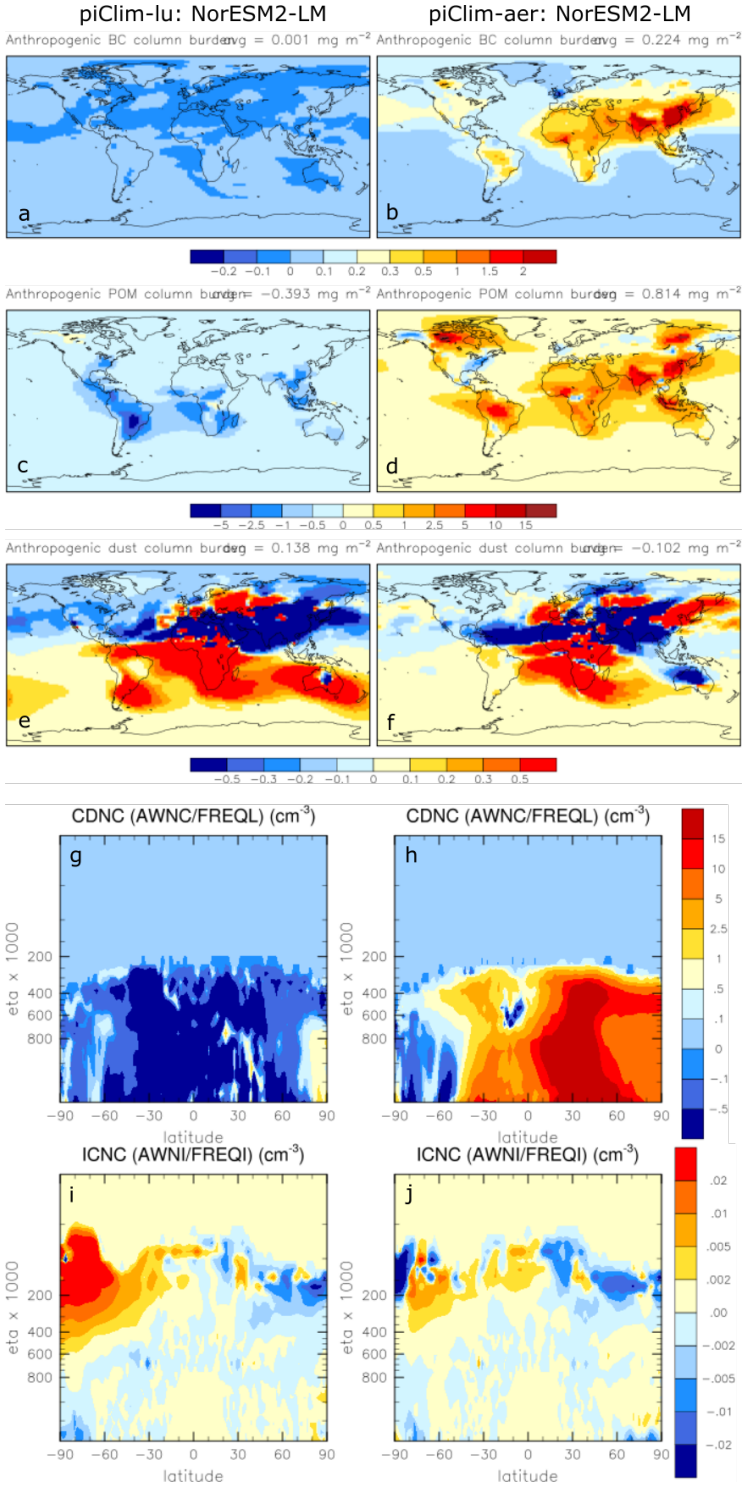

Figure S3. Change in (a,b) black carbon loading, (c,d) organic carbon loading, (e,f) mineral dust loading, (g,h) liquid cloud droplet number concentration and (i,j) ice cloud particle concentration for (left column) piClim-lu and (right column) piClim-aer in NorESM2-LM relative to piClim-control.

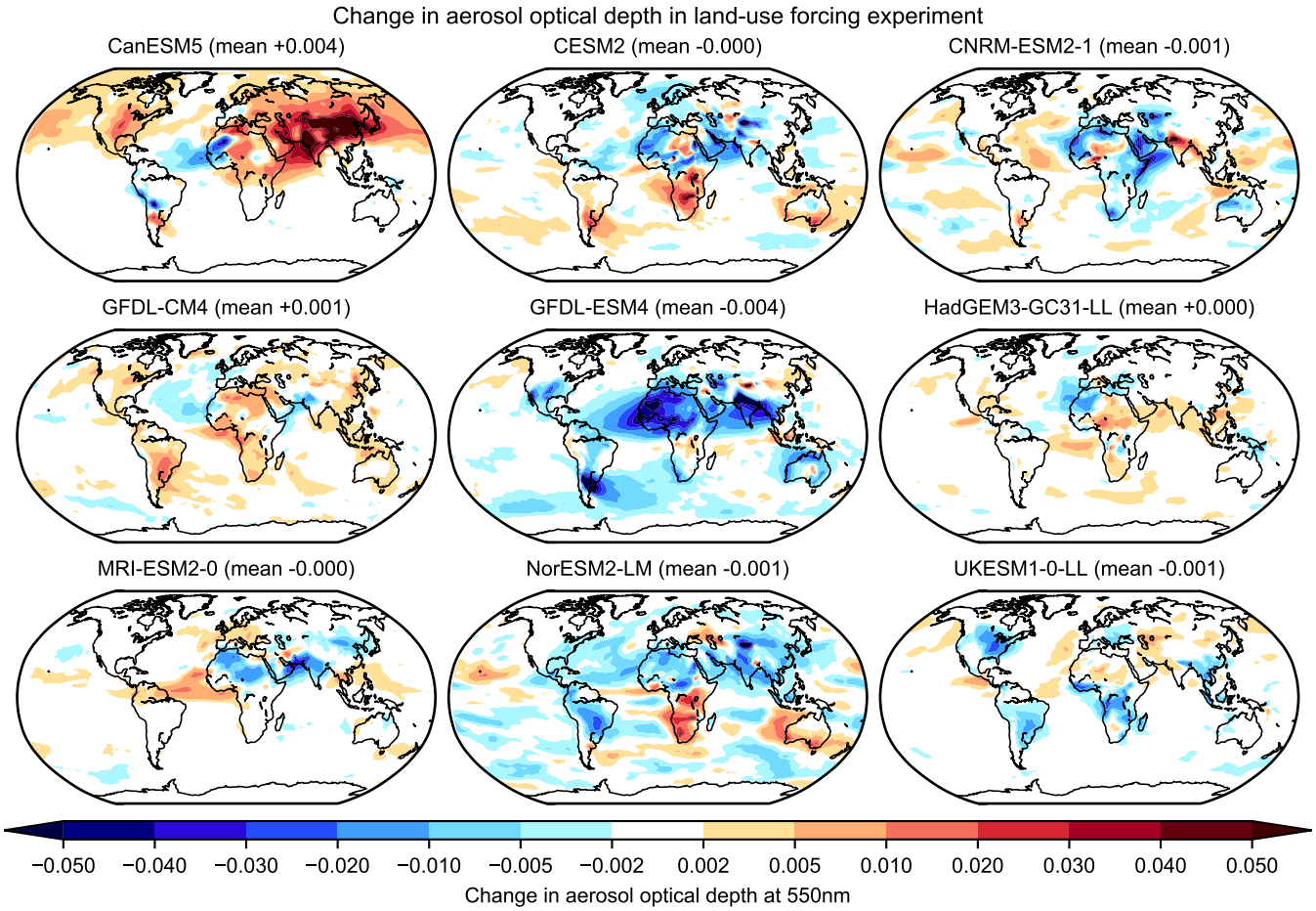

Figure S4. Aerosol optical depth change at 550 nm in the land-use forcing experiment.

References

Soden, B., Held, I., Colman, R., Shell, K., Kiehl, J., and Shields, C.: Quantifying Climate Feedbacks Using Radiative Kernels, J. Climate, 21, 3504–3520, https://doi.org/10.1175/2007JCLI2110.1, 2008.

Watson-Parris, D., Bellouin, N., Deaconu, L. T., Schutgens, N. A. J., Yoshioka, M., Regayre, L. A., Pringle, K. J., Johnson, J. S., Smith, C. J., Carslaw, K. S., and Stier, P.: Constraining Uncertainty in Aerosol Direct Forcing, Geophysical Research Letters, 47, e2020GL087 141, https://doi.org/10.1029/2020GL087141, 2020.

Table S1. Different definitions of $4\times CO_2$ [effective] radiative forcing as shown in Figure 1. ERFreg150 is the 150-year Gregory regression from an abrupt-4xCO2 experiment

#	Model	ERFreg150	ERF_reg	RF	ERF_trop	ERF_ts	ERF_λ	ERF
1	ACCESS-CM2	6.73	8.11	7.47	8.87	8.36	8.27	7.95
2	CanESM5	7.40	7.54	7.70	8.43	8.03	7.93	7.61
3	CESM2	6.42	8.47	7.47	9.74	9.42	9.28	8.91
4	CNRM-CM6-1	7.45	7.89	8.39	8.76	8.43	8.40	8.00
5	CNRM-ESM2-1	5.98	5.51	8.39	8.54	8.28	8.21	7.93
6	EC-Earth3	6.29	7.33		8.95	8.49	8.45	8.09
7	GFDL-CM4	6.37	8.64	7.67	9.17	8.62	8.69	8.24
8	GFDL-ESM4	7.82	7.45	6.87	8.08	8.09	8.41	7.74
9	GISS-E2-1-G p1	7.83	7.87	7.94	8.39	7.75	7.89	7.35
11	HadGEM3-GC31-LL	6.97	7.74	7.59	9.33	8.56	8.42	8.09
12	IPSL-CM6A-LR	6.83	7.78	8.06	8.99	8.50	8.48	8.00
13	MIROC6	7.26	7.79	7.63	8.17	7.76	7.76	7.32
14	MPI-ESM1-2-LR	8.59	9.42	7.86	9.34	8.82	9.17	8.35
15	MRI-ESM2-0	6.80	7.64	7.89	8.30	7.99	8.10	7.65
16	NorESM2-LM	6.98	9.28	7.52	8.97	8.62	8.89	8.15
17	NorESM2-MM	7.34	8.70	7.60	9.16	8.87	9.22	8.38
18	UKESM1-0-LL	7.25	7.82	7.33	9.15	8.42	8.32	7.94
	Mean	7.11	7.94	7.71	8.84	8.41	8.46	7.98
	Standard dev.	0.63	0.82	0.37	0.45	0.41	0.44	0.38

Table S2. As for table S1 but for 1850–2014 well-mixed greenhouse gas forcing.

#	Model	RF	ERF_trop	ERF_ts	ERF_λ	ERF
1	ACCESS-CM2	2.89	3.25	3.17	3.14	3.04
2	CanESM5	2.88	3.07	3.02	2.98	2.87
3	CESM2	2.67	3.18	3.18	3.13	3.03
4	CNRM-CM6-1	2.78	2.94	2.89	2.87	2.74
5	CNRM-ESM2-1	2.58	2.74	2.61	2.59	2.51
6	EC-Earth3		2.96	2.88	2.87	2.75
7	GFDL-CM4	2.92	3.44	3.26	3.28	3.13
8	GFDL-ESM4	2.95	3.34	3.35	3.46	3.23
9	GISS-E2-1-G p1	3.15	3.16	3.03	3.17	2.89
11	HadGEM3-GC31-LL	2.84	3.34	3.25	3.21	3.11
12	IPSL-CM6A-LR	2.66	3.11	2.95	2.99	2.82
13	MIROC6	2.85	2.83	2.82	2.67	2.69
14	MPI-ESM1-2-LR	2.75	2.92	2.83	2.94	2.69
15	MRI-ESM2-0	3.02	3.21	3.15	3.18	3.03
16	NorESM2-LM	2.76	3.01	2.93	3.01	2.80
18	UKESM1-0-LL	2.67	3.31	3.11	3.07	2.95
	Mean	2.82	3.11	3.03	3.04	2.89
	Standard dev.	0.15	0.19	0.19	0.21	0.19

Table S3. As for table S1 but for 1850–2014 aerosol forcing.

#	Model	RF	ERF_trop	ERF_ts	ERF_λ	ERF
1	ACCESS-CM2		−1.18	−1.16	−1.13	−1.09
2	CanESM5	−0.61	−0.86	−0.87	−0.86	−0.85
3	CESM2	−1.50	−1.32	−1.35		−1.37
4	CNRM-CM6-1	−1.20	−1.19	−1.23	−1.20	−1.15
5	CNRM-ESM2-1	−0.76	−0.80	−0.80	−0.77	−0.74
6	EC-Earth3	−0.66	−1.43	−0.87	−0.83	−0.80
7	GFDL-CM4	−0.58	−0.79	−0.78	−0.77	−0.73
8	GFDL-ESM4	−0.38	−0.67	−0.74	−0.73	−0.70
9	GISS-E2-1-G p1	−0.49	−1.32	−1.37	−1.41	−1.32
10	GISS-E2-1-G p3	−1.03	−1.04	−0.98	−1.00	−0.93
11	HadGEM3-GC31-LL	−1.03	−1.13	−1.16	−1.13	−1.10
12	IPSL-CM6A-LR	−0.71	−0.77	−0.69	−0.63	−0.63
13	MIROC6	−1.13	−1.16	−1.10	−1.14	−1.04
15	MRI-ESM2-0	−0.47	−1.20	−1.24	−1.23	−1.21
16	NorESM2-LM	−1.14	−1.17	−1.21	−1.20	−1.21
17	NorESM2-MM	−1.12	−1.38	−1.29	−1.30	−1.26
18	UKESM1-0-LL	−0.95	−1.14	−1.17	−1.13	−1.11
	Mean	−0.86	−1.09	−1.06	−1.03	−1.01
	Standard dev.	0.31	0.22	0.22	0.23	0.23

Table S4. As for table S1 but for 1850–2014 land-use forcing.

#	Model	RF	ERF_trop	ERF_ts	ERF_λ	ERF
2	CanESM5	−0.09	−0.15	−0.09	−0.08	−0.08
3	CESM2	−0.09	−0.08	−0.02	−0.03	−0.04
5	CNRM-ESM2-1	−0.10	−0.06	−0.08	−0.09	−0.07
6	EC-Earth3	−0.11	−0.20	−0.15	−0.17	−0.13
7	GFDL-CM4	−0.41	−0.41	−0.30	−0.34	−0.33
8	GFDL-ESM4	−0.26	−0.27	−0.24	−0.28	−0.28
9	GISS-E2-1-G p1	0.03	0.06	0.02	0.01	−0.00
11	HadGEM3-GC31-LL	−0.17	−0.16	−0.12	−0.13	−0.11
12	IPSL-CM6A-LR	−0.09	−0.10	−0.04	−0.03	−0.05
13	MIROC6	−0.06	−0.09	−0.02	−0.24	−0.03
14	MPI-ESM1-2-LR	−0.05	−0.11	−0.09	−0.10	−0.10
15	MRI-ESM2-0	−0.32	−0.17	−0.17	−0.17	−0.17
16	NorESM2-LM	−0.00	0.16	0.26	0.25	0.26
18	UKESM1-0-LL	−0.17	−0.27	−0.18	−0.19	−0.18
	Mean	−0.14	−0.13	−0.09	−0.11	−0.09
	Standard dev.	0.12	0.14	0.13	0.14	0.13

Table S5. As for table S1 but for 1850–2014 anthropogenic forcing.

#	Model	RF	ERF_trop	ERF_ts	ERF_λ	ERF
1	ACCESS-CM2		2.09	1.98	1.98	1.90
2	CanESM5	2.72	2.55	2.51	2.49	2.37
3	CESM2	1.68	2.31	2.22	2.18	2.05
4	CNRM-CM6-1	1.56	1.82	1.68	1.70	1.61
5	CNRM-ESM2-1	1.78	1.73	1.70	1.70	1.66
6	EC-Earth3		2.38	2.18	2.17	2.09
7	GFDL-CM4	2.85	3.03	2.45	2.44	2.34
8	GFDL-ESM4	2.63	2.64	2.29	2.37	2.17
9	GISS-E2-1-G p1	2.81	1.88	2.01	2.11	1.93
11	HadGEM3-GC31-LL	1.97	2.26	1.90	1.88	1.81
12	IPSL-CM6A-LR	2.36	2.67	2.43	2.43	2.32
13	MIROC6	1.98	1.96	1.89	1.74	1.80
14	MPI-ESM1-2-LR		2.35	2.23		2.13
15	MRI-ESM2-0	2.69	2.40	2.05	2.10	1.95
16	NorESM2-LM	2.17	2.36	2.20	2.29	2.06
18	UKESM1-0-LL	1.87	2.19	1.90	1.87	1.79
	Mean	2.24	2.29	2.10	2.10	2.00
	Standard dev.	0.44	0.33	0.25	0.27	0.23

Table S6. Contribution of cloud adjustments to aerosol forcing. LWP = liquid water path; CLT = cloud fraction; ISCCP = ISCCP simulator kernel; MMPRP = monthly mean partial radiative perturbation; CRE = cloud radiative effect. Columns are left blank where estimates are either unavailable or it is not appropriate to use them (e.g. CRE and ISCCP estimates for models which include ice-cloud nucleation). LW adjustment is the mean of available methods in each model.

Model	SW LWP	SW CLT	SW adj.	LW CRE	LW ISCCP	LW MMPRP	LW adj.	Net adj.
CanESM5	−0.06	−0.14	−0.19	−0.08	−0.10		−0.09	−0.28
CESM2	−0.10	−0.01	−0.11			0.16	0.16	0.05
CNRM-CM6-1	0.01	0.05	0.06	−0.05	−0.12	−0.08	−0.09	−0.03
CNRM-ESM2-1	0.00	−0.03	−0.02	−0.02	−0.07	−0.00	−0.03	−0.06
EC-Earth3	−0.04	−0.08	−0.12	−0.02			−0.02	−0.14
GFDL-CM4	−0.04	−0.09	−0.13	−0.06	−0.03	−0.03	−0.04	−0.17
GFDL-ESM4	−0.06	−0.06	−0.12	−0.17		−0.10	−0.14	−0.26
GISS-E2-1-G p1	−0.07	−0.94	−1.01	0.10		0.05	0.07	−0.93
GISS-E2-1-G p3	−0.00	−0.06	−0.07	−0.05		0.01	−0.02	−0.09
HadGEM3-GC31-LL	−0.02	−0.07	−0.09	−0.00	−0.07	−0.09	−0.05	−0.14
IPSL-CM6A-LR	0.00	0.06	0.06	−0.07	−0.13	−0.08	−0.09	−0.03
MIROC6	0.01	−0.01	−0.00			−0.02	−0.02	−0.02
MRI-ESM2-0	−0.08	−0.38	−0.46			−0.22	−0.22	−0.68
NorESM2-LM	−0.08	−0.10	−0.19			0.06	0.06	−0.12
NorESM2-MM	−0.12	−0.17	−0.29	0.04		0.15	0.10	−0.19
UKESM1-0-LL	−0.03	−0.10	−0.13	−0.01	−0.05	−0.09	−0.05	−0.18
Mean	−0.04	−0.13	−0.17	−0.03	−0.08	−0.02	−0.03	−0.20

Table S7. Shortwave clear-sky ERF from the APRP method from CMIP6 models used in Watson-Parris et al. (2020).

Model	Clear-sky SW ERFari (W m^{-2})
ACCESS-CM2	-0.70
CanESM5	-0.35
CESM2	-0.07
CNRM-CM6-1	-0.54
CNRM-ESM2-1	-0.35
EC-Earth3	-0.59
GFDL-CM4	-0.49
GFDL-ESM4	-0.41
GISS-E2-1-G p1	-0.94
GISS-E2-1-G p3	-1.01
HadGEM3-GC31-LL	-0.67
IPSL-CM6A-LR	-0.56
MIROC6	-0.49
MRI-ESM2-0	-0.48
NorESM2-LM	-0.42
NorESM2-MM	-0.46
UKESM1-0-LL	-0.59
Mean	-0.54
St. Dev.	0.21