

Supporting Information for "On the Range of Marine Cloud Brightening Forcing across Global Climate Models"

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5 S1 ARG2000 Parameter adjustments

Following Ghosh et al. (2025), we update the f and g parameters in the ARG2000 calculation of the maximum supersaturation for a parcel

$$S_{max} = \left\{ \sum_i \frac{1}{S_{mi}^2} \left[f_i \left(\frac{\zeta}{\eta_i} \right)^p + g_i \left(\frac{S_{mi}^2}{\eta_i + 3\zeta} \right)^{3/4} \right] \right\}^{-1/2} \quad (\text{S1})$$

For critical supersaturation S_m and mode index i , η and ζ are non-dimensional variables defined as:

$$10 \quad \zeta = \frac{2A}{3} \left(\frac{\alpha w}{G} \right)^{1/2} \quad (\text{S2})$$

$$\eta = \frac{2 \left(\frac{\alpha w}{G} \right)^{3/2}}{\gamma^* N_i} \quad (\text{S3})$$

For Kelvin coefficient A , updraft velocity w , thermodynamic terms α and γ^* , aerosol number concentration N_i , and growth coefficient G . Ghosh et al. (2025) identified updates to f , g , and p that better fit to parcel model results which depend on the accumulation mode width σ_{acc} as

$$15 \quad f = 0.0135e^{2.367\sigma_{acc}} \quad (\text{S4})$$

$$g = 1.1058 - 0.315\sigma_{acc} \quad (\text{S5})$$

$$p = \begin{cases} 0.5073 + 1.5088\sigma_{acc} - 0.3699\sigma_{acc}^2 & \zeta/\eta_i > 1 \\ 1.5 & \zeta/\eta_i \leq 1 \end{cases} \quad (\text{S6})$$

For CESM2-Ghosh, $\sigma_g = 1.6$ so $f = 0.596$ (from 0.86), $g = 0.602$ (from 1.11), and $p = 0.960$ when $\zeta/\eta_i > 1$ (from 1.5).

20 For E3SMv2-Ghosh, $\sigma_g = 1.8$ so $f = 0.957$ (from 1.18), $g = 0.539$ (from 1.14), and $p = 1.010$ when $\zeta/\eta_i > 1$ (from 1.5).
For UKESM1-Ghosh, $\sigma_g = 1.4$ so $f = 0.371$ (from 0.66), $g = 0.665$ (from 1.08), and $p = 0.880$ when $\zeta/\eta_i > 1$ (from 1.5).
See also Table 3 in Ghosh et al. (2025).

References

- Ghosh, P., Evans, K. J., Grosvenor, D. P., Kang, H.-G., Mahajan, S., Xu, M., Zhang, W., and Gordon, H.: Assessing modifications to the Abdul-Razzak and Ghan aerosol activation parameterization (version ARG2000) to improve simulated aerosol–cloud radiative effects in the UK Met Office Unified Model (UM version 13.0), *Geoscientific Model Development*, 18, 4899–4913, <https://doi.org/10.5194/gmd-18-4899-2025>, 2025.

Model	a (Wm^{-2})	$\sigma(a)$ (Wm^{-2})	b (yr Tg^{-1})	$\sigma(b)$ (yr Tg^{-1})	c ($\text{Wm}^{-2}/\text{Tg yr}^{-1}$)	$\sigma(c)$ ($\text{Wm}^{-2}/\text{Tg yr}^{-1}$)	
CESM2	-0.552	0.117	2.23	1.67	-0.00977	2.17×10^{-4}	
CESM2-Ghosh	-0.862	0.138	1.18	0.709	-0.00785	1.67×10^{-4}	
E3SMv2	-0.280	0.088	0.965	1.10	-0.0106	1.29×10^{-4}	
E3SMv2-Ghosh	-0.859	0.821	0.114	0.194	-0.0103	1.30×10^{-4}	
CanAM5-PAM	-0.562	0.082	0.562	0.232	-0.0122	1.49×10^{-4}	
CanAM5-PAM-Adj	-1.353	0.185	0.389	0.137	-0.0178	1.97×10^{-4}	
NorESM2	-1.088	1.353	0.027	0.052	-0.0083	2.01×10^{-4}	
UKESM1	-0.204	0.097	0.545	0.848	-0.0124	2.04×10^{-4}	
UKESM1-Ghosh	-0.228	0.052	6.33	7.37	-0.0108	1.79×10^{-4}	
GFDL-AM4	-21.286	5.6×10^5	8.48×10^{-6}	0.238	-0.00420	0.778×10^{-4}	

Table S1. Fitting parameters for $F_{cld} = a \ln(1 + bM_{ssa})$ and $F_{aer} = cM_{ssa}$ and one-standard deviation errors for each parameter.

Experiment name	iSSA Mass flux (Tg yr^{-1})	iSSA Number flux (s^{-1})	Simulation years
F2010climo	0.0	0.0e+00	19
NEPSEPSEA_0.05	0.1	1.6e+18	4
NEPSEPSEA_2.50	2.5	8.2e+19	1
NEPSEPSEA_5.00	5.0	1.6e+20	1
NEPSEPSEA_7.50	7.5	2.5e+20	25
NEPSEPSEA_10.00	10.0	3.3e+20	1
NEPSEPSEA_15.00	15.0	4.9e+20	1
NEPSEPSEA_25.00	25.0	8.2e+20	1
NEPSEPSEA_50.00	50.0	1.6e+21	1
NEPSEPSEA_100.00	100.0	3.3e+21	1
NEPSEPSEA_125.00	125.0	4.1e+21	1
NEPSEPSEA_150.00	150.0	4.9e+21	5
NEPSEPSEA_250.00	250.0	8.2e+21	5

Table S2. CESM2 experiments. F2010climo is the control no-MCB 2010 climatology simulation.

References

- Ghosh, P., Evans, K. J., Grosvenor, D. P., Kang, H.-G., Mahajan, S., Xu, M., Zhang, W., and Gordon, H.: Assessing modifications to the Abdul-Razzak and Ghan aerosol activation parameterization (version ARG2000) to improve simulated aerosol–cloud radiative effects in

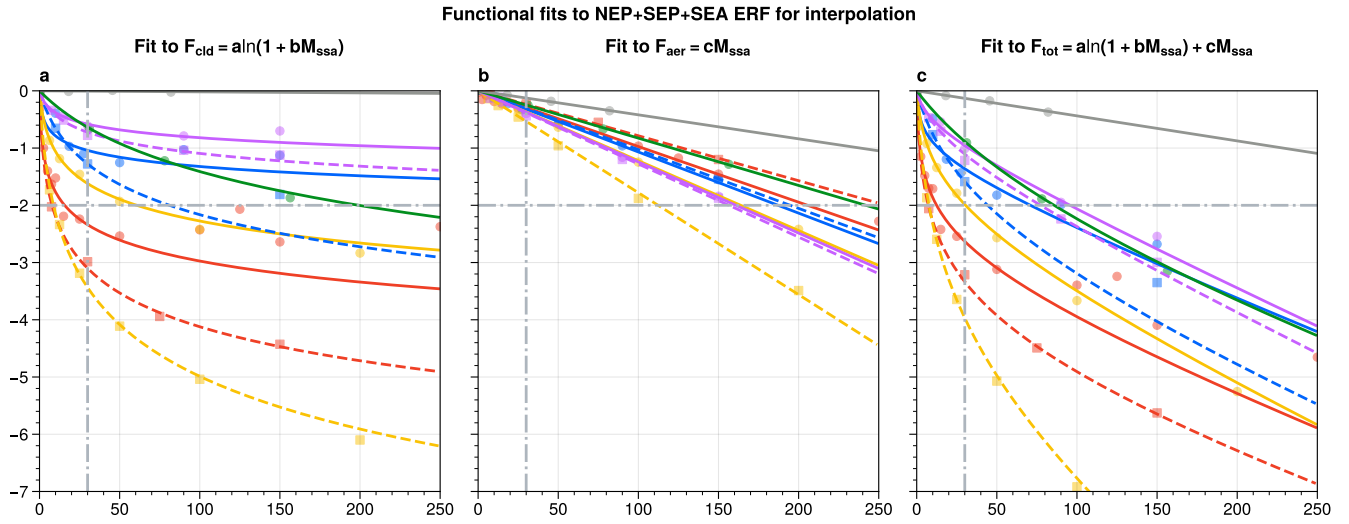


Figure S1. Annual global mean anomalies of ERF_{aci} (a), ERF_{ari} (b), and ERF_{tot} (c) for the NEP+SEP+SEA simulations. Solid and dashed lines show the functional fits for each model in each panel and points show simulations values. A horizontal dash-dotted line shows the -2 Wm^{-2} reference forcing and a vertical dash-dotted shows the 30 Tg yr^{-1} reference emission rate used in section ??.

Experiment name	iSSA Mass flux (Tg yr^{-1})	iSSA Number flux (s^{-1})	Simulation years
F2010climo	0.0	0.0e+00	14
NEPSEPSEA_10.00	10.0	3.3e+20	4
NEPSEPSEA_18.50	18.5	6.1e+20	11
NEPSEPSEA_27.50	27.5	9.0e+20	21
NEPSEPSEA_50.00	50.0	1.6e+21	11
NEPSEPSEA_90.00	90.0	3.0e+21	6
NEPSEPSEA_150.00	150.0	4.9e+21	6
NEPSEPSEA_300.00	300.0	9.9e+21	5

Table S3. E3SMv2 experiments. F2010climo is the control no-MCB 2010 climatology simulation.

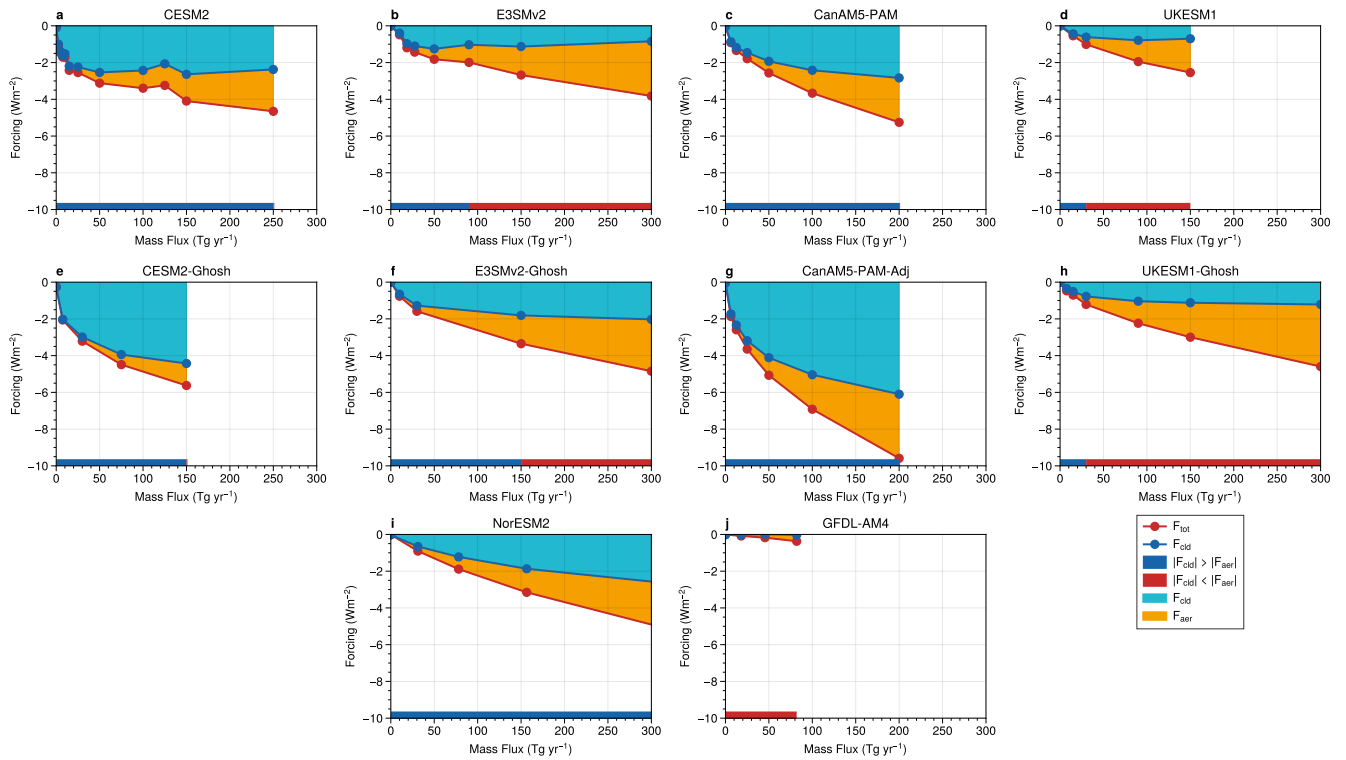


Figure S2. Annual global mean anomalies of ERF_{tot} for each model: CESM2 (a), CESM2 with Ghosh ARG (b), E3SMv2 (c), E3SMv2 with Ghosh ARG (d), CanAM5-PAM (e), CanAM5-PAM-Adj (f), NorESM2 (g), UKESM1 (h), and GFDL-AM4 (i). Shading under curves indicates the fraction of the total forcing that is from ERF_{aci} (cyan shading) and ERF_{ari} (orange shading). At the bottom of each panel, blue bars indicate emission rates where ERF_{aci} is stronger than ERF_{ari} and red bars indicate ERF_{ari} is stronger than ERF_{aci} .

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
2000_climo	0.0	0.0e+00	10
NEPSEPSEA_6.25	6.2	6.4e+19	10
NEPSEPSEA_12.50	12.5	1.3e+20	10
NEPSEPSEA_25.00	25.0	2.5e+20	10
NEPSEPSEA_50.00	50.0	5.1e+20	10
NEPSEPSEA_100.00	100.0	1.0e+21	10
NEPSEPSEA_200.00	200.0	2.0e+21	10

Table S4. CanAM5-PAM experiments. 2000_climo is the control no-MCB 2000 climatology simulation.

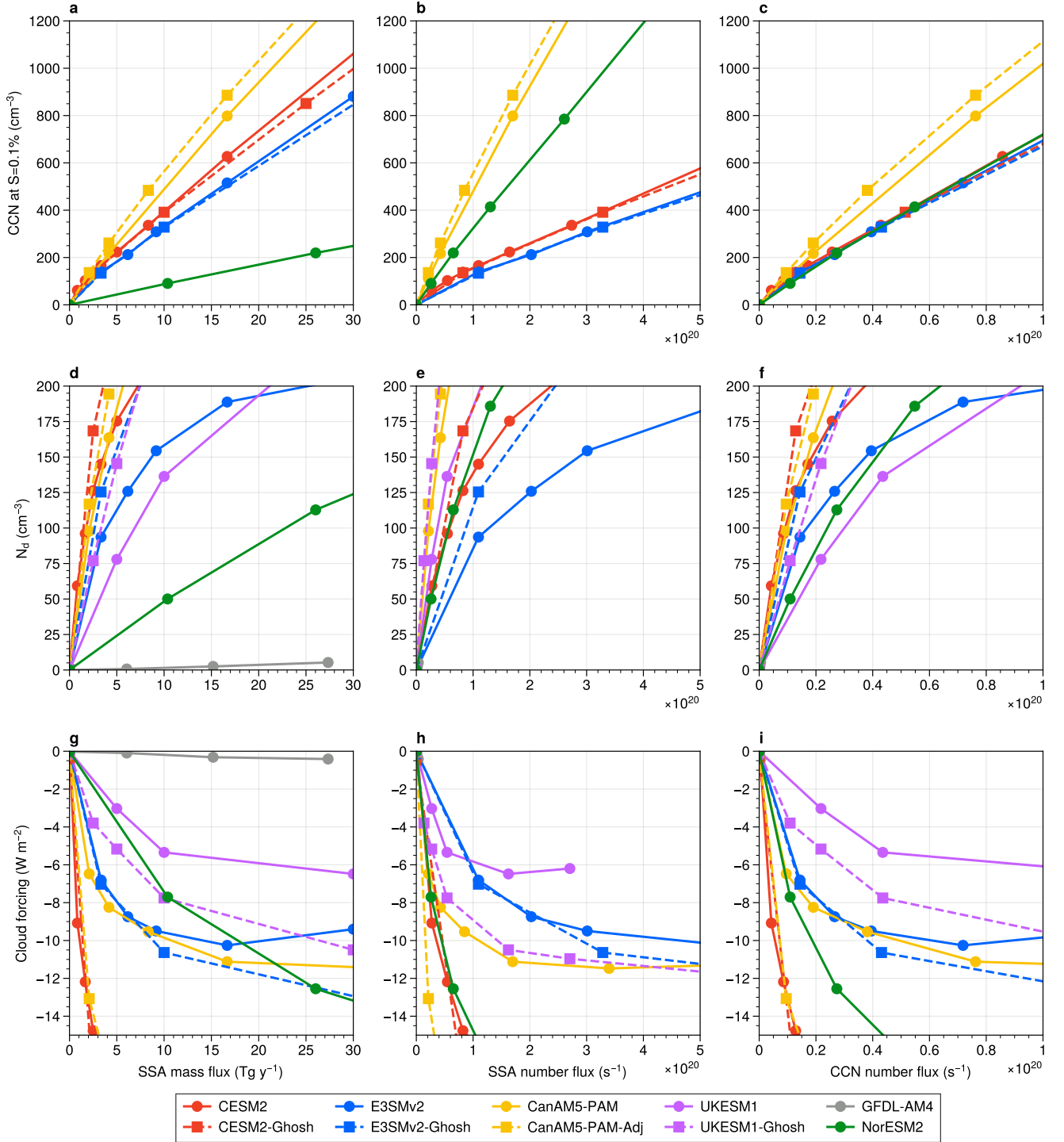


Figure S3. Annual NEP, SEP, and SEA mean anomalies of CCN concentration at $S=0.1\%$ (top row), N_d concentration (middle row), and F_{cld} (bottom row) versus the iSSA mass flux (left column), iSSA number flux (middle column), and approximate CCN number flux for $S=0.1\%$ (left row)

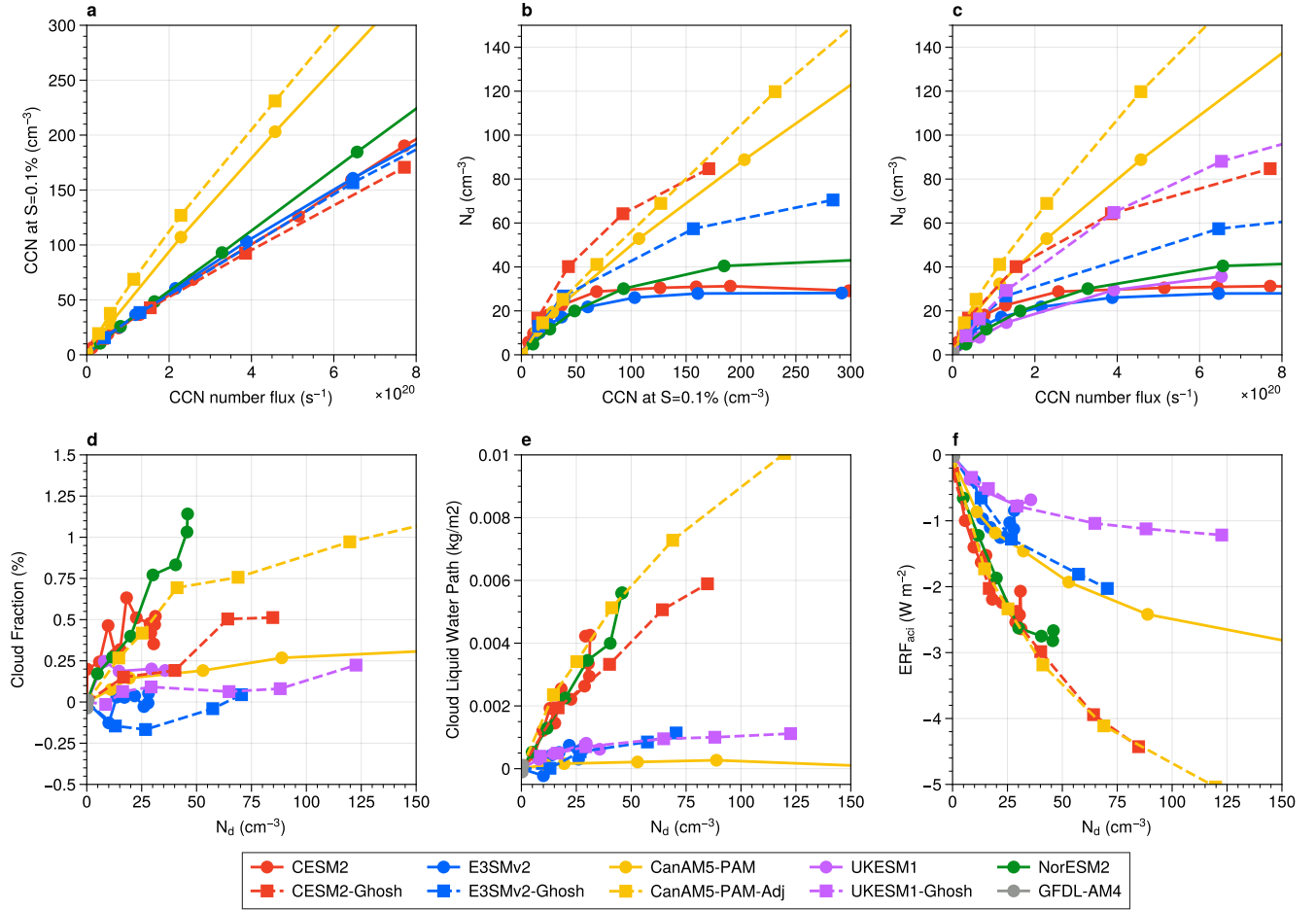


Figure S4. Annual mean global mean anomalies across different models. Each panel captures some aspect of the aerosol-cloud interaction: a) aerosol lifetime and mixing to cloud base (CCN at $S = 0.1\%$ vs. CCN number flux), b) aerosol activation (N_d vs. CCN at $S = 0.1\%$), c) aerosol lifetime, mixing, and activation (N_d at cloud base vs. CCN number flux), d) cloud lifetime effect (cloud fraction vs. N_d), e) cloud liquid water effect (LWP vs. N_d), and f) total aerosol indirect effect (APRP cloud forcing vs. N_d). Note that GFDL-AM4 is displayed in panels c, d, e, and f, but is not visible due to the small N_d anomalies in this model.

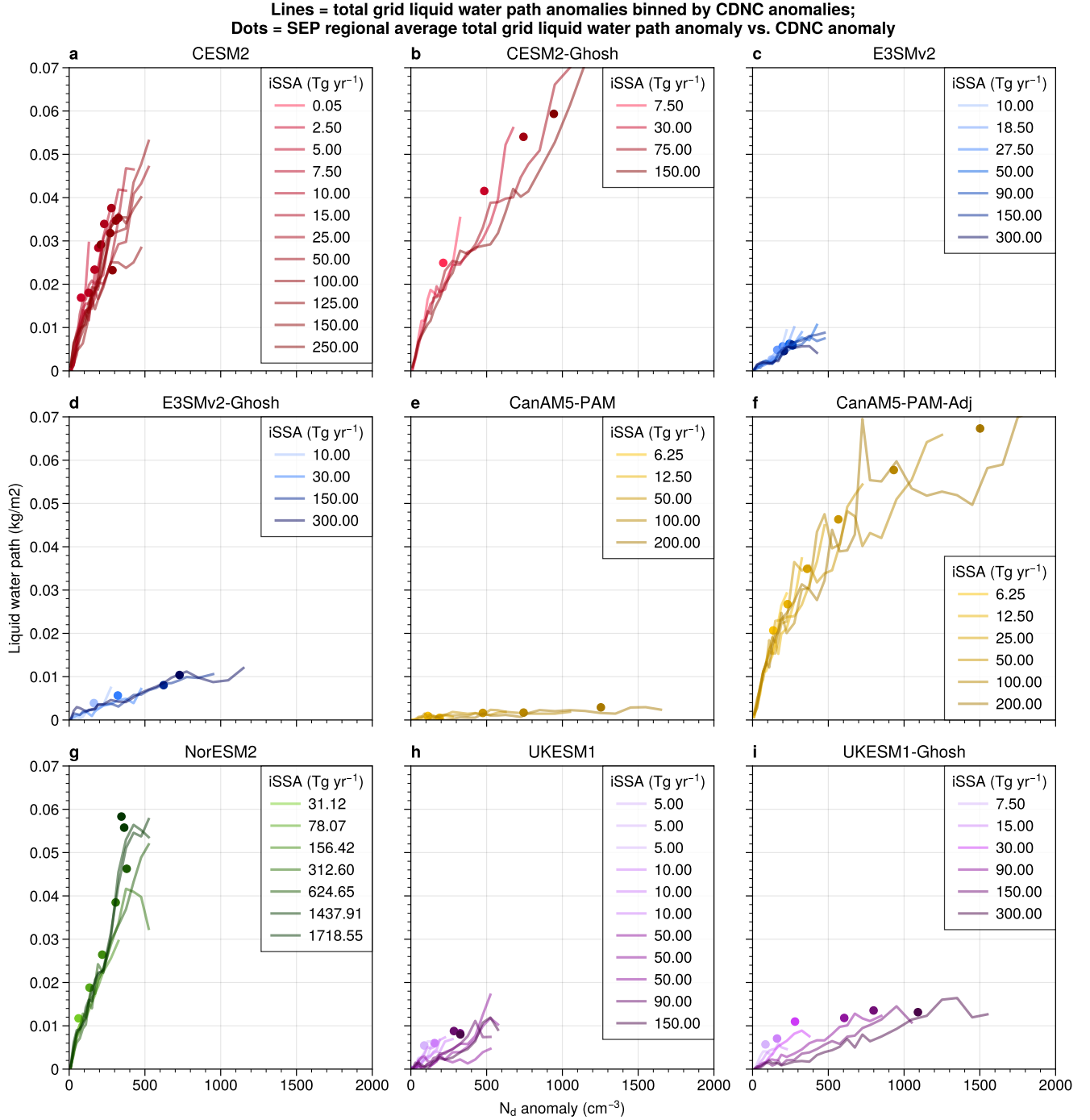


Figure S5. Time mean grid-box average cloud liquid water path (LWP) anomalies bin-averaged across spatial grid points by the time mean N_d anomaly for CESM2 (a), CESM2-Ghosh (b), E3SMv2 (c), E3SMv2-Ghosh (d), CanAM5-PAM (e), CanAM5-PAM-Adj (f), and NorESM2 (g). Line colours indicate the iSSA emission rate, with lighter colours corresponding to lower emission rates and darker colours corresponding to higher emission rates. We omit CCN bins that contain fewer than 0.1% of grid points.

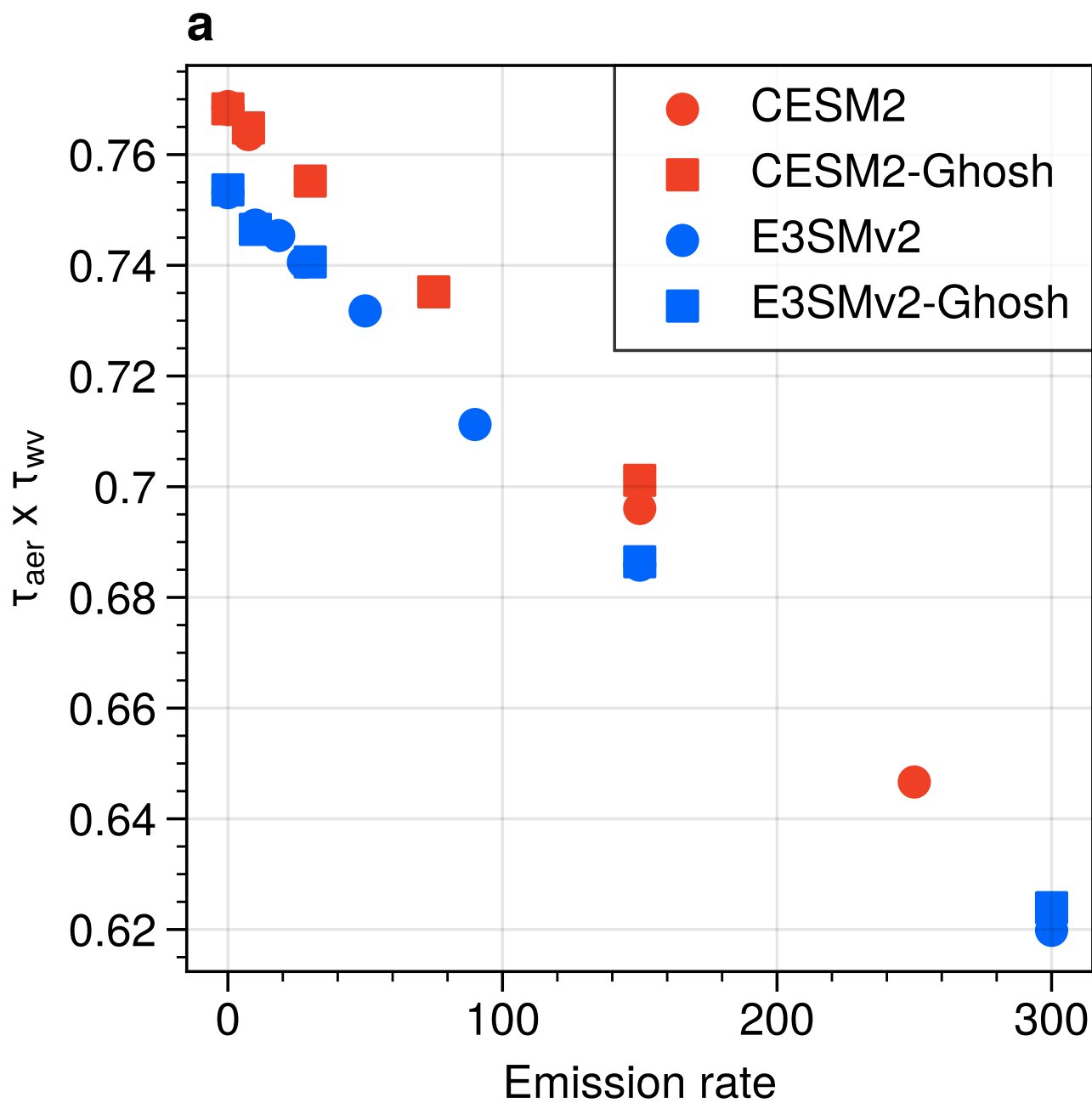
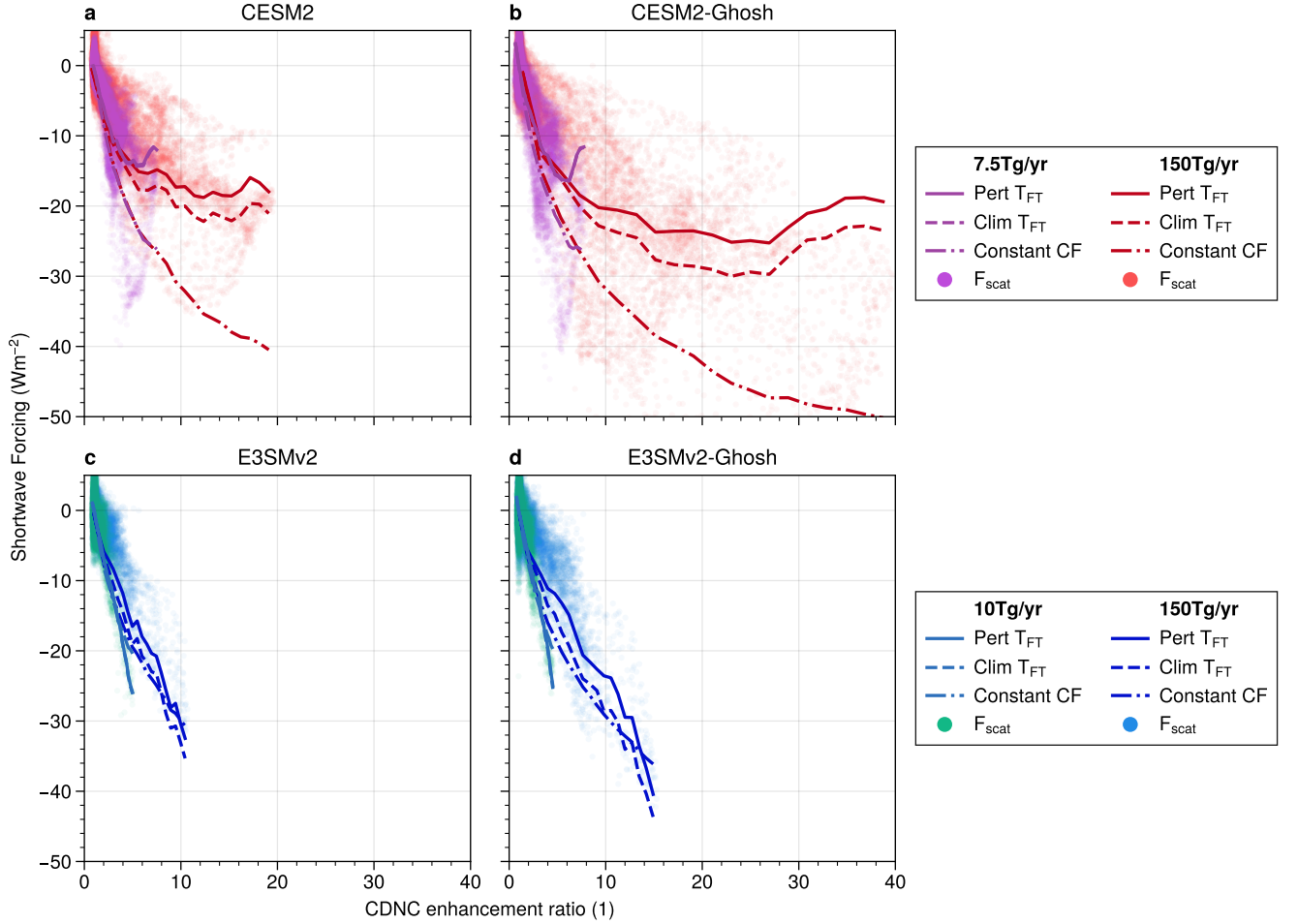


Figure S6. Free troposphere aerosol transmissivity versus iSSA emission rate for CESM2, CESM2-Ghosh, E3SMv2, and E3SMv2-Ghosh computed by integrating aerosol extinction at 550nm above 850hPa and multiplying it by an assumed water vapour transmissivity of $\tau_{\text{wv}} = 0.8$.



The Twomey effect estimate is computed using the equation $F_{scat} = -\phi_{atm} F_{sol} \Delta\alpha_c$, where $\phi_{atm} = \frac{T_{FT}^2}{(1-\alpha_{FT}\alpha_c)^2}$ for free troposphere transmissivity T_{FT} and albedo α_{FT} and $\Delta\alpha_c = \frac{\alpha_c(\alpha_c-1)(r_N^{1/3}-1)}{1+\alpha_c(r_N^{1/3}-1)}$ (Wood, 2021).

The Twomey effect estimate is computed using the equation $F_{scat} = -\phi_{atm} F_{sol} \Delta\alpha_c$, where $\phi_{atm} = \frac{T_{FT}^2}{(1-\alpha_{FT}\alpha_c)^2}$ for free troposphere transmissivity T_{FT} and albedo α_{FT} and $\Delta\alpha_c = \frac{\alpha_c(\alpha_c-1)(r_N^{1/3}-1)}{1+\alpha_c(r_N^{1/3}-1)}$ (Wood, 2021).

Figure S7. Comparison of APRP diagnosed cloud scattering (scatter points) and the binned average Twomey effect estimate (lines) versus the ratio of perturbed N_d over climatological N_d (r_N) for CESM2 (a), CESM2-Ghosh (b), E3SMv2 (c), and E3SMv2-Ghosh (d). Dashed lines show the Twomey effect estimate assuming climatological free troposphere transmissivity T_{FT} . Dot-dashed lines show the Twomey effect estimate assuming a uniform cloud fraction set to the global mean cloud fraction.

The Twomey effect estimate is computed using the equation $F_{scat} = -\phi_{atm} F_{sol} \Delta\alpha_c$, where $\phi_{atm} = \frac{T_{FT}^2}{(1-\alpha_{FT}\alpha_c)^2}$ for free troposphere transmissivity T_{FT} and albedo α_{FT} and $\Delta\alpha_c = \frac{\alpha_c(\alpha_c-1)(r_N^{1/3}-1)}{1+\alpha_c(r_N^{1/3}-1)}$ (Wood, 2021).

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
AMIP1979	0.0	0.0e+00	10
NEP_5.00	5.0	2.7e+19	10
SEA_5.00	5.0	2.7e+19	10
SEP_5.00	5.0	2.7e+19	10
SEA_10.00	10.0	5.4e+19	10
NEP_10.00	10.0	5.4e+19	10
SEP_10.00	10.0	5.4e+19	10
NEP_50.00	50.0	2.7e+20	10
SEA_50.00	50.0	2.7e+20	10
SEP_50.00	50.0	2.7e+20	10
NEPSEPSEA_90.00	90.0	4.9e+20	10
NEPSEPSEA_150.00	150.0	8.1e+20	10

Table S5. UKESM1 experiments. AMIP1979 is the control AMIP simulation with forcing and SST from 1979-1989.

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
AMIP2000	0.0	0.0e+00	5
NEPSEPSEA_31.12	31.1	7.8e+19	5
NEPSEPSEA_78.07	78.1	2.0e+20	5
NEPSEPSEA_156.42	156.4	3.9e+20	5
NEPSEPSEA_312.60	312.6	7.8e+20	5
NEPSEPSEA_624.65	624.6	1.6e+21	5
NEPSEPSEA_1437.91	1437.9	3.6e+21	5
NEPSEPSEA_1718.55	1718.5	4.3e+21	5

Table S6. NorESM2 experiments. AMIP2000 is the control no-MCB 2000 climatology simulation.

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
2010_climo	0.0	0.0e+00	15
NEPSEPSEA_18.16	18.2	2.3e+18	15
NEPSEPSEA_45.54	45.5	5.8e+18	15
NEPSEPSEA_82.01	82.0	1.0e+19	15

Table S7. GFDL-AM4 experiments. 2010_climo is the control no-MCB 2010 climatology simulation.

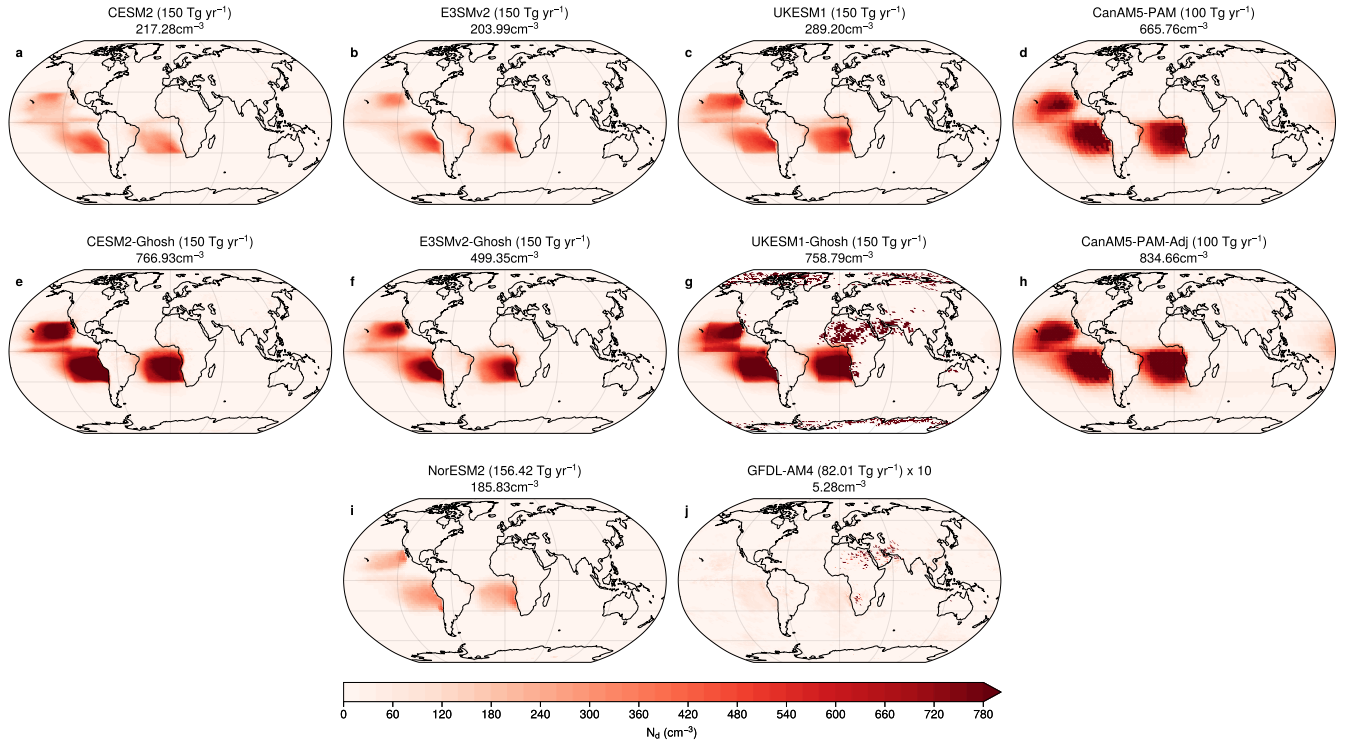


Figure S8. Annual mean cloud top N_d anomalies from fixed SST simulations for SSA emission rates ranging from 100 Tg yr⁻¹ to 150 Tg yr⁻¹. Titles show global mean for each panel.

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
2000_climo	0.0	0.0e+00	10
NEPSEPSEA_6.25	6.2	6.4e+19	10
NEPSEPSEA_12.50	12.5	1.3e+20	10
NEPSEPSEA_25.00	25.0	2.5e+20	10
NEPSEPSEA_50.00	50.0	5.1e+20	10
NEPSEPSEA_100.00	100.0	1.0e+21	10
NEPSEPSEA_200.00	200.0	2.0e+21	10

Table S8. CanAM5-PAM-Adj experiments. 2000_climo is the control no-MCB 2000 climatology simulation.

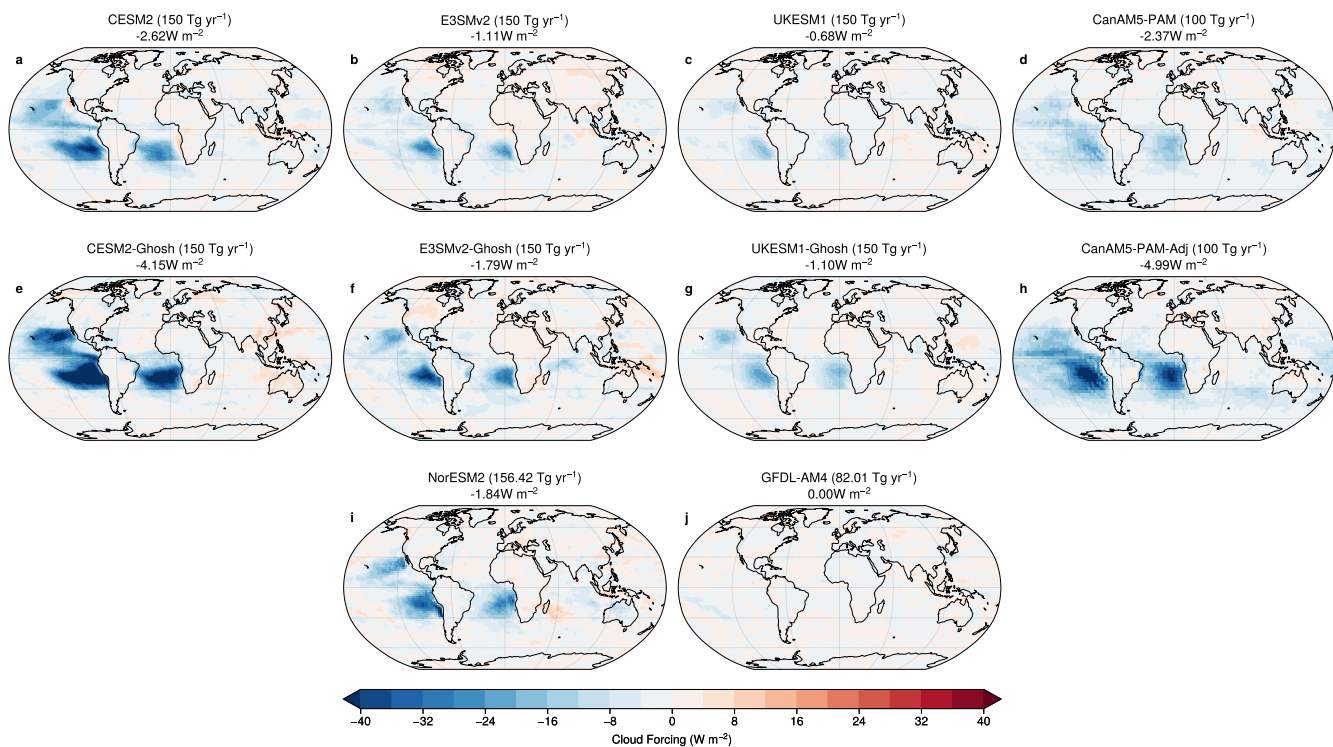


Figure S9. Annual mean APRP cloud forcing anomalies from fixed SST simulations for about 150Tg/yr SSA emission rates. Titles show global mean for each panel.

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
F2010climo	0.0	0.0e+00	5
NEPSEPSEA_7.50	7.5	2.5e+20	5
NEPSEPSEA_30.00	30.0	9.9e+20	5
NEPSEPSEA_75.00	75.0	2.5e+21	5
NEPSEPSEA_150.00	150.0	4.9e+21	5

Table S9. CESM2-Ghosh experiments. F2010climo is the control no-MCB 2010 climatology simulation.

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
F2010climo	0.0	0.0e+00	5
NEPSEPSEA_10.00	10.0	3.3e+20	5
NEPSEPSEA_30.00	30.0	9.9e+20	5
NEPSEPSEA_150.00	150.0	4.9e+21	5
NEPSEPSEA_300.00	300.0	9.9e+21	5

Table S10. E3SMv2-Ghosh experiments. F2010climo is the control no-MCB 2010 climatology simulation.

Experiment name	iSSA Mass flux (Tg yr ⁻¹)	iSSA Number flux (s ⁻¹)	Simulation years
AMIP2005	0.0	0.0e+00	27
NEPSEPSEA_7.50	7.5	5.7e+20	9
NEPSEPSEA_15.00	15.0	1.1e+21	9
NEPSEPSEA_30.00	30.0	2.3e+21	9
NEPSEPSEA_90.00	90.0	6.8e+21	9
NEPSEPSEA_150.00	150.0	1.1e+22	9
NEPSEPSEA_300.00	300.0	2.3e+22	9

Table S11. UKESM1-Ghosh experiments. AMIP2005 is the control AMIP simulation with forcing and SST from 2005-2014.

the UK Met Office Unified Model (UM version 13.0), Geoscientific Model Development, 18, 4899–4913, <https://doi.org/10.5194/gmd-18-4899-2025>, 2025.