Supplementary Information

Antarctic sea-ice loss shifts the Pacific Decadal Oscillation toward its positive phase

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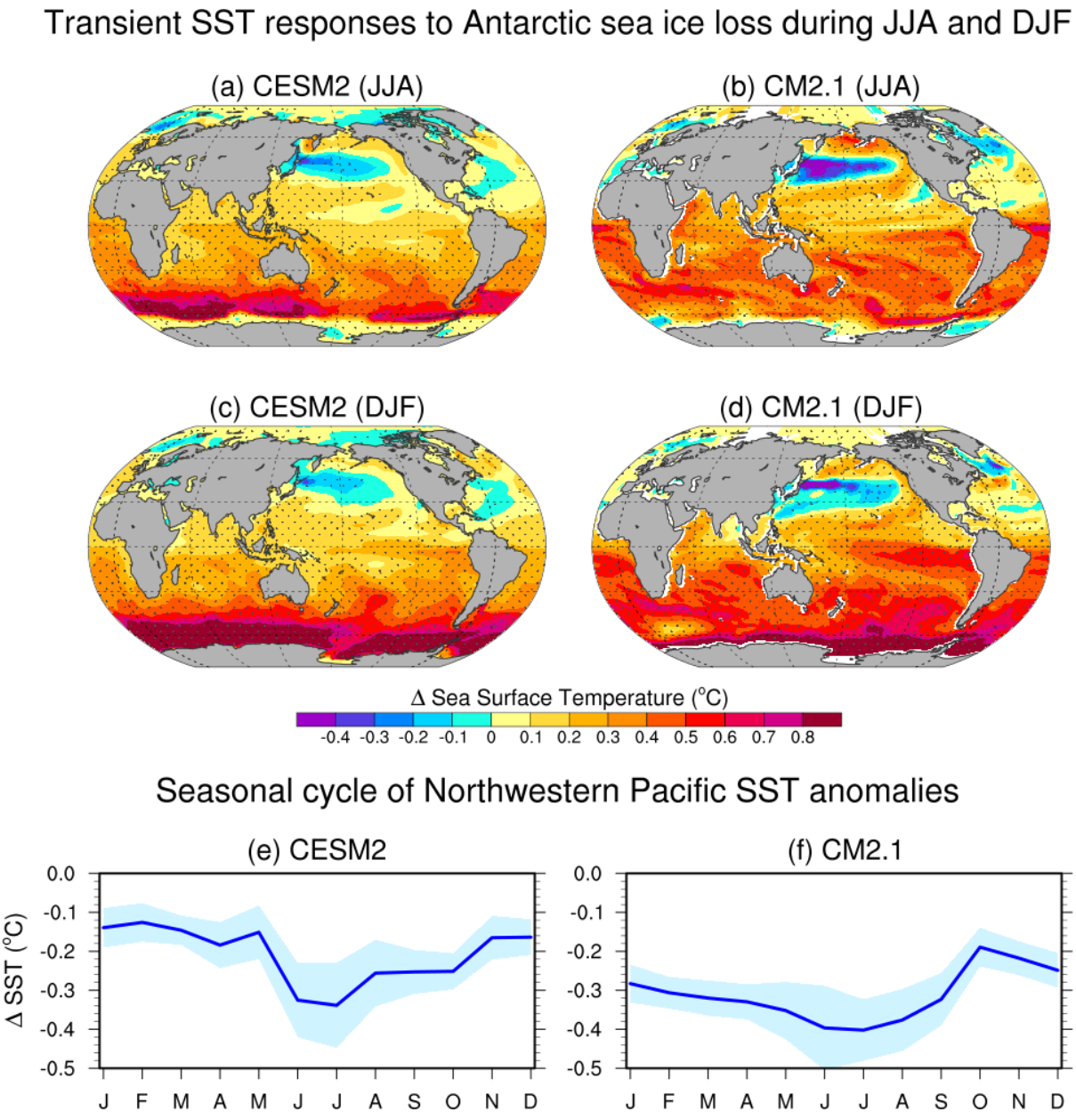
Supplementary Table 1. | Summary of CESM2 and CM2.1 control (Ctrl) and reduced Antarctic sea ice albedo (rALB) experiments.

Model	Experiment	Ensemble members	Integration length	Antarctic sea ice albedo change (Antarctic only; Arctic unchanged)	Initial conditions
CESM2	Ctrl	5	100 years	None	Restart files from NCAR pre-industrial control
CESM2	rALB	5	100 years	~25% reduction	Same as Ctrl
CM2.1	Ctrl	5	100 years	None	Restart files from GFDL long pre-industrial control
CM2.1	rALB	5	100 years	Stronger reduction; 40% (members 1-3), 60% (members 4-5)	Same as Ctrl

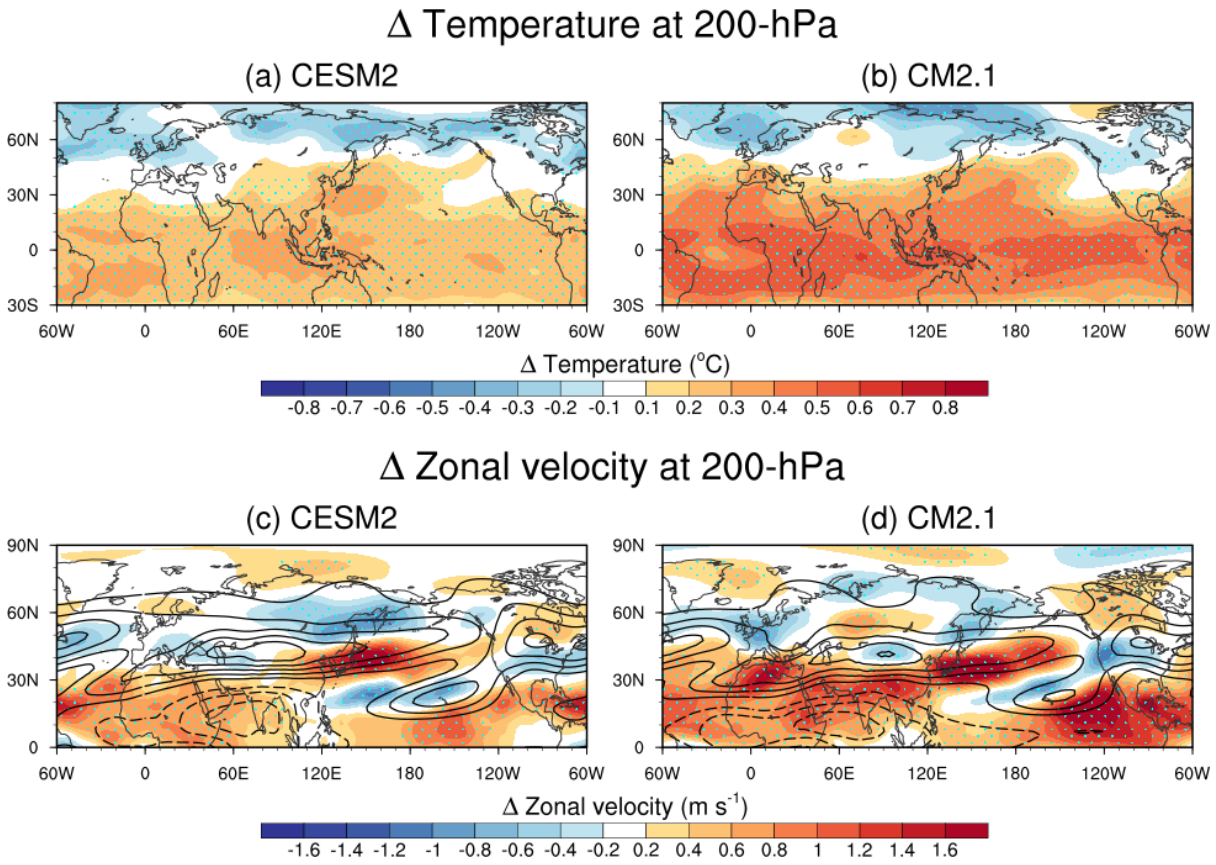
Supplementary Table 2. | Summary of CESM2 Asian jet nudging experiments.

Experiment set	Target climatology for nudging	Ensemble members	Integration length	Nudging region	Initial conditions
Ctrl-nudge	1-30 year monthly climatology from CESM2 Ctrl	3	30 years	28°–53°N, 40°–90°E (Tibetan Plateau, see green box in Fig. 3a)	Restart files from NCAR pre-industrial control
rALB-nudge	1-30 year monthly climatology from CESM2 rALB	3	30 years	Same as above	Same as Ctrl



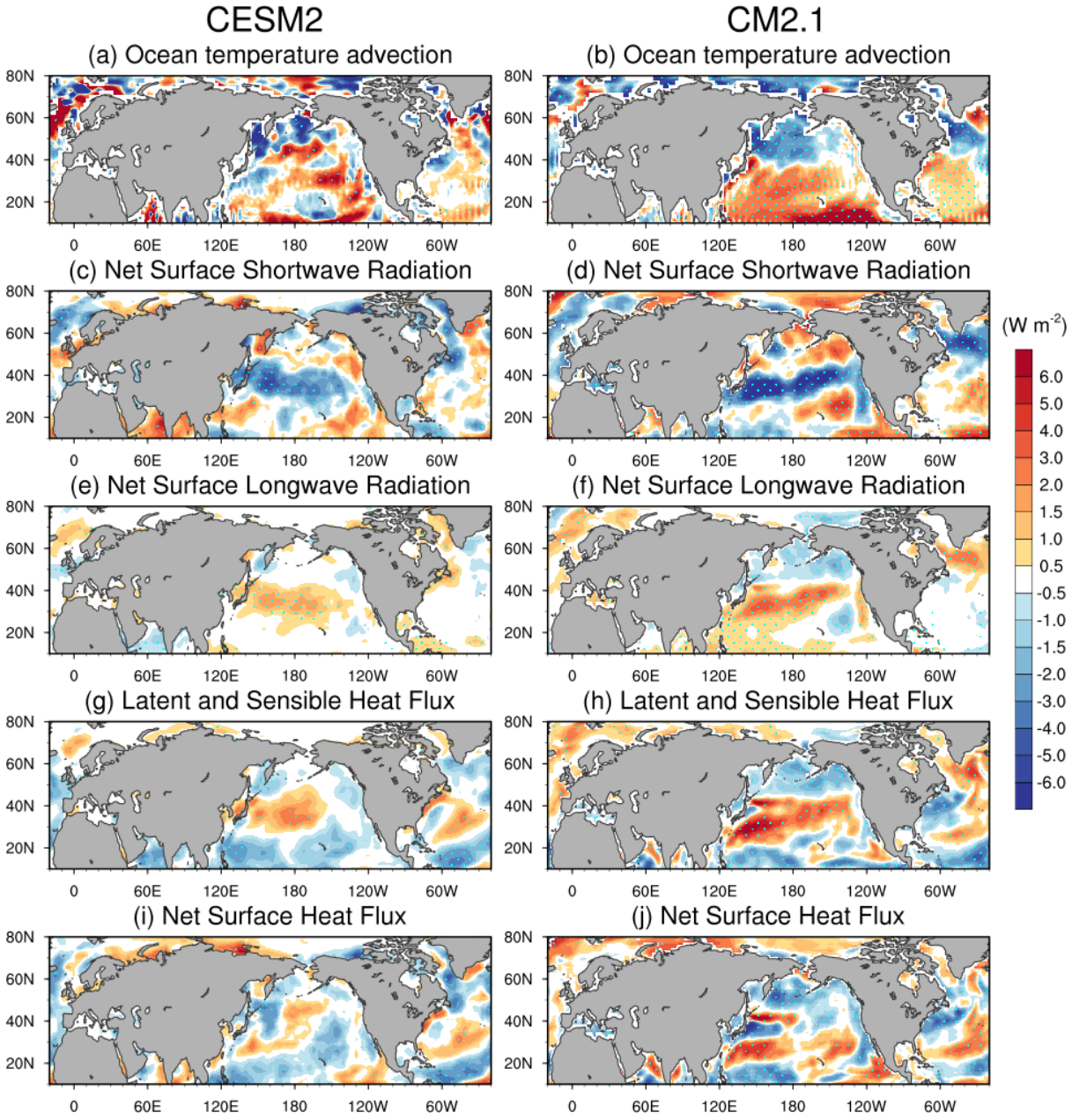
Supplementary Fig. 1 | Seasonal SST responses to Antarctic sea ice loss in CESM2 and CM2.1 models.

(a, b) Sea surface temperature (SST; °C) anomalies averaged over years 1–20 in **(a)** CESM2 and **(b)** CM2.1 during June–July–August (JJA). Stippling indicates regions where anomalies are statistically significant at the 95% confidence level. **(c, d)** Same as (a, b), but for December–January–February (DJF). **(e, f)** Seasonal cycle of SST anomalies (°C) in the northwestern Pacific (30°-60°N, 120°E-160°W), with the solid line denoting the ensemble mean and shading indicating the inter-member spread (± 1 standard deviation).



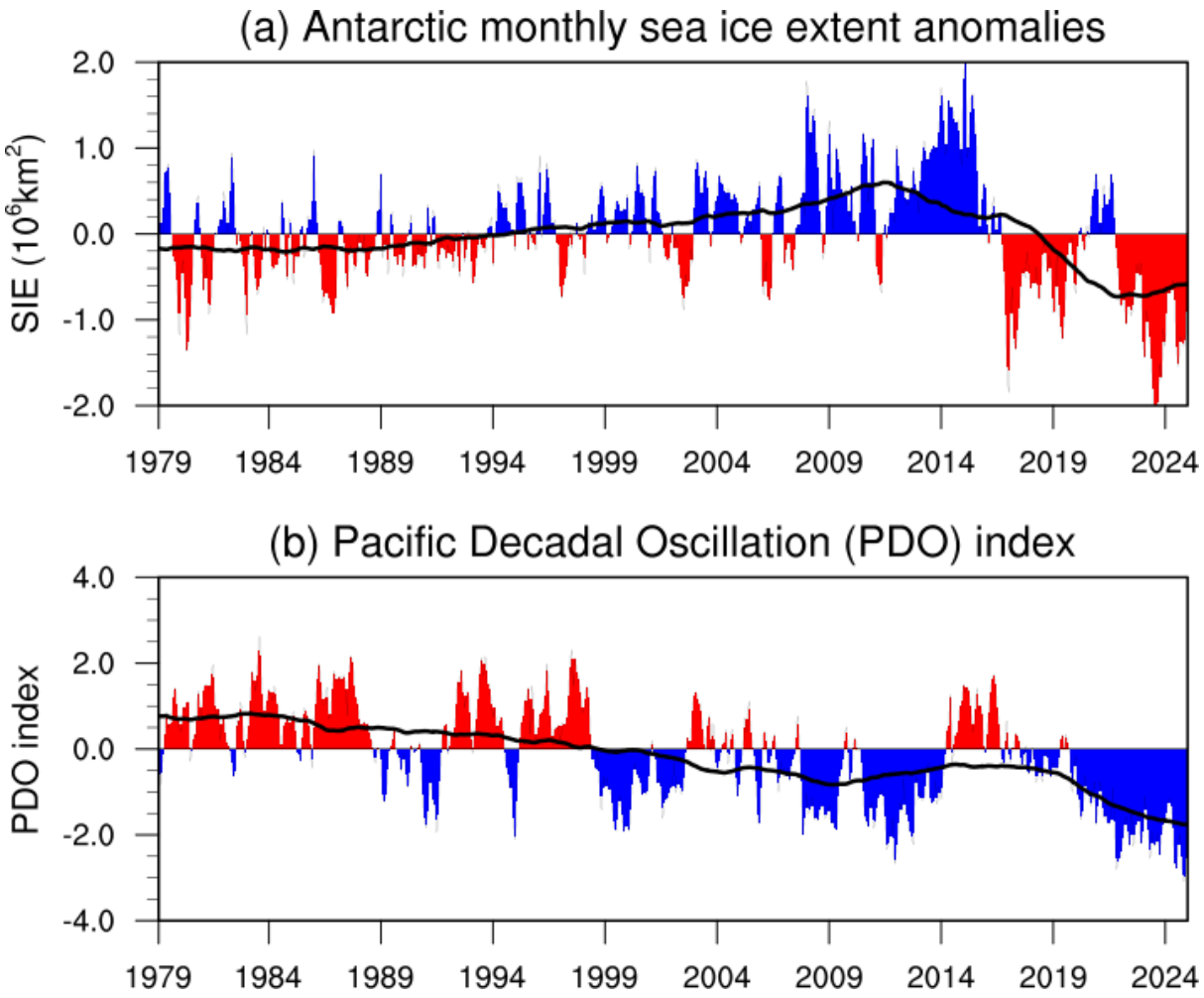
Supplementary Fig. 2 | Atmospheric response to Antarctic sea ice loss in CESM2 and CM2.1 models.

(a, b) Temperature anomalies (°C, shading) at 200 hPa in June–July–August (JJA) due to reduced Antarctic sea ice albedo for (a) CESM2 and (b) CM2.1, averaged over years 1–30 of the 100-year integration to represent the transient response. **(c, d)** Same as (a, b), but for zonal wind anomalies (m s^{-1}, shading). Contours in (c, d) show the climatological zonal wind (m s^{-1}). Statistically significant values ($p < 0.05$) are stippled.



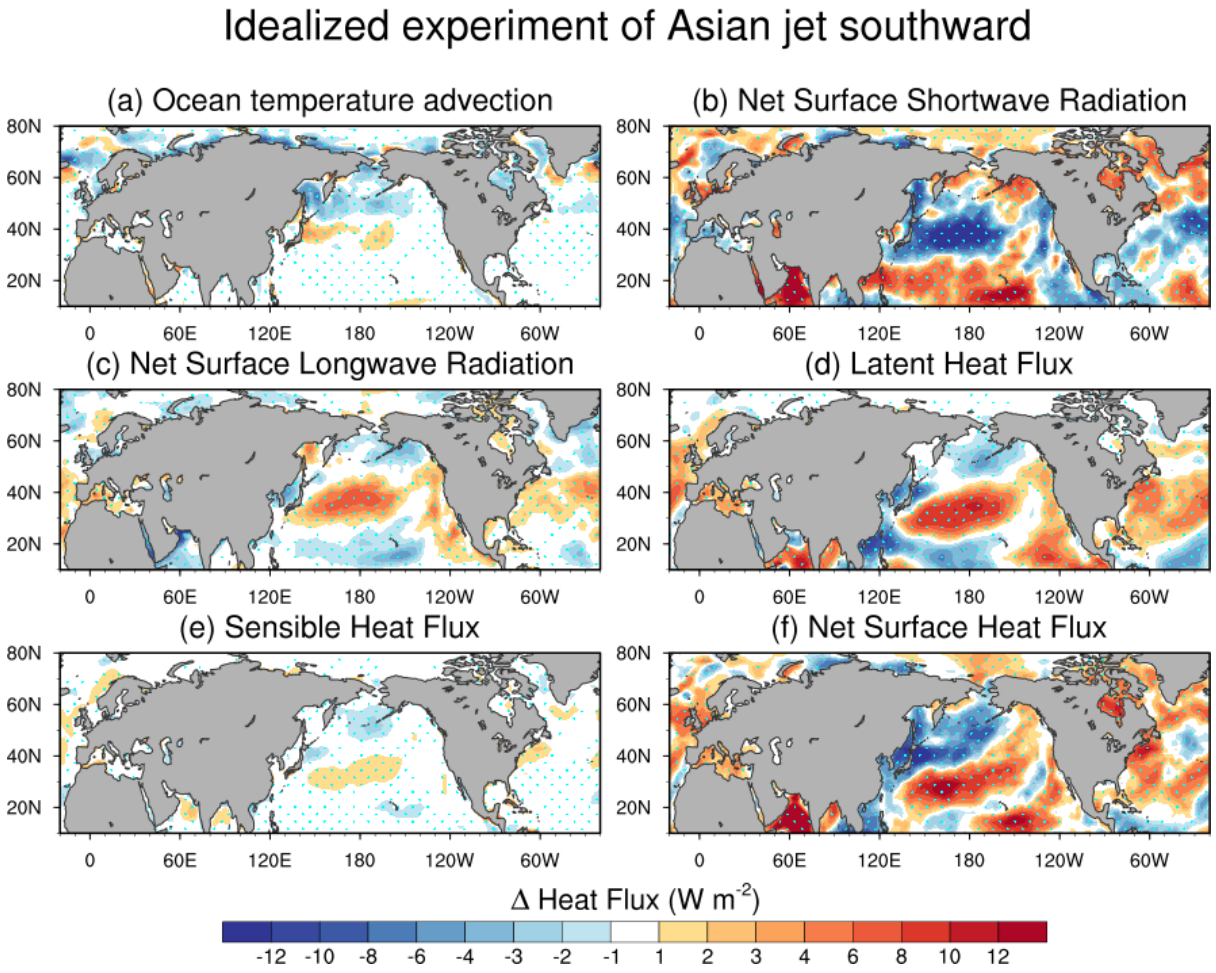
Supplementary Fig. 3 | Surface energy budget responses to Antarctic sea ice loss in CESM2 and CM2.1 models.

(a, b) Ocean temperature advection anomalies for (a) CESM2 and (b) CM2.1. The advection term is originally diagnosed in units of K s^{-1} and converted into an equivalent surface heat flux (W m^{-2}) by multiplying with seawater density, specific heat capacity, and local mixed layer depth. **(c, d)** Same as (a, b), but for net surface shortwave radiation anomalies (W m^{-2}). **(e, f)** Same as (a, b), but for net surface longwave radiation anomalies. **(g, h)** Same as (a, b), but for latent and sensible heat flux anomalies. **(i, j)** Same as (a, b), but for net surface heat flux anomalies. All anomalies are averaged over years 1–30 of the 100-year integration to represent the transient response. Statistically significant values ($p < 0.05$) are stippled.



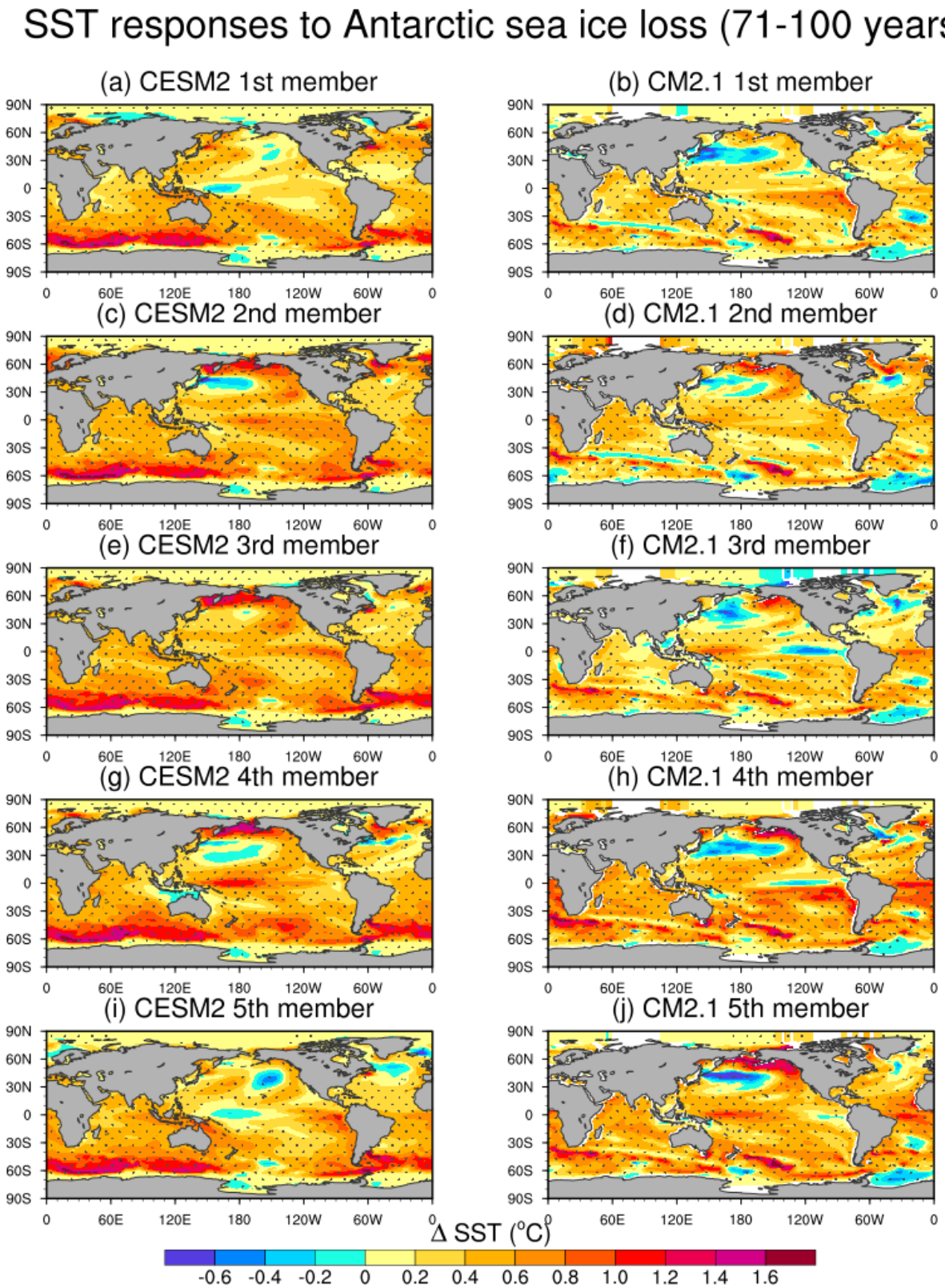
Supplementary Fig. 4 | Observed Antarctic sea ice extent anomalies and Pacific Decadal Oscillation (PDO) index.

(a) Monthly Antarctic sea ice extent (SIE) anomalies (10^6 km^2) relative to the 1979–2024 climatology. Blue (red) bars indicate positive (negative) anomalies. **(b)** Monthly PDO index for 1979–2024. Red (blue) bars indicate positive (negative) phase of PDO. In both panels, the black line denotes the 10year running mean.



Supplementary Fig. 5 | Surface energy budget anomalies from the idealized experiment of the southward shift of the Asian jet.

(a) Ocean temperature advection anomalies, originally diagnosed in K s^{-1} and converted to W m^{-2} by multiplying with seawater density, specific heat, and local mixed layer depth. **(b)** Net surface shortwave radiation (W m^{-2}), **(c)** Net surface longwave radiation, **(d)** Latent heat flux, **(e)** Sensible heat flux, and **(f)** Net surface heat flux anomalies. All anomalies are shown for June–July–August (JJA). Stippling indicates statistically significant values ($p < 0.05$).



Supplementary Fig. 6 | Global SST responses to Antarctic sea ice loss in CESM2 and CM2.1.

(a–j) June–July–August (JJA) mean SST anomalies (°C, shading) averaged over years 71–100 of the 100-year integration, representing the quasi-equilibrium response to reduced Antarctic sea ice albedo. Results are shown for five ensemble members from CESM2 (a, c, e, g, i) and CM2.1 (b, d, f, h, j). Stippling denotes statistically significant values ($p < 0.05$).