Supplementary Information for:

Southern Ocean mean state constrains historical warming via radiative forcing and evaporative damping

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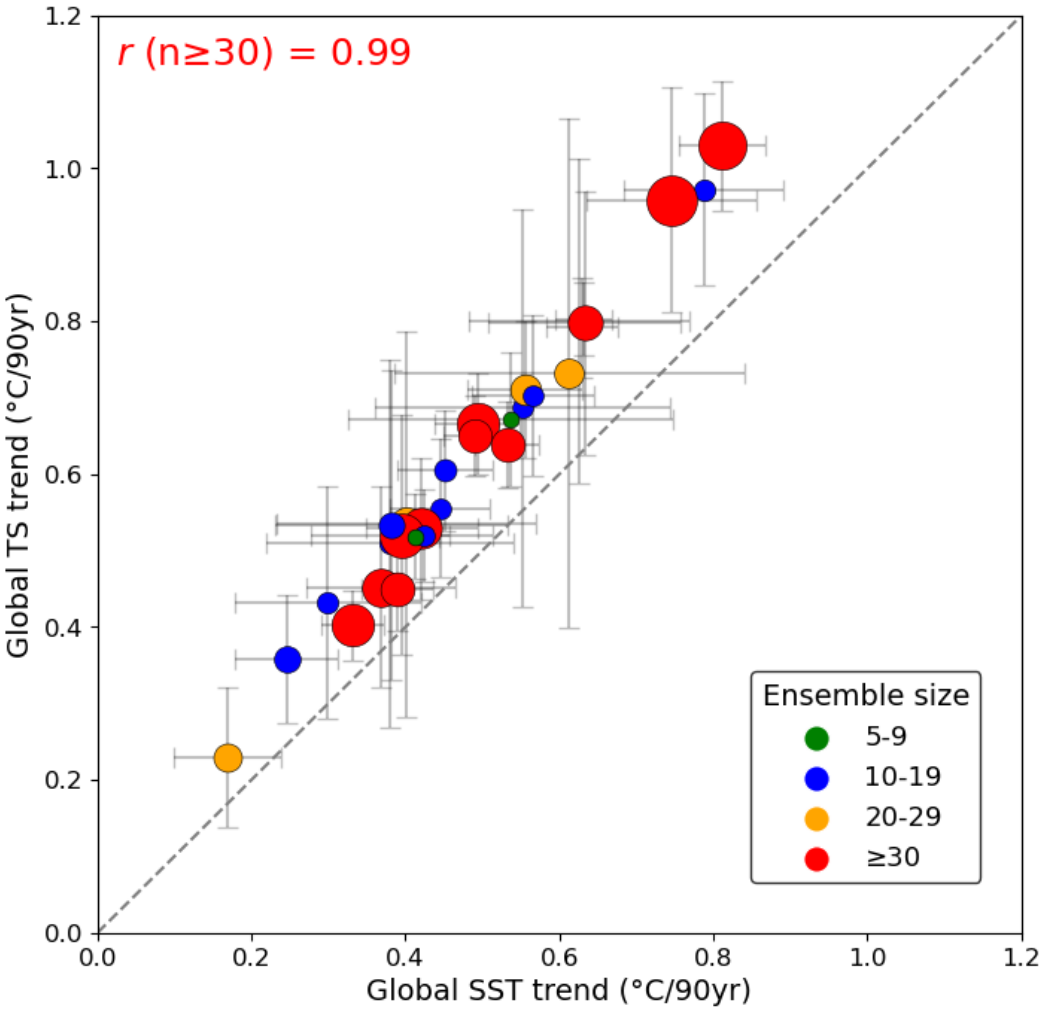
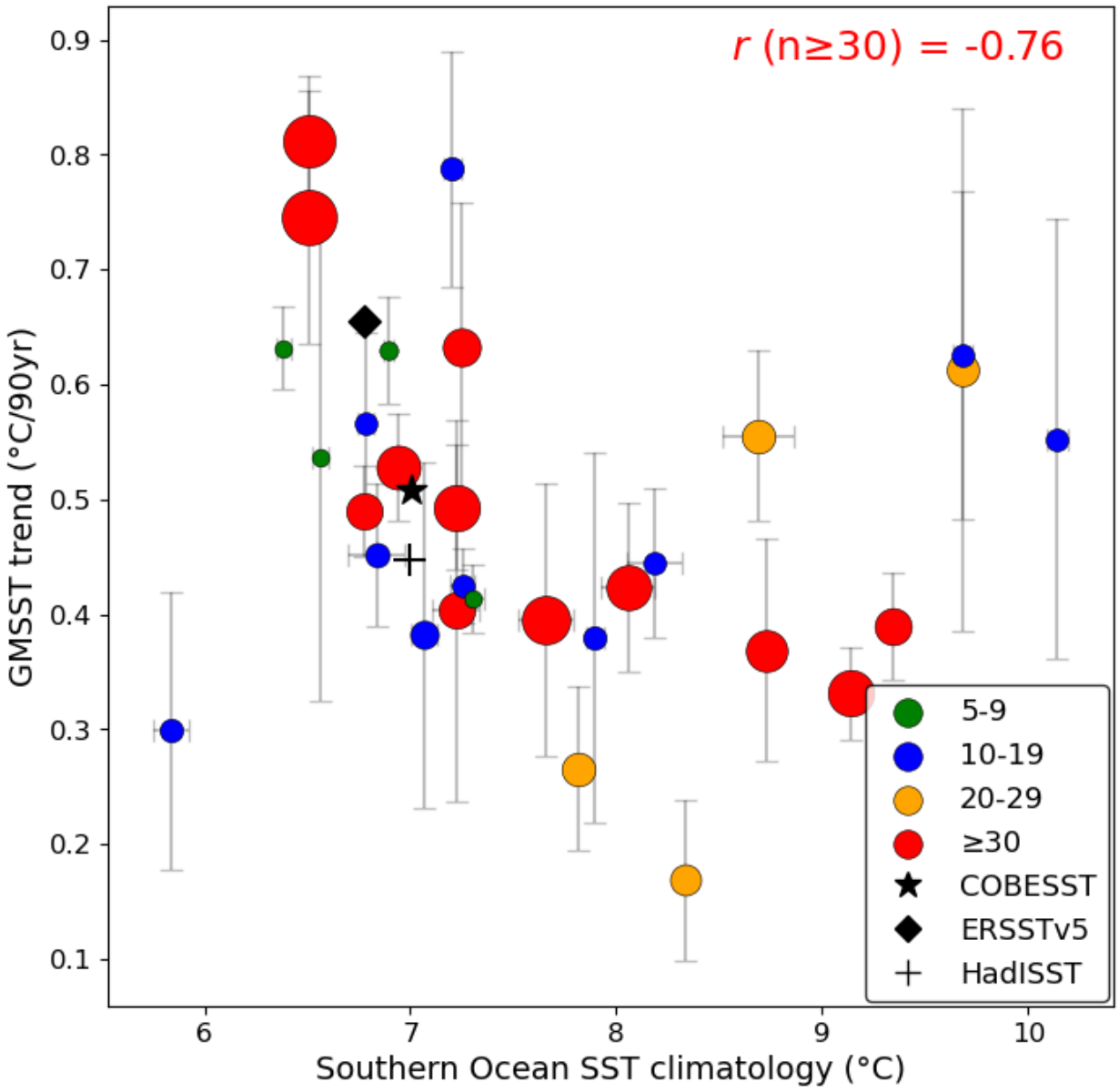
Table S1. CMIP6 models and their ensemble sizes for key variables analyzed.

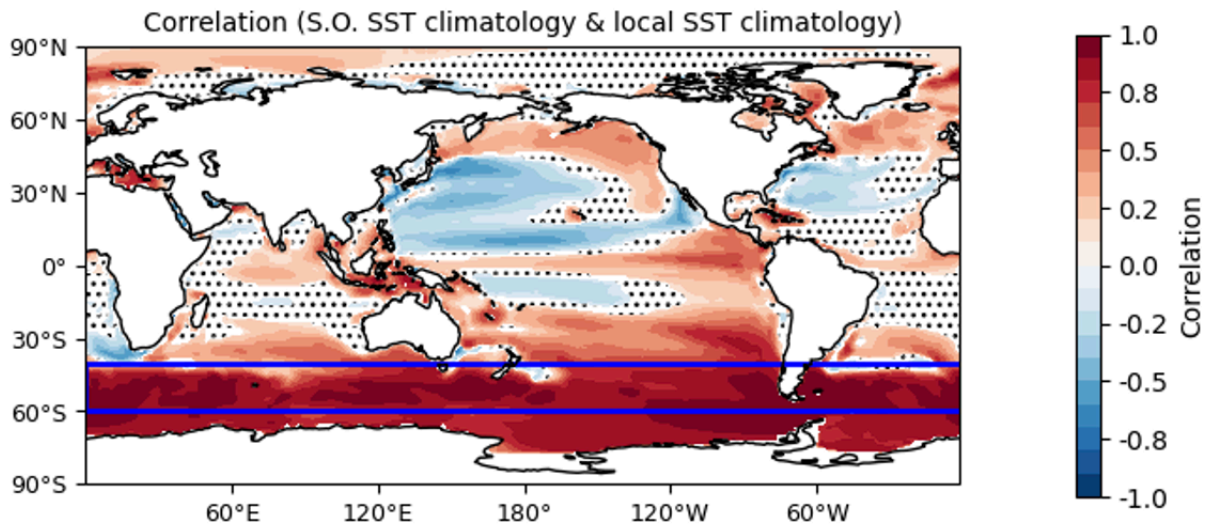
Model	tos	ts	prw	hfls	siconc	mlosts	sos
ACCESS-CM2	10	10	10	10	10	10	10
ACCESS-ESM1-5	40	40	40	40	40	40	40
AWI-CM-1-1-MR	5	5	5	5	NA	5	NA
CESM2	50	50	50	50	50	50	50
CMCC-CM2-SR5	11	11	11	11	11	11	11
CNRM-CM6-1	30	29	30	29	21	29	29
CNRM-ESM2-1	11	11	11	11	10	11	11
CanESM5-1	72	72	72	72	72	72	72
CanESM5	65	65	65	65	65	65	65
E3SM-1-0	25	18	25	23	22	22	19
E3SM-2-0	21	21	21	21	21	21	21
EC-Earth3-CC	10	10	10	10	10	10	10
EC-Earth3-Veg	10	10	11	11	9	10	10
EC-Earth3	23	24	23	23	22	24	24
FGOALS-g3	6	6	6	6	6	5	5
GISS-E2-1-G	47	46	47	47	NA	47	46
GISS-E2-1-H	25	25	23	24	25	NA	25
GISS-E2-2-G	11	11	11	11	NA	11	11
GISS-E2-2-H	5	5	5	5	5	NA	5
HadGEM3-GC31-LL	55	55	55	55	55	55	55
INM-CM5-0	10	10	10	10	10	NA	10
IPSL-CM6A-LR	33	33	33	33	26	26	26
MIROC-ES2L	31	31	30	31	31	NA	31
MIROC6	50	50	50	50	50	NA	50
MPI-ESM1-2-HR	10	10	10	10	10	10	10
MPI-ESM1-2-LR	45	31	45	45	51	46	31
MRI-ESM2-0	12	12	12	12	12	12	12
NESM3	5	5	5	5	5	5	5
NorCPM1	30	30	30	30	30	30	30
UKESM1-0-LL	17	18	19	19	17	17	18



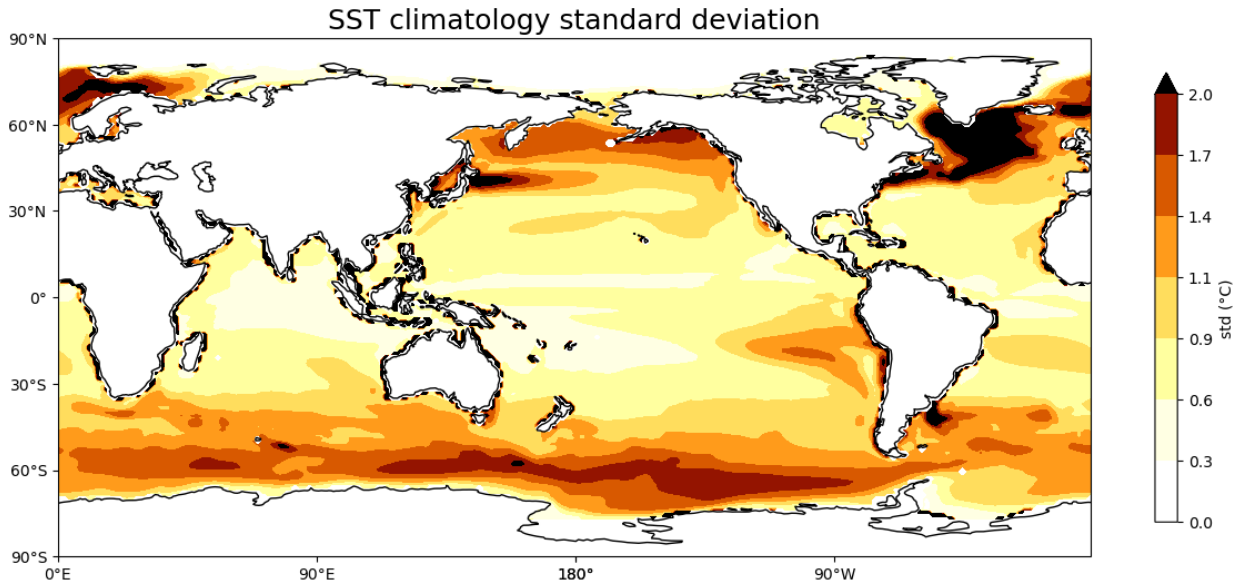
Extended Data Figure 1. Global-mean warming trends. Relation between global-mean sea surface temperature (SST) trend (1925-2014) and surface temperature (TS) trend across models. Uncertainty bars denote one inter-model standard deviation, and *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members). Marker color indicates the ensemble size category and marker size is proportional to the number of ensemble members in each model.



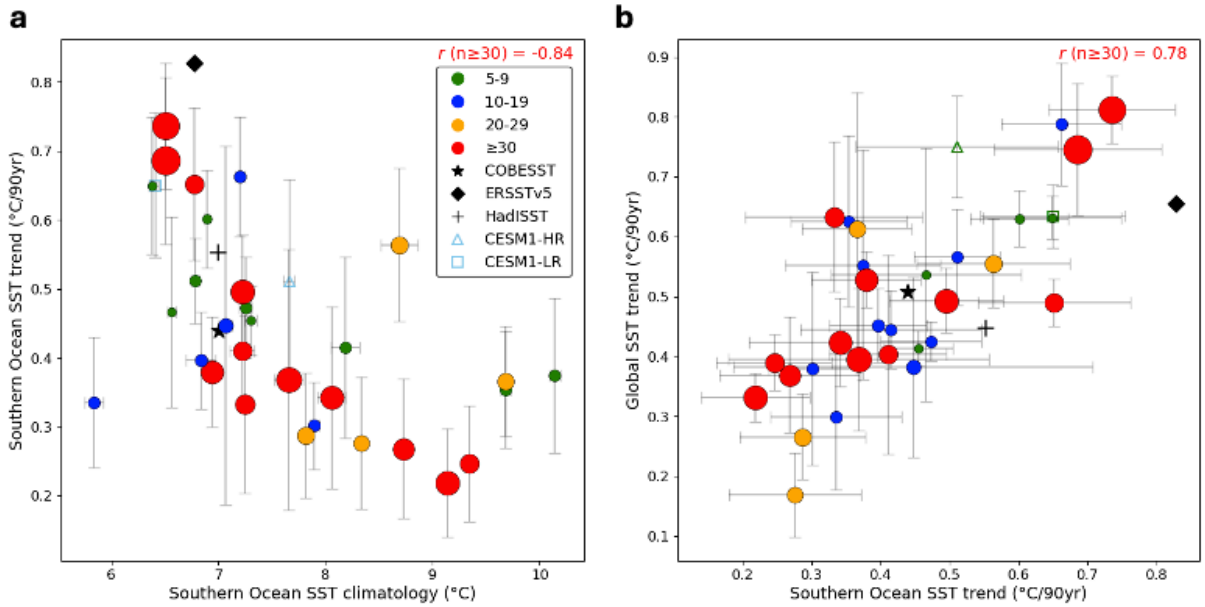
Extended Data Figure 2. Stronger global mean SST (GMSST) warming rate associated with cooler Southern Ocean (SO) sea surface temperature (SST). Relation between SO (40°S-60°S) SST climatology (1850-1920) and GMSST trend (1925-2014). Uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, and marker size is proportional to the number of ensemble members in each model. Observations are in black markers.



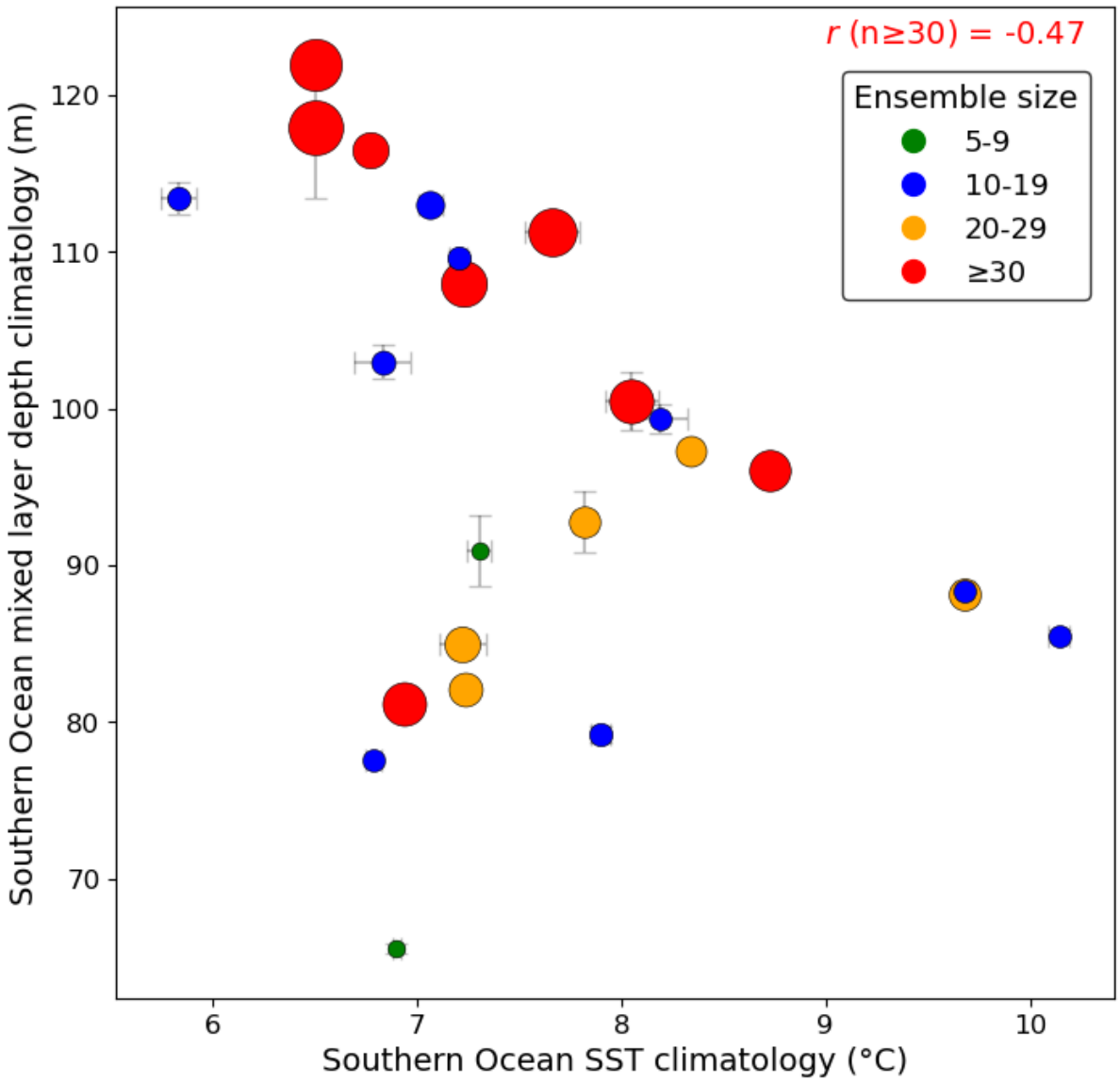
Extended Data Figure 3. Connections between Southern Ocean (SO) sea surface temperature (SST) climatology and local SST climatology. Inter-model correlation between SO (40°S-60°S; highlighted with a blue box) SST climatology (1850-1920) and local SST climatology across the 12 large-ensemble (LE) models' (≥30 members each) ensemble means. Stippling marks areas where the correlation is insignificant at the 95% confidence level, according to a two-sided Student's t-test.



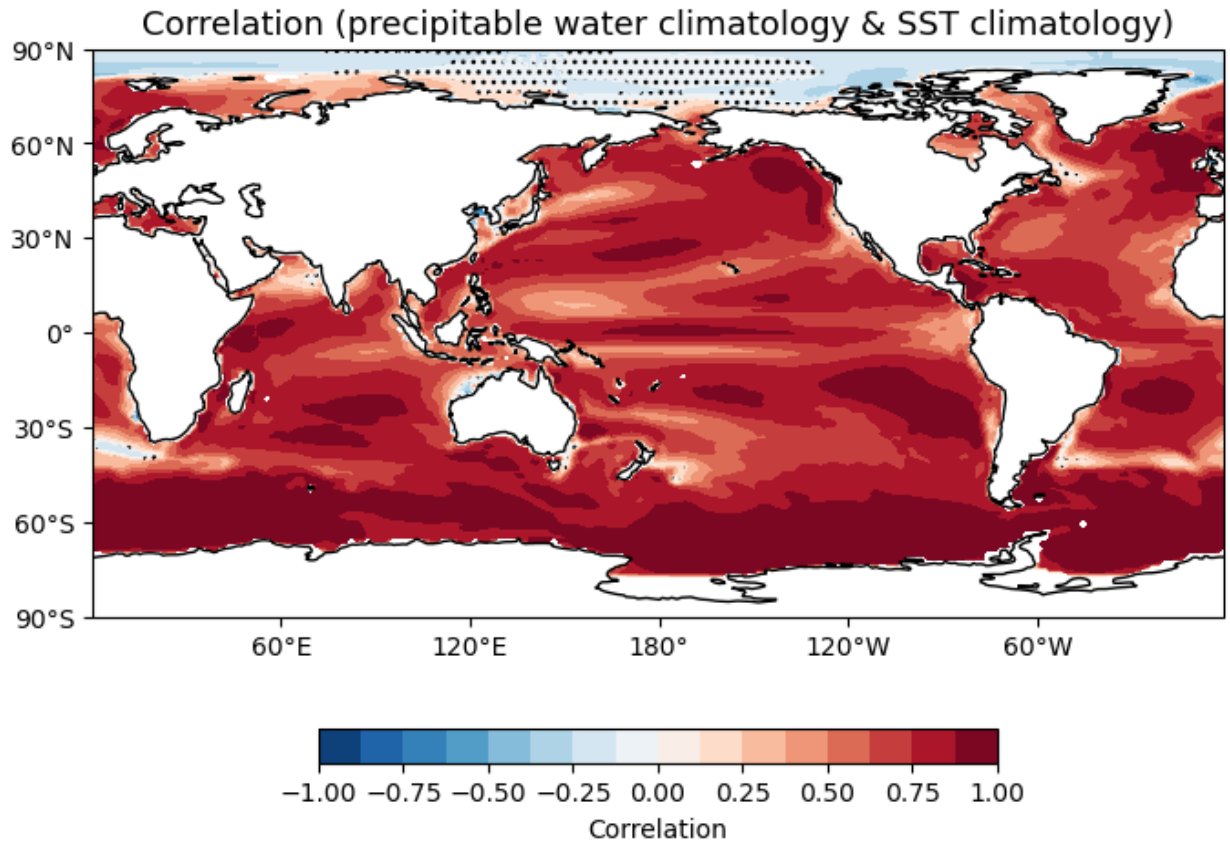
Extended Data Figure 4. Inter-model spread in climatological sea surface temperature (SST). Spatial distribution of the inter-model standard deviation of SST climatology across the 30 climate models. Long-term (1850-1920), multi-member ensemble means are used to compute the SST climatology.



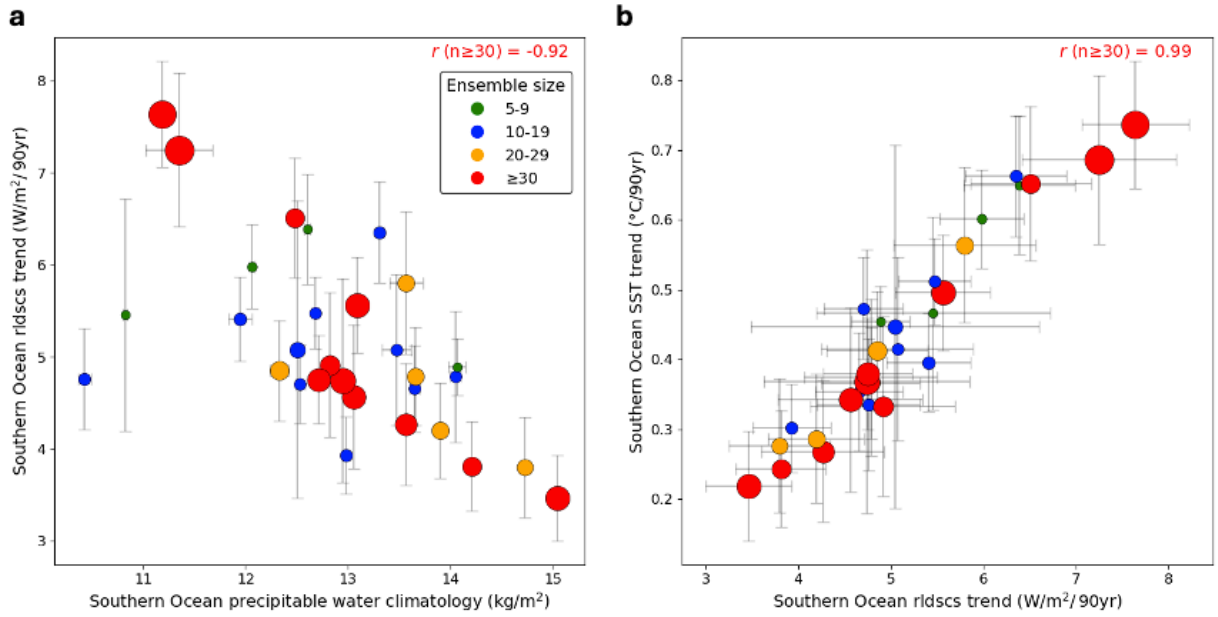
Extended Data Figure 5. Links between Southern Ocean (SO) climatological sea surface temperature (SST) and global-mean SST trend. a, Relation between SO (40°S-60°S) SST climatology and SO SST trend (1925-2014). **b,** Relation between SO SST trend and global SST trend. In panels **a** and **b**, uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, black marker indicates observation, and marker size is proportional to the number of ensemble members in each model.



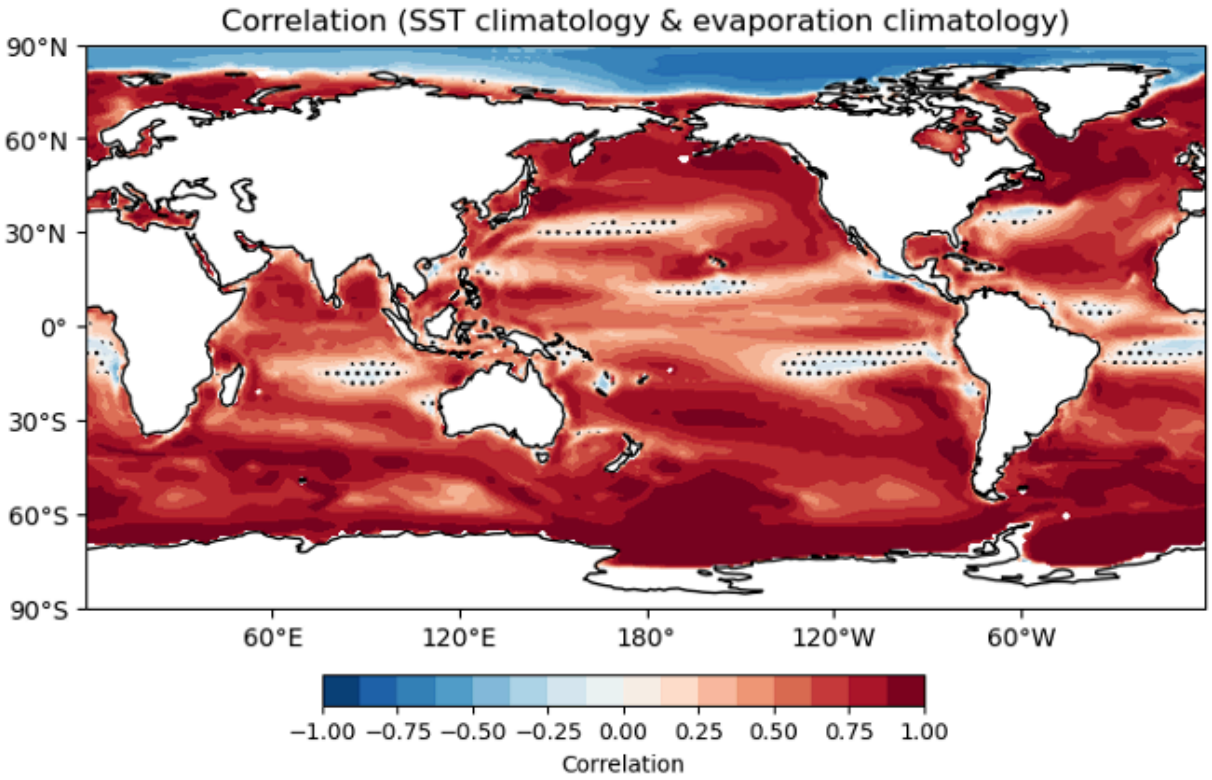
Extended Data Figure 6. Links between Southern Ocean (SO) climatological sea surface temperature (SST) and ocean mixed-layer depth. Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO ocean mixed layer depth climatology. Uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, and marker size is proportional to the number of ensemble members in each model.



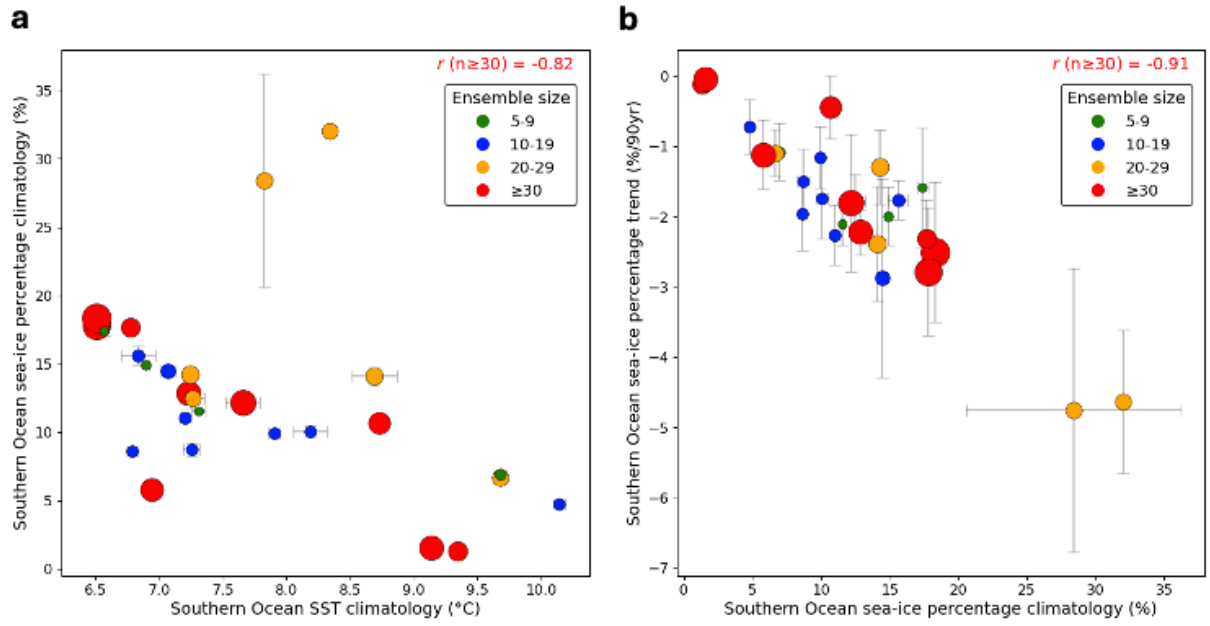
Extended Data Figure 7. Atmosphere over a warmer ocean holds more water vapor. Inter-model correlation between local climatological SST (1850-1920) and precipitable water across the 12 large-ensemble models' ensemble means (≥30 members each). Stippling marks areas where the correlation is insignificant at the 95% confidence level, according to a two-sided Student's t-test.



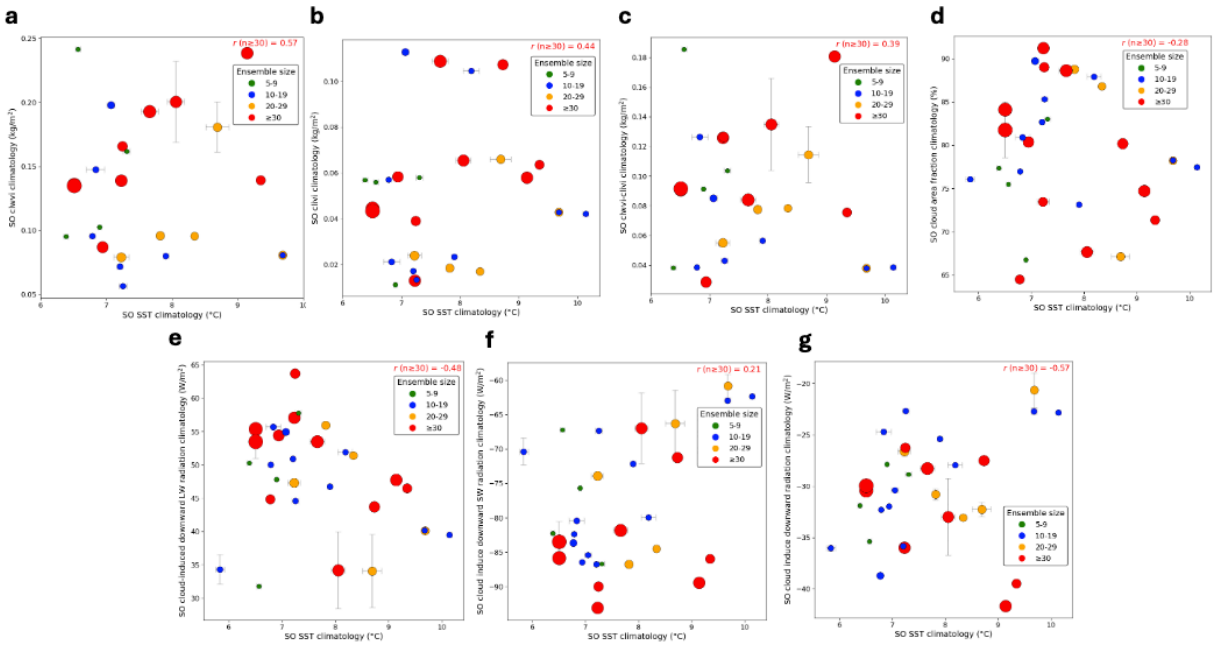
Extended Data Figure 8. Clear-sky surface downward longwave radiative flux (rldscs). a, Relation between SO climatological (1850-1920) precipitable water and SO rldscs (downward positive) trend (1925-2014). **b,** Relation between SO rldscs trend and SO sea surface temperature trend. In panels **a** and **b**, uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, and marker size is proportional to the number of ensemble members in each model.



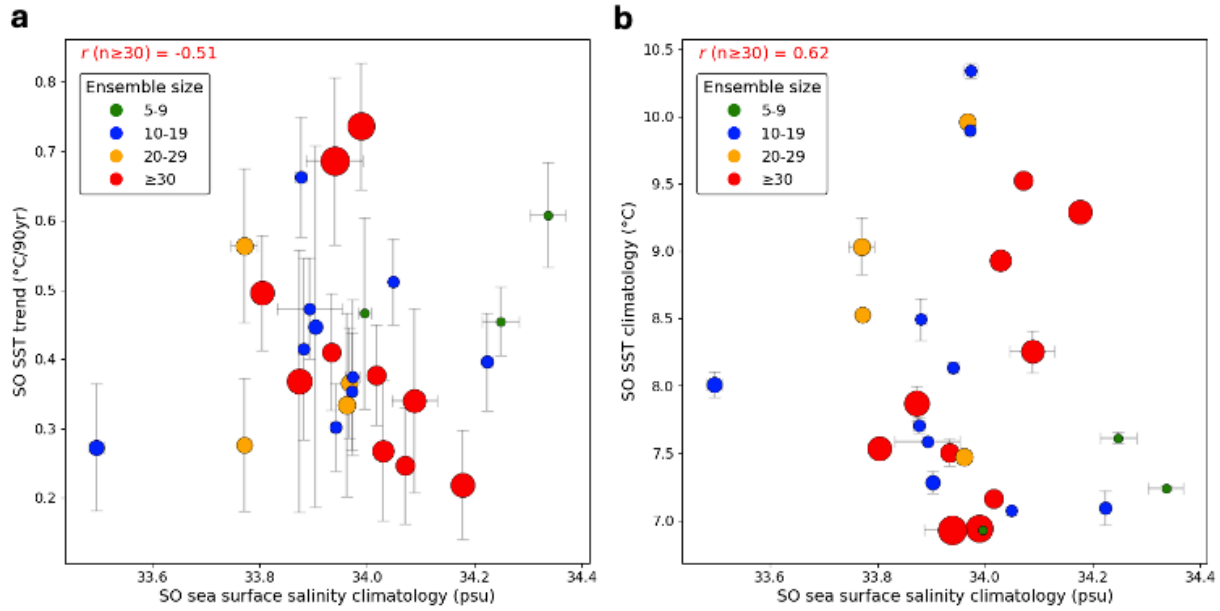
Extended Data Figure 9. Warmer oceans evaporate more. Inter-model correlation between local SST climatology (1850-1920) and local evaporation climatology across the 12 large-ensemble models' ensemble means (≥30 members each). Stippling marks areas where the correlation is insignificant at the 95% confidence level, according to a two-sided Student's t-test.



Extended Data Figure 10. State dependence of Southern Ocean (SO) sea-ice percentage (siconc). a, Relation between SO (40°S-60°S) sea surface temperature climatology (1850-1920) and SO siconc climatology. **b,** Relation between siconc climatology and SO siconc trend (1925-2014). In panels **a** and **b**, uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, and marker size is proportional to the number of ensemble members in each model.



Extended Data Figure 11. Links between Southern Ocean (SO) climatological sea surface temperature (SST) and cloud properties. a, Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud condensed water content (clwvi) climatology. **b,** Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud ice content (clivi) climatology. **c,** Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud liquid water content (clwvi - clivi) climatology. **d,** Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud area fraction (clt) climatology. **e,** Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud-induced downward longwave radiative flux climatology. **f,** Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud-induced downward shortwave radiative flux climatology. **g,** Relation between SO (40°S-60°S) SST climatology (1850-1920) and SO atmosphere cloud-induced downward radiative flux climatology. In panels **a**-**g**, uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, and marker size is proportional to the number of ensemble members in each model. The radiative fluxes in panels **e**-**g** are downward positive.



Extended Data Figure 12. Links between Southern Ocean (SO) climatological sea surface salinity (sos) and sea surface temperature (SST). a, Relation between SO (40°S-60°S) sos climatology (1850-1920) and SO SST trend (1925-2014). **b,** Relation between sos climatology and SO SST climatology. In panels **a** and **b**, uncertainty bars denote one inter-model standard deviation, *r* indicates the Pearson correlation coefficient (computed from models with ≥30 ensemble members), marker color indicates the ensemble size category, and marker size is proportional to the number of ensemble members in each model.