

Supplementary information for “Multi-objective observational constraint of tropical Atlantic and Pacific low-cloud variability narrows uncertainty in cloud feedback”

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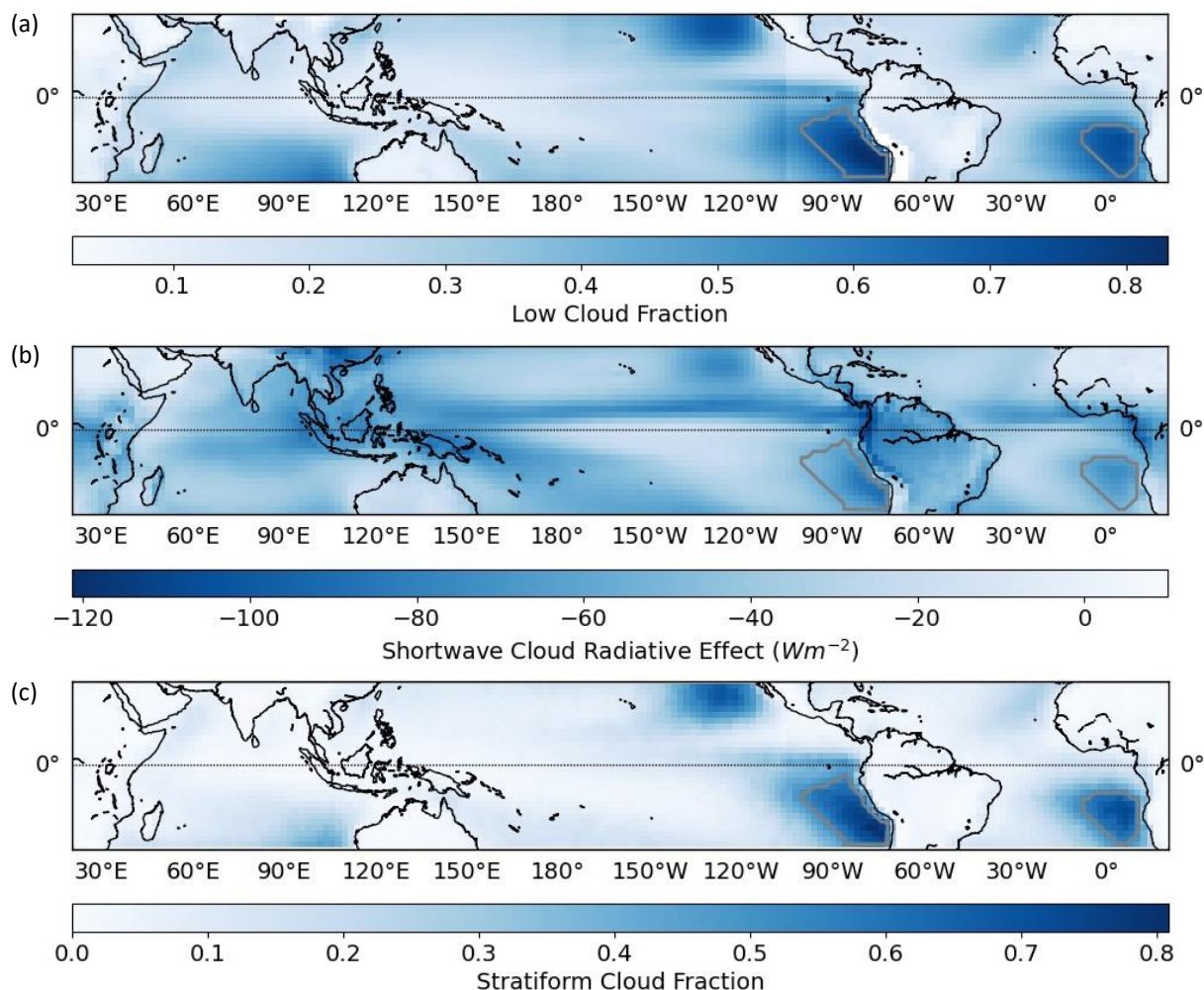
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Supplementary Note 1

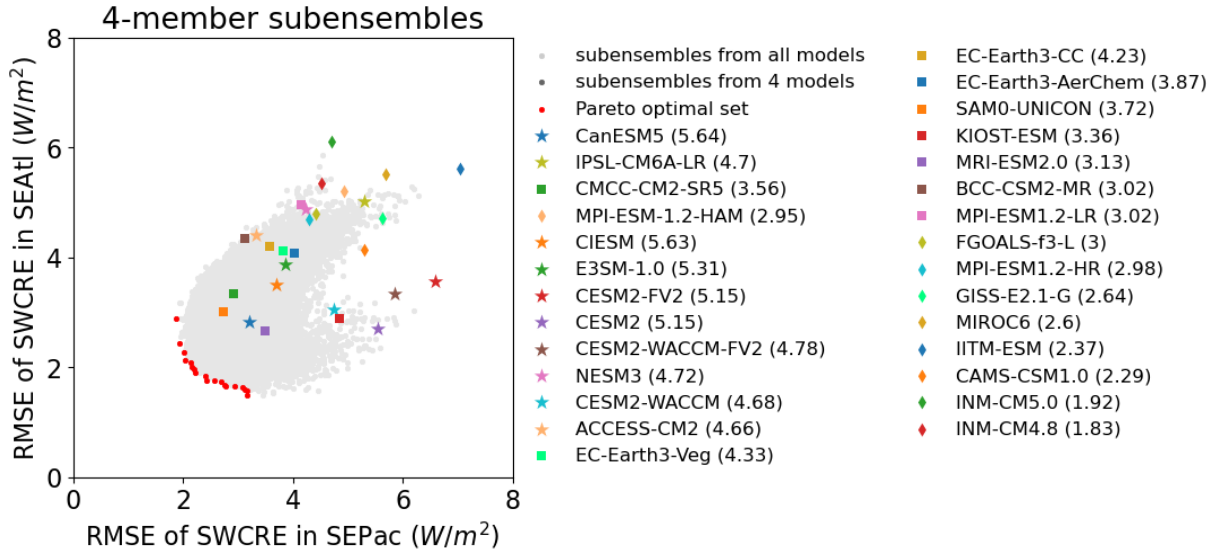
In addition to the inversion strength and cloud top entrainment considered by EIS and ECTEI, local SST may exert additional influence over marine low cloud cover through surface latent heat flux ([22, 41]), which can be parameterized with a bulk formula

$$Q = Cu(q_s - q_a) \approx Cuq_s^*(1 - r) \quad (S1)$$

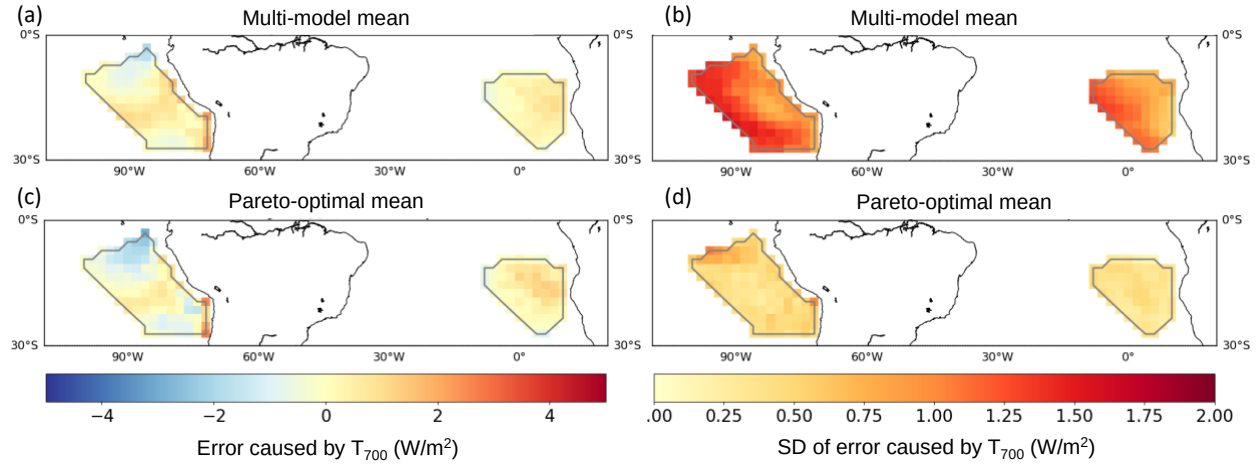
where Q is the surface latent heat flux, u is the surface wind speed, q_s^* is the saturation specific humidity near the surface, r is the relative humidity near the surface, and C is a given coefficient. From this formula, we can infer that marine low cloud cover may be more sensitive to local SST if the surface wind is stronger and/or the surface relative humidity is lower. ERA5 reanalysis data suggest that the mean surface wind at 10 m is slightly weaker (-15%) in the SEAtl region than in the SEPac region while the relative humidity term $(1 - r)$ is 1.5 times higher in the SEAtl region. Therefore, a relatively larger low cloud sensitivity to local SST in the SEAtl region, indicated by a flatter linear fit in solid black line in Fig. 2, is likely to be driven by a lower surface relative humidity and thus a stronger surface latent heat flux there.



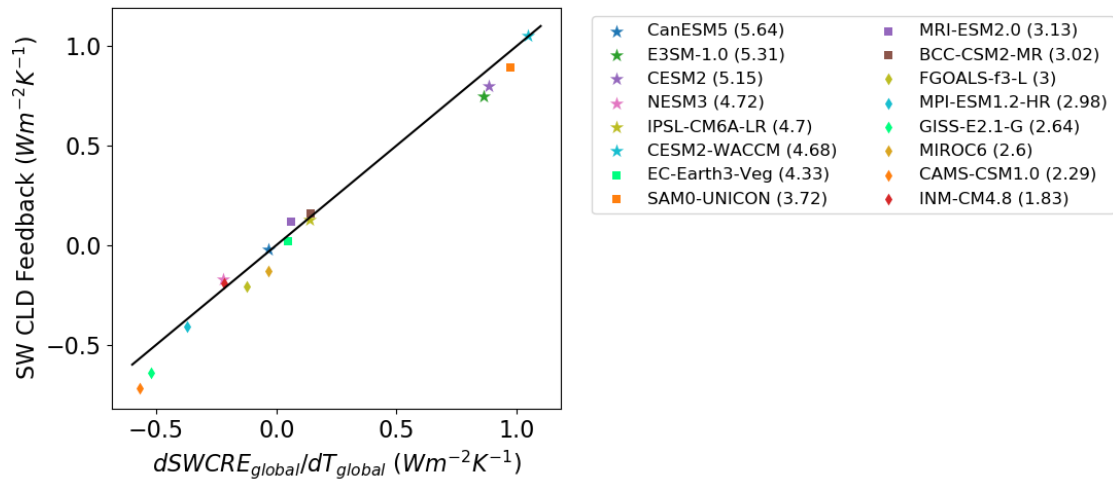
Supplementary Figure 1: Observed low cloud fraction (a), shortwave cloud radiative effect (b) and stratiform cloud fraction (c) in the tropics. Locations of the two selected marine stratocumulus regions in this study are shown in gray contours.



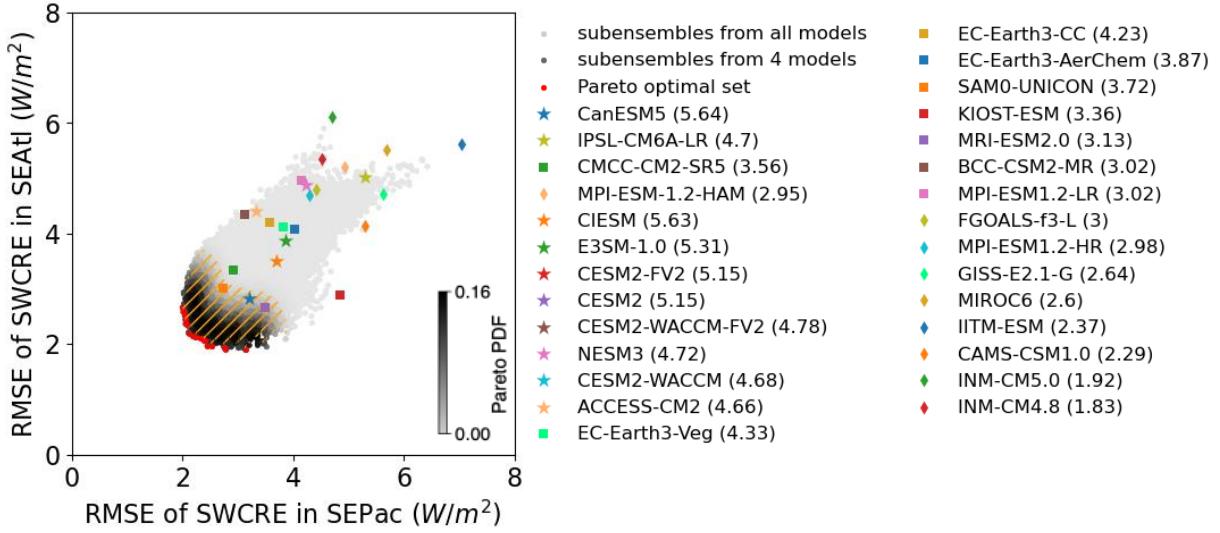
Supplementary Figure 2: Model performance relative to observations in the Southeastern Pacific (SEPaC) and Southeastern Atlantic (SEAtl) stratocumulus regions. Similar to Fig. 3b, model-observation root mean squared errors (RMSE) with respect to the shortwave cloud radiative effect (SWCRE) sensitivities to local sea surface temperature and air temperature at 700 mb (Methods) for 28 CMIP6 models are drawn in colored dots. However, gray dots represent all 4-member (repetition allowed) model subensembles, and red dots represent the Pareto-optimal set of these 4-member subensembles. Compared with Fig. 3b, increasing the subensemble sizes from 4 to 5 only bring marginal changes to the Pareto-optimal set.



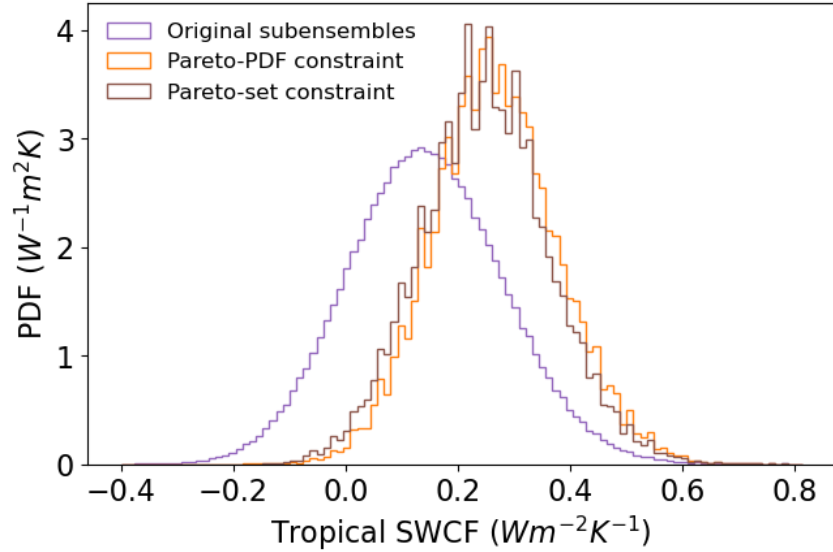
Supplementary Figure 3: Model performance with respect to the observed shortwave cloud radiative effect (SWCRE) sensitivities to air temperature at 700 mb (T_{700}) in the Southeastern Pacific and Southeastern Atlantic stratocumulus regions. Similar to Fig. 4, model-observation root mean squared error (a, c) caused by the SWCRE sensitivity to local SST (Methods) and its standard deviation (b, d) for the simple multi-model mean (a, b) and the Pareto-optimal set (c, d) defined in Fig. 3. For a fair comparison, the standard deviations (SD) in (b) are scaled by the square root of subensemble size ($n = 5$) following the central limit theorem.. Pareto optimization (c) does not show an outstanding performance relative to the multi-model mean (a) because the majority of the model errors comes from SWCRE sensitivities to sea surface temperature, where Pareto optimization clearly outperforms the multi-model mean (Fig. 4).



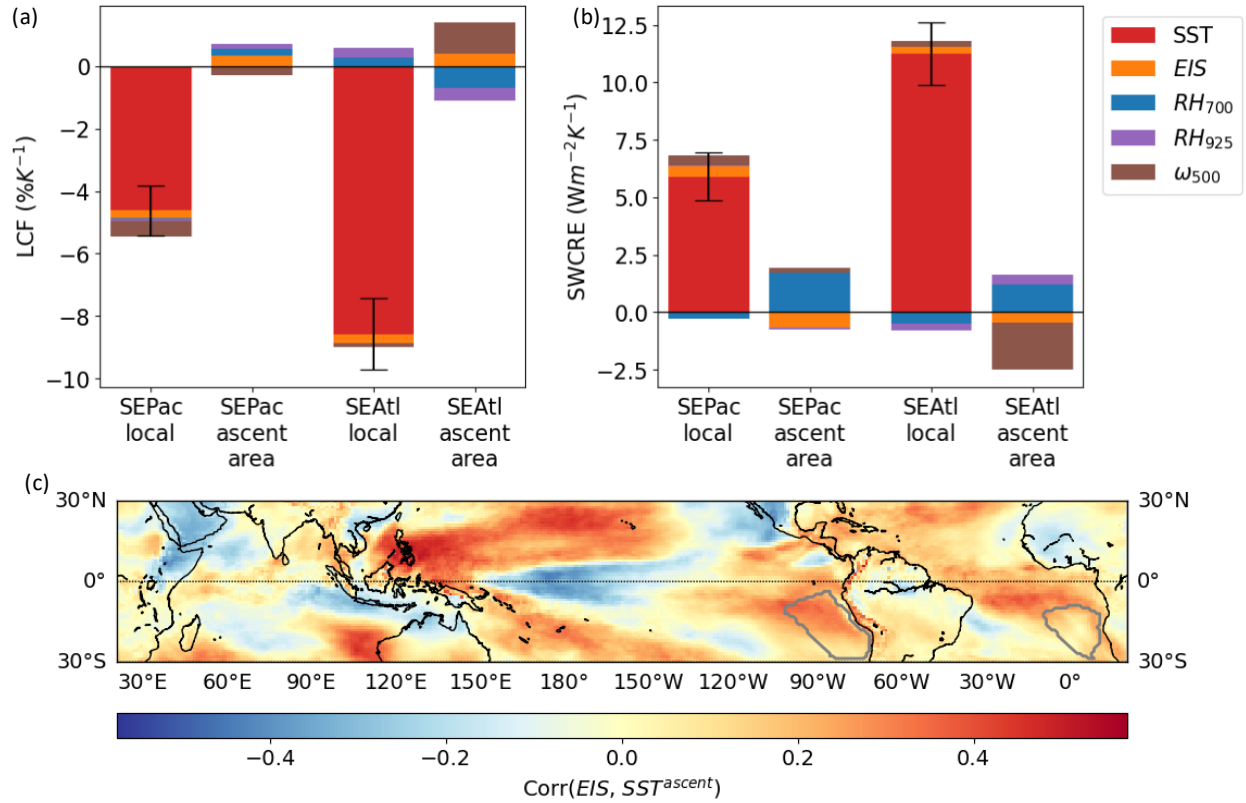
Supplementary Figure 4: Comparison between the simple estimate of global shortwave (SW) cloud (CLD) feedback (x -axis) using the ratio of global mean shortwave cloud radiative effect ($SWCRE_{global}$) change to global mean sea surface temperature (T_{global}) change from the first 30 years (Year 1-30) to the last 30 years (Year 121-150), and more accurate results computed using a radiative kernel (y -axis) [5]. The solid line is the 1:1 line.



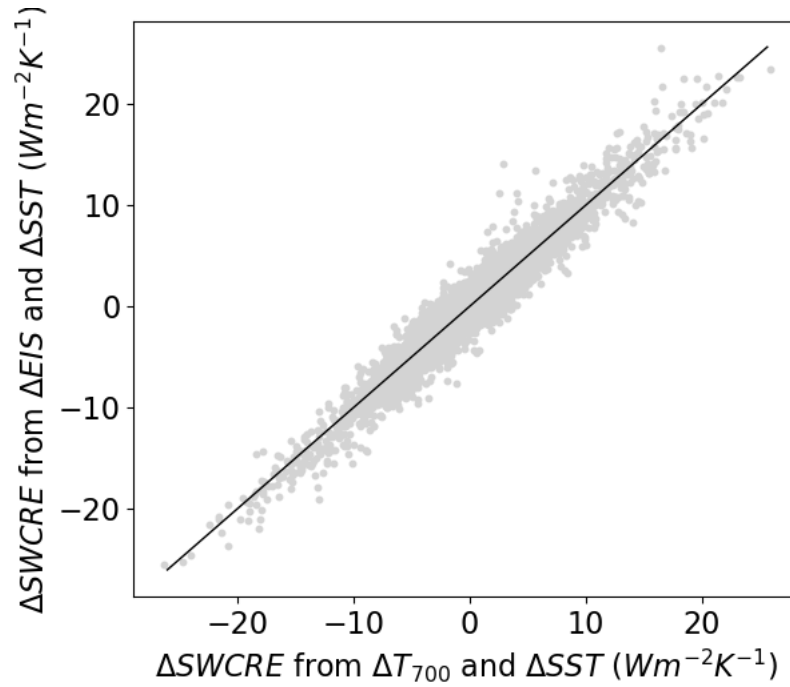
Supplementary Figure 5: Model performance relative to observations in the Southeastern Pacific (SEPa) and Southeastern Atlantic (SEAtl) stratocumulus regions. Similar to Fig. 3b and 3c, model-observation errors with respect to the shortwave cloud radiative effect (SWCRE) sensitivities to local sea surface temperature and air temperature at 700 mb (Methods) for 24 CMIP6 models are drawn in colored dots, but the CESM2 model family (CESM2-FV2, CESM2, CESM2-WACCM-FV2 and CESM2-WACCM) are excluded. For consistency, the same legend as in Fig. 3 is used here, which still includes the four excluded CESM2 models. Although the entire data cloud looks different from Fig. 3, the Pareto-optimal set (red dots), the 95% confidence interval (orange hatching) and the probability density function (PDF, grayscale) are similar to Fig. 3.



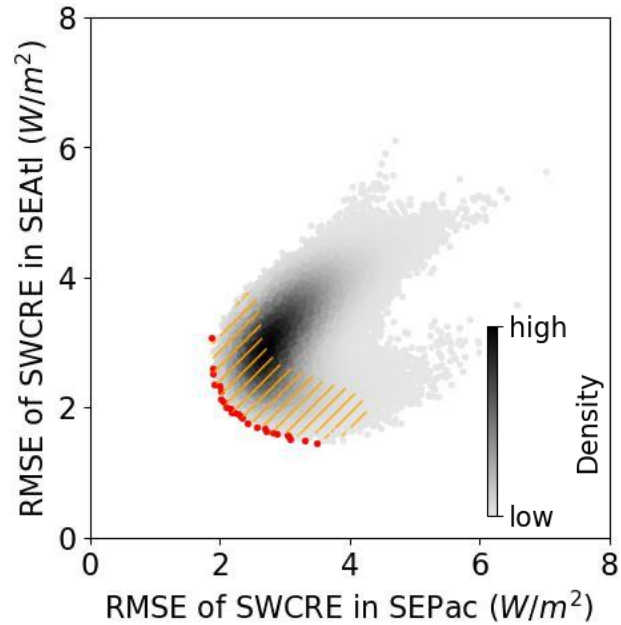
Supplementary Figure 6: Probability distribution of tropical shortwave cloud feedback (SWCF) among all CMIP6 models and subensembles. The probability distribution from original subensembles (purple) is updated using multi-objective Pareto constraints (orange and brown). Similar to Fig. 5, but the CESM2 model family (CESM2-FV2, CESM2, CESM2-WACCM-FV2 and CESM2-WACCM) are excluded. Because the CESM2 family are all high-equilibrium-climate-sensitivity models with a large positive SWCF, both unconstrained and constrained probability density functions (PDFs) shift slightly leftward compared with Fig. 5. However, all our major conclusions still hold in this figure: (1) the multi-objective observational constraint increases the peak SWCF by 71%; (2) the likelihood of a negative SWCF is almost eliminated by the observational constraint; (3) and the probability of a large positive SWCF ($> 0.5 \text{ Wm}^{-2}\text{K}^{-1}$) greatly increases.



Supplementary Figure 7: Contributions from selected cloud controlling factors (CCFs) to the sensitivities of (a) low cloud fraction (LCF) or (b) shortwave cloud radiative effect (SWCRE) to local and ascent area interannual sea surface temperature (SST) variability (defined in Methods) in the Southeastern Pacific (SEPac) and Southeastern Atlantic (SEAtl) stratocumulus regions. Similar to Fig. 1, but air temperature at 700 mb (T_{700}) is replaced by estimated inversion strength (EIS, orange) as a CCF. Other CCFs include relative humidity at 700 mb (RH_{700} , blue) and 925 mb (RH_{925} , purple) and subsidence rate at 500 mb (ω_{500} , brown). Error bars representing one standard error in ordinary-least-square linear regression are only shown for SST (red). (c) Locations of these two marine stratocumulus regions (gray contours) and the correlation map between EIS anomalies of each grid box and average SST anomalies of ascent areas (SST^{ascent}). Unlike T_{700} , EIS does not show a consistent positive correlation with remote tropical SST. In addition, the set of CCFs without T_{700} has difficulty reconstructing the marine stratocumulus response to ascent area warming from interannual observations. Therefore, T_{700} has an advantage that it can explicitly represent the contributions from remote ascent area SST to marine stratocumulus variability.



Supplementary Figure 8: Comparison of the two bivariate linear regression models. Shortwave cloud radiative effect (SWCRE) anomalies of each CMIP6 AMIP experiment are predicted using two different bivariate linear regression models: sea surface temperature (SST) + air temperature at 700 mb (T_{700}) and SST + estimated inversion strength (EIS). All the results are summarized in the plot, where the predictions from two models (gray dots) are always close to the 1:1 line (solid black).



Supplementary Figure 9: Density of data points in Fig. 3. Model-observation root mean squared errors (RMSE) with respect to the shortwave cloud radiative effect (SWCRE) sensitivities to local sea surface temperature and air temperature at 700 mb in the Southeastern Pacific (SEPac) and Southeastern Atlantic (SEAtl) stratocumulus regions (Methods) for all 5-member model subensembles (gray dots) are colored based on the local density of data points. Red dots represent the Pareto-optimal set, and the orange hatched region indicates subensembles within the observational uncertainty (95% CI) of the Pareto-optimal set.

Supplementary Table 1: Ordinary-least-square linear regression of shortwave cloud radiative effect (SWCRE) sensitivities to sea surface temperature (SST) and air temperature at 700 mb (T_{700}) in the Southeastern Pacific and the Southeastern Atlantic. σ denotes one standard error of the estimated regression coefficients. The significance level of t-tests and F-tests is indicated by * (0.1), ** (0.05) and *** (0.01).

Name	Southeastern Pacific					Southeastern Atlantic				
	SST	σ	T_{700}	σ	F-test	SST	σ	T_{700}	σ	F-test
Observation	5.5 ***	0.6	-3.5 ***	0.4	***	8.5 ***	0.9	-2.8 ***	0.6	***
ACCESS-CM2	3.3 ***	0.1	-2.6 ***	0.1	***	2.5 ***	0.1	-0.8 ***	0.1	***
BCC-CSM2-MR	4.3 ***	0.1	-3.3 ***	0.1	***	3.7 ***	0.2	-0.1	0.2	
CanESM5	4.4 ***	0.1	-1.3 ***	0.1	***	6.5 ***	0.2	-0.2 **	0.1	***
CAMS-CSM1.0	5.4 ***	0.2	0.9 ***	0.1	***	5.9 ***	0.3	0.3	0.2	***
CESM2	9.5 ***	0.2	-7.2 ***	0.1	***	8.3 ***	0.2	-2.7 ***	0.2	***
CESM2-FV2	8.2 ***	0.2	-8.2 ***	0.2	***	7.1 ***	0.3	-5.4 ***	0.2	***
CESM2-WACCM	8.4 ***	0.2	-5.8 ***	0.2	***	7.8 ***	0.2	-5.1 ***	0.2	***
CESM2-WACCM-FV2	8.5 ***	0.2	-6.8 ***	0.2	***	7.5 ***	0.3	-4.2 ***	0.2	***
CIESM	2.4 ***	0.1	-1.4 ***	0.1	***	4.3 ***	0.2	-0.3 ***	0.1	**
CMCC-CM2-SR5	3.7 ***	0.1	-3.5 ***	0.1	***	5.7 ***	0.2	-0.1	0.2	***
E3SM-1.0	6.3 ***	0.2	-4.3 ***	0.1	***	4.8 ***	0.2	-5.6 ***	0.2	***
EC-Earth3-AerChem	1.4 ***	0.1	-1.4 ***	0.1	***	2.4 ***	0.2	-0.4 ***	0.1	***
EC-Earth3-CC	1.6 ***	0.1	-1.9 ***	0.1	***	1.8 ***	0.2	-2.1 ***	0.2	***
EC-Earth3-Veg	1.7 ***	0.1	-1.1 ***	0.1	***	2 ***	0.2	-1.5 ***	0.1	***
FGOALS-f3-L	4.3 ***	0.1	-4.6 ***	0.1	***	4.7 ***	0.2	-7.8 ***	0.1	***
GISS-E2.1-G	1.6 ***	0.1	1.5 ***	0.1	***	1.9 ***	0.2	-0.5 ***	0.1	***
IITM-ESM	-0.9 ***	0.1	2.7 ***	0.1	***	0.2 **	0.1	0.6 ***	0.1	***
INM-CM4.8	2.2 ***	0.1	0.2 **	0.1	***	2.5 ***	0.2	-1.0 ***	0.1	***

INM-CM5.0	2.3 ***	0.1	0.2 **	0.1	***	1.4 ***	0.2	-0.1	0.2	*
IPSL-CM6A	-0.2 **	0.1	-1.2 ***	0.1	***	1.3 ***	0.2	-2.6 ***	0.1	***
KIOST-ESM	3.1 ***	0.2	-1.2 ***	0.1	***	4.5 ***	0.3	-3.0 ***	0.2	***
MIROC6	0.3 ***	0.1	0.2 **	0.1	***	1.2 ***	0.1	-0.3 ***	0.1	***
MPI-ESM1.2-HR	4.4 ***	0.2	-3.6 ***	0.1	***	4.5 ***	0.3	0.2	0.2	
MPI-ESM1.2-LR	3.8 ***	0.2	-1.4 ***	0.1	***	2.4 ***	0.2	-0.1	0.2	
MPI-ESM-1.2- HAM	3.2 ***	0.1	0.1	0.1	**	2.9 ***	0.2	0.9 ***	0.1	***
MRI-ESM2.0	2.7 ***	0.1	-1.7 ***	0.1	***	5.2 ***	0.2	-3.9 ***	0.1	***
NESM3	4.6 ***	0.2	-1.0 ***	0.1	***	2.2 ***	0.2	-0.1	0.2	***
SAM0-UNICON	4.3 ***	0.1	-5.0 ***	0.1	***	4.9 ***	0.2	-1.5 ***	0.2	***

Supplementary Table 2: List of 28 Coupled Model Intercomparison Project phase 6 (CMIP6) models used in this study and their respective equilibrium climate sensitivity (ECS).

Model Name	ECS [46]
ACCESS-CM2	4.66
BCC-CSM2-MR	3.02
CanESM5	5.64
CAMS-CSM1.0	2.29
CESM2	5.15
CESM2-FV2	5.15
CESM2-WACCM	4.68
CESM2-WACCM-FV2	4.78
CIESM	5.63
CMCC-CM2-SR5	3.56
E3SM-1.0	5.31
EC-Earth3-AerChem	3.87
EC-Earth3-CC	4.23
EC-Earth3-Veg	4.33
FGOALS-f3-L	3.00
GISS-E2.1-G	2.64
IITM-ESM	2.37
INM-CM4.8	1.83
INM-CM5.0	1.92
IPSL-CM6A	4.70
KIOST-ESM	3.36
MIROC6	2.60
MPI-ESM1.2-HR	2.98
MPI-ESM1.2-LR	3.02
MPI-ESM-1.2-HAM	2.95
MRI-ESM2.0	3.13
NESM3	4.72
SAM0-UNICON	3.72