

Supplementary Information

Stronger ENSO-induced Global SST Variability in a Warming Climate

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Supplementary Notes

Decomposition of changes in El Niño impacts on SSTA

The changes in El Niño impacts on SST is calculated as follows:

$$Y' = \beta \times \text{Niño3.4} + \text{Res}_1, \quad (S1)$$

where Y' is $\text{SSTA}(\tau)$, β is regression coefficient which indicates ENSO-induced SSTA, and Res_1 is the residual. Unit of β is K per 1K of DJF Niño3.4 SSTA (DJF Niño3.4). We used the $|\beta|$ as a representation of ENSO impacts on SSTA.

Following the Lin et al. (2024) and Wu et al. (2021), $\text{SSTA}(\tau)$ regression is also conducted with DJF Niño3.4_{std}, which represent standardized Niño3.4 SSTA as follows:

$$\begin{aligned} \text{Niño3.4}_{std} &= \text{Niño3.4} / \sigma \\ Y' &= \beta_{std} \times \text{Niño3.4}_{std} + \text{Res}_2, \end{aligned} \quad (S2)$$

where σ is standard deviation of DJF Niño3.4, β_{std} is regression coefficient indicating ENSO-induced SSTA per one-standard deviation of ENSO, and Res_2 is the residual. β_{std} consists of two influences: (i) non-amplitude factor (the regression coefficient, β) and (ii) ENSO amplitude factor (the standard deviation of the ENSO index, σ). Since the $|\beta_{std}| \approx |\beta| \times \sigma$ from Eq. S2 and S3, decomposition of these two factors is calculated as follows:

$$\Delta|\beta_{std}| = \Delta|\beta| \times \sigma_{PD} + |\beta_{PD}| \times \Delta\sigma + \text{Res}_3, \quad (S3)$$

where Δ means difference between 2100 and PD periods, the subscript PD indicates the PD period, Res_3 is the residual term. Using Eqs. S2 and S3, we decompose the contribution of non-amplitude and amplitude factor.

Decomposition of El Niño-induced latent heat flux anomalies

We decompose the changes in El Niño-induced latent heat flux ($\Delta Q'_{LH}$) following Lin et al. (2024), using the bulk formula equation:

$$\begin{aligned} \Delta Q'_{LH} &\approx \Delta[-\rho_0 L C_e U (q_s - q_a)]' \\ &= -\rho_0 L C_e \Delta[\bar{U} (q_s - q_a)'] - \rho_0 L C_e \Delta[U' (\bar{q}_s - \bar{q}_a)] - \rho_0 L C_e \Delta[U' (q_s - q_a)'], \end{aligned} \quad (S4)$$

where Δ denotes the difference between PD and 2100 period. ρ_0 is air density (1 kg m^{-3}), L is latent heat vaporization ($2.5 \times 10^6 \text{ J kg}^{-1}$), C_e is the turbulent exchange coefficient (1.4×10^{-3}),

U is the 10 m wind speed, q_s is the saturation specific humidity at ocean surface, and q_a is 2 m air specific humidity. Since the third term (nonlinear term) of Eq. S4 is negligible, we further decompose the first, and second term as follows:

$$-\rho_0 LC_e \Delta[\bar{U}(q_s - q_a)'] \approx -\rho_0 LC_e \Delta\bar{U}(q_s - q_a)' - \rho_0 LC_e \bar{U} \Delta(q_s - q_a)' + R_1, \quad (S5)$$

$$-\rho_0 LC_e \Delta[U'(q_s - q_a)] \approx -\rho_0 LC_e \Delta U' \overline{(q_s - q_a)} - \rho_0 LC_e U' \overline{\Delta(q_s - q_a)} + R_2, \quad (S6)$$

where an overbar and a prime (') denote climatology and the regression coefficient onto DJF Niño3.4, respectively. R_1 and R_2 are residuals, including each nonlinear term.

Regional mechanisms behind the changes in ENSO-induced latent heat flux

To illuminate the physical pathways underlying the regional amplification of El Niño-induced SST anomalies, we examine four representative basins—the East China Sea (EastCS), the U.S. East Coast, the South Indian Ocean (SIO), and the subtropical North Pacific (SNP)—where impacts are evident in the PD simulation and intensify under warming (Fig. 4). Because we found that the changes in ENSO-induced SSTA of all the four regions are dominated by ENSO-induced latent heat flux ($\Delta Q'_{LH}$) (Supplementary Fig. 7; EastCS ~65%, U.S. East Coast ~81%, SIO ~124%, and SNP ~59%), we further decompose the $\Delta Q'_{LH}$: the changes in climatological wind speed, climatological δq , ENSO-induced wind speed anomalies, and ENSO-induced δq , following the bulk-aerodynamic framework of Lin et al. (2024).

In the EastCS, during El Niño, particularly from D(0)JF(1) to MAM(1), an intensified anomalous western North Pacific anticyclone extends further northeastward and weakens climatological northwesterly (Supplementary Figs. 8a, i and 10). This weakening reinforces the increase in $\Delta Q'_{LH}$ (downward positive, i.e., reduced evaporation) via two pathways: (i) a larger negative wind speed anomaly, and (ii) a larger positive ENSO-induced q_a anomaly that reduces δq . Both effects suppress evaporation and thus promote stronger warm SSTA, peaking in MAM(1)⁴⁶ (Fig.4b and Supplementary Figs. 7 and 9). The U.S. East Coast is predominantly influenced by enhanced ENSO-induced wind speed (~72%) and climatological δq (~26%) variations (Supplementary Fig. 9b). From ASO(0) to JFM(1), stronger westerly winds enhance local evaporation (Supplementary Figs. 8b, f, 10b, j), resulting in significant cooling and a cold SSTA that peaks in FMA(1).

In the SIO, $\Delta Q'_{LH}$ account for 124% of the warm ΔSST_{SFC} because they are partially counterbalanced by reduced shortwave heating ($\Delta Q'_{SW} \approx -88\%$) associated with cloud⁴⁷, which is in turn largely offset by increased longwave heating ($\Delta Q'_{LW} \approx +60\%$). Within $\Delta Q'_{LH}$, humidity difference effects dominate (climatological $\sim 54\%$; ENSO-induced $\sim 33\%$), whereas the ENSO-induced wind speed term is net negative ($\sim -13\%$; Supplementary Fig.9c). The SIO shows climatological easterlies; during ENSO development, the resulting weak northeasterly anomalies (Supplementary Fig. 11) advect moister air into the region, suppressing evaporation, and reinforcing the warm SSTA while the wind speed anomalies remain weak negative. In the decay phase, ENSO-induced westerlies oppose the climatological easterlies and reduce wind speed, while warm SSTA raises ENSO-induced δq , which acts as a cooling contribution (Supplementary Fig. 8). Even so, the combined effect remains positive in both phases, and the changes in climatological δq always acts as a positive effect to increase in $\Delta Q'_{LH}$.

The SNP experiences cooler SSTA in future climate, driven by $\Delta Q'_{LH}$, especially the changes in ENSO-induced wind speed ($\sim 119\%$), while the changes in ENSO-induced δq acts as a damping ($\sim -38\%$, Supplementary Fig. 9). Because the change in ENSO-induced wind from ND(0)J(1) to AMJ(1) not only becomes stronger but aligns with the trade wind, significantly increasing wind speed in SNP (Supplementary Fig. 7, 8 and 9). In contrast, ENSO-induced δq damps the SST, because much cooler SSTA reduces q_s . Across regions, the changes in MLD have a relatively larger contribution in the SIO and SNP compared to the EastCS and U.S. East Coast, yet the contributions are insignificant across all regions. Overall, each region exhibits distinct seasonal characteristics and dominant contributing factors: the U.S. East Coast, and SNP are dominated by ENSO-induced wind changes, whereas the EastCS and SIO are shaped mainly by ENSO-induced and climatological δq , respectively. Although ENSO-induced δq can be sizable locally, only the climatological humidity difference contributes consistently positively across all four regions, indicating that the global-scale enhancement of ENSO-SST variability is not driven by ENSO-induced δq but by robust increases in the climatological δq .

103 **Supplementary Tables**

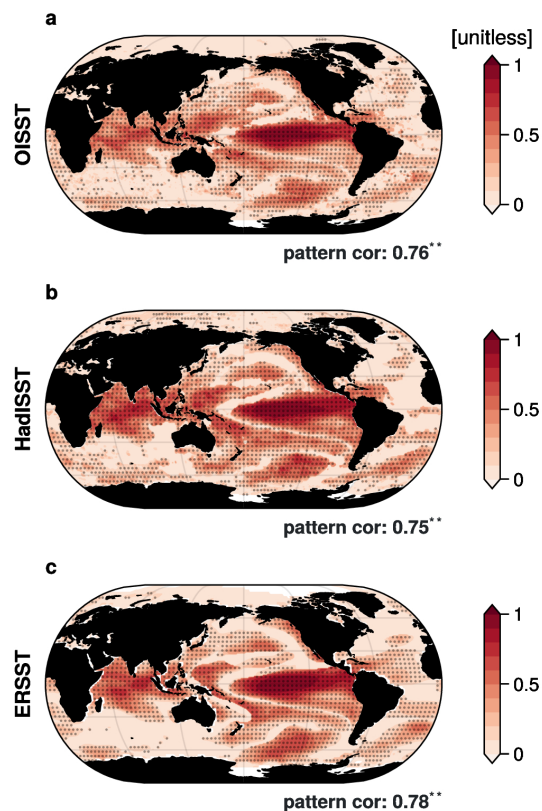
Model number	Model name	Model year (pi-control)	Model number	Model name	Model year (pi-control)
1	ACCESS-ESM1-5	400	18	GFDL-ESM4	400
2	AWI-CM-1-1-MR	400	19	GISS-E2-1-G	400
3	AWI-ESM-1-1-LR	100	20	GISS-E2-1-H	400
4	BCC-CSM2-MR	400	21	GISS-E2-2-G	151
5	BCC-ESM1	400	22	GISS-E2-2-H	251
6	CAMS-CSM1-0	250	23	ICON-ESM-LR	400
7	CESM2-FV2	400	24	MCM-UA-1-0	400
8	CESM2-WACCM-FV2	400	25	MIROC6	400
9	CESM2-WACCM	400	26	MPI-ESM-1-2-HAM	400
10	CESM2	400	27	MPI-ESM1-2-HR	400
11	CMCC-CM2-SR5	400	28	MPI-ESM1-2-LR	400
12	CMCC-ESM2	400	29	MRI-ESM2-0	400
13	EC-Earth3-CC	400	30	NESM3	400
14	EC-Earth3-Veg-LR	400	31	NorCPM1	400
15	FGOALS-f3-L	400	32	NorESM2-LM	400
16	FIO-ESM-2-0	400	33	NorESM2-MM	400
17	GFDL-CM4	400	34	SAM0-UNICON	400

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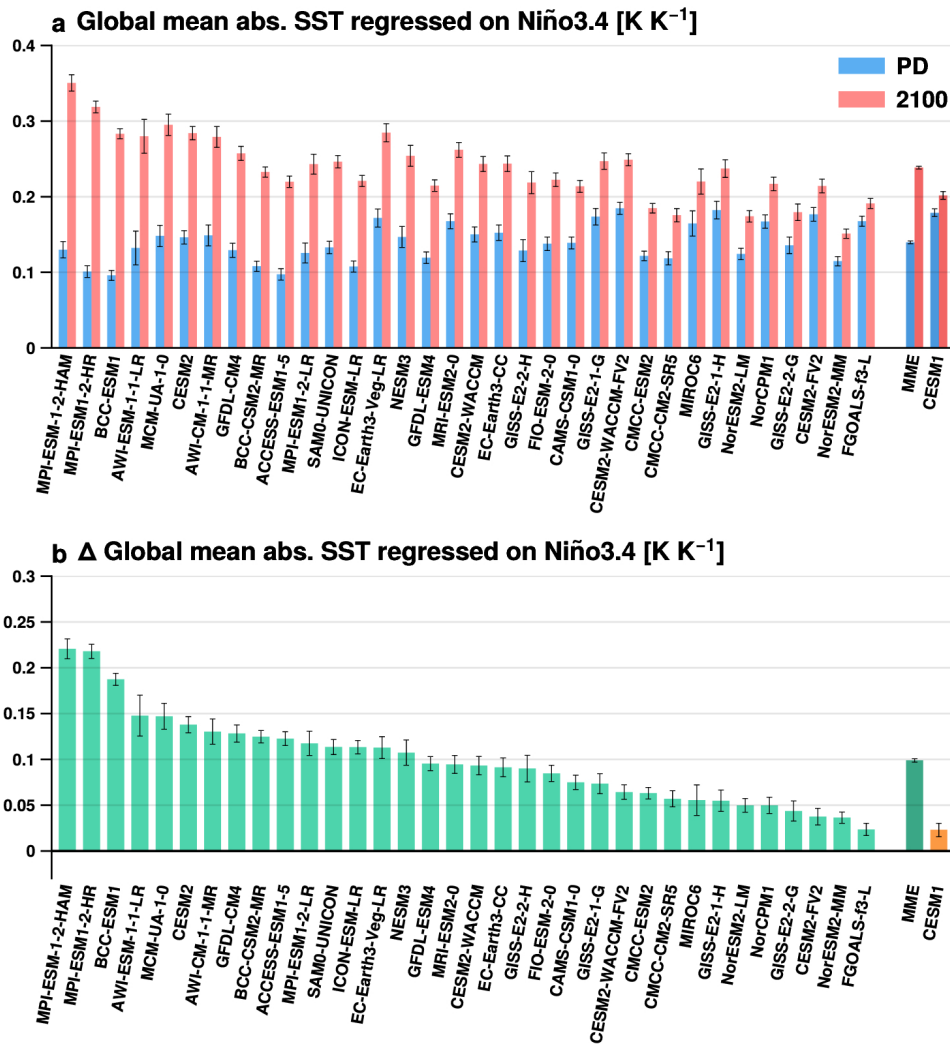
105 **Supplementary Table 1 | CMIP6 34 model list.** CMIP6 models used in this study and the
106 duration of the pi-Control scenario.

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108 **Supplementary Figures**



109
 110 **Supplementary Figure 1 | El Niño impacts on SSTs in observation. a-c** Same as Figure 1a
 111 but for observation data of **a** NOAA Optimum Interpolated Sea Surface Temperature (OISST),
 112 **b** Hadley Centre Global Sea Ice Sea Surface Temperature (HadISST) and **c** Extended
 113 Reconstructed Sea Surface Temperature version 5 (ERSSTv5) for 1981-2023.
 114

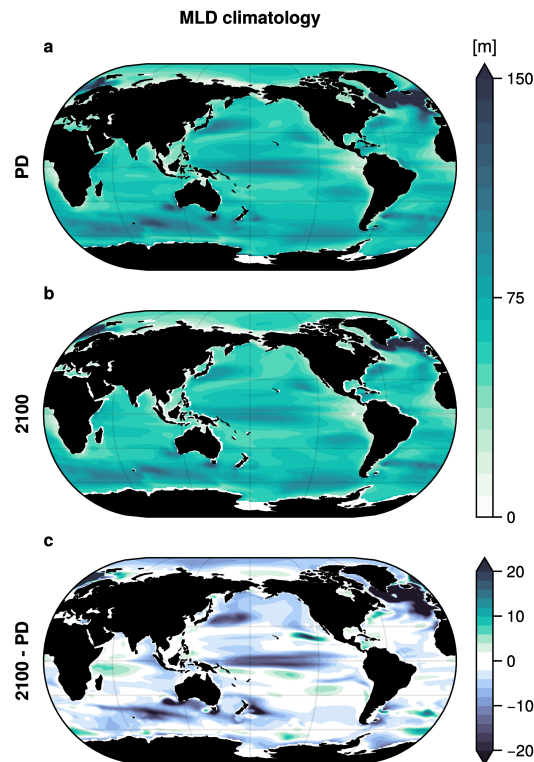


Supplementary Figure 2 | The changes in El Niño impacts on SSTs in CMIP6. a Global mean of absolute values of regression coefficients between the optimal R^2 period (τ) sea surface temperature (SST) and December(0)-February(1) (D(0)JF(1)) Niño3.4 SST anomaly. **b** Difference between pre-industrial and 31-year window after 100 years in 1pctCO2 scenario (2085-2115 model year for CMIP6). All error bars are calculated at the 95% confidence level.

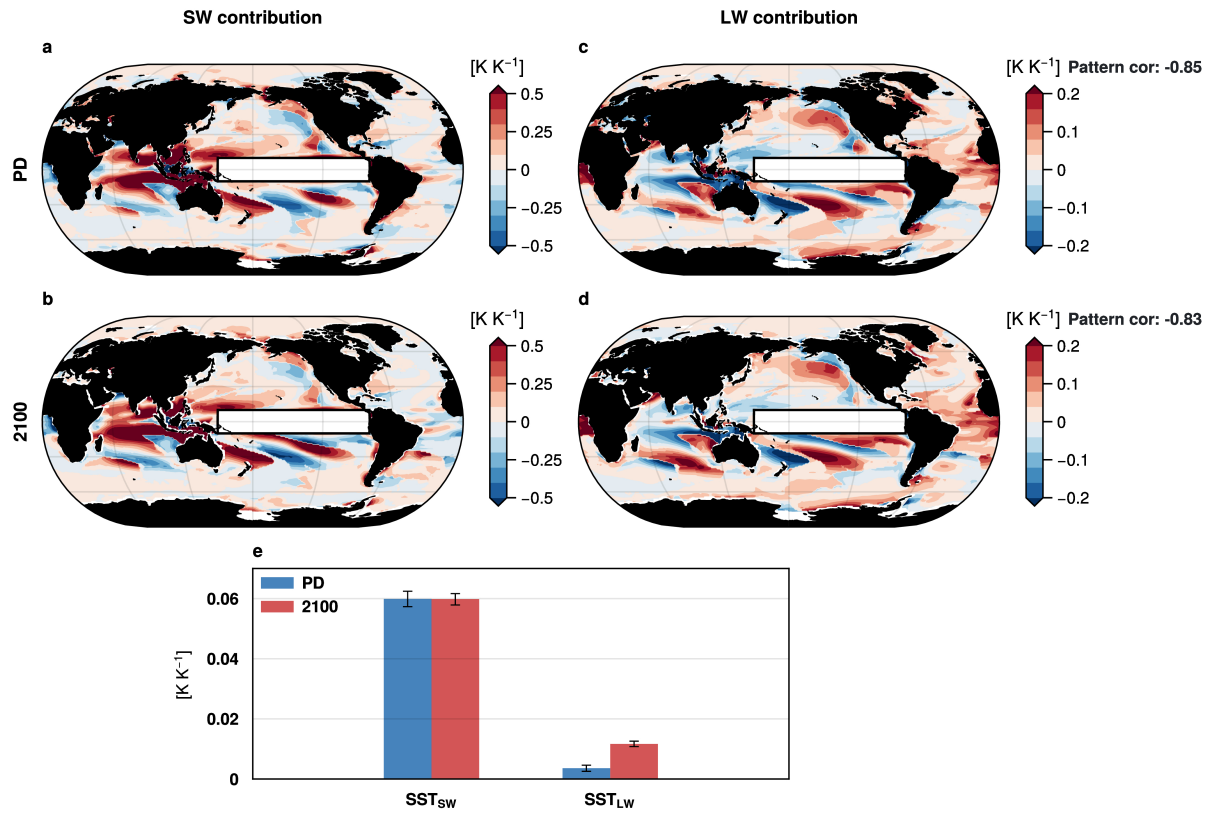


Supplementary Figure 3 | The changes in the maximum R^2 values in each CMIP6 models.

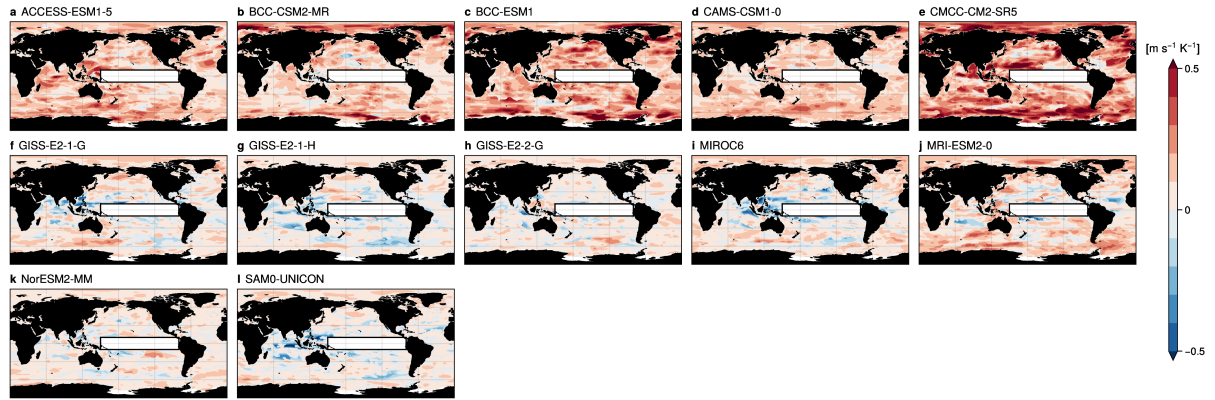
a-hh The changes in maximum R^2 between sea surface temperature anomaly and December(0)-February(1) (D(0)JF(1)) Niño3.4 SST anomaly from pre-industrial to 31-year window after 100 years in 1pctCO2 scenario (2085-2115 model year for CMIP6) in each CMIP6 models.



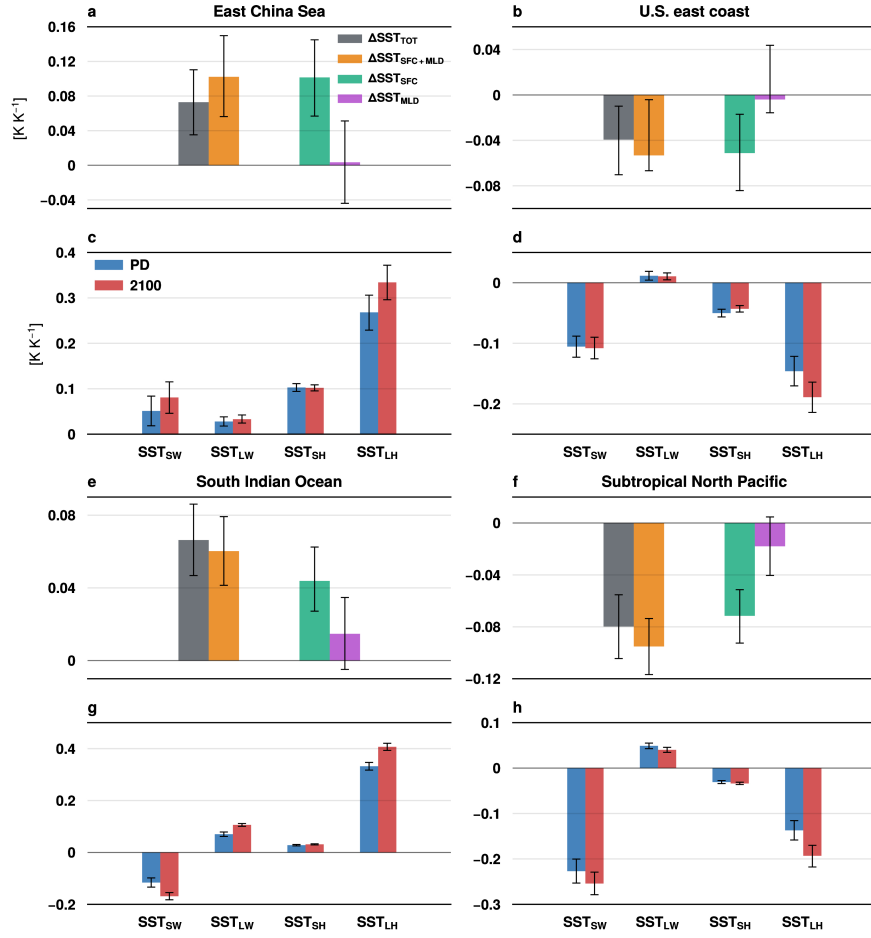
Supplementary Figure 4 | The changes in climatological mixed layer depth. a Climatological mixed layer depth in **a** Present-day (PD) and **b** 2085 – 2115 (2100) using CESM1. **c** The change in climatological mixed layer depth from PD to 2100.



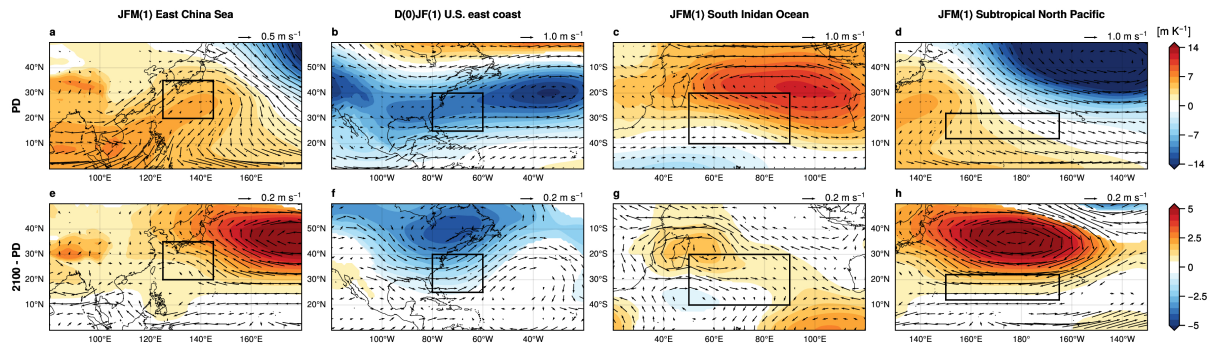
Supplementary Figure 5 | Compensation between the contributions of El Niño-induced shortwave and longwave radiation to global SST. a Shortwave radiation contribution to $SST_{SFC+MLD}$ during Present-day (PD) period in CESM1. **b** Same as **a** but during 2085–2115 (2100). **c-d** Same as **a** and **b** but longwave radiation. **e** Global mean of shortwave radiation contribution (left) and longwave radiation contribution (right) in PD and 2100 period. Error bars are calculated at the 95% confidence level using bootstrap test.



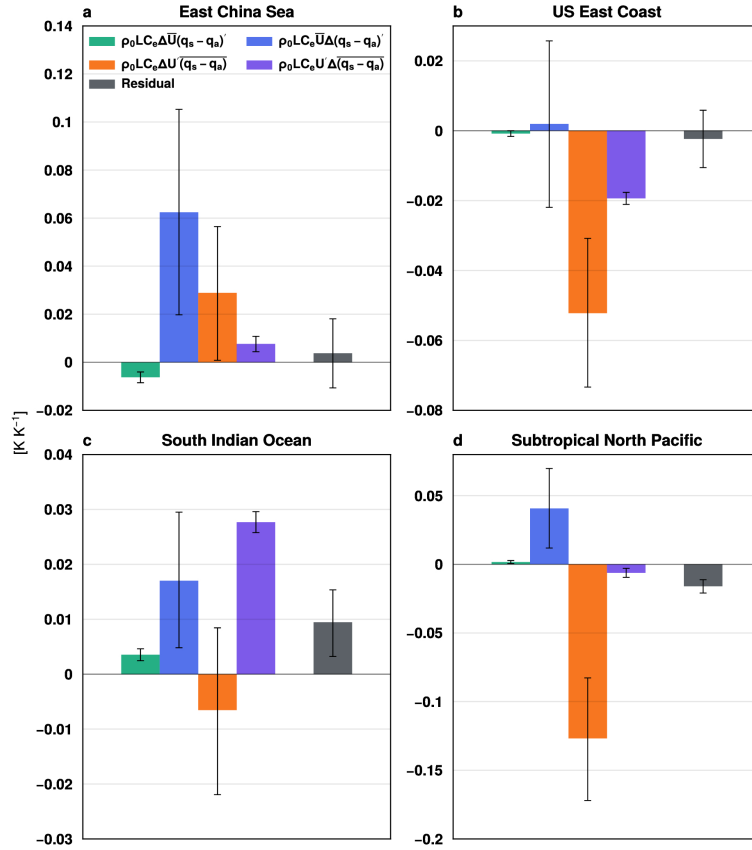
Supplementary Figure 6 | The changes in surface wind speed responses in each CMIP6 models. a-l The difference in absolute maximum of surface wind speed regressed onto December(0)-February(1) (D(0)JF(1)) Niño3.4 sea surface temperature anomaly from March-May(0) to June-August(1) between Present-day to 2085–2115.



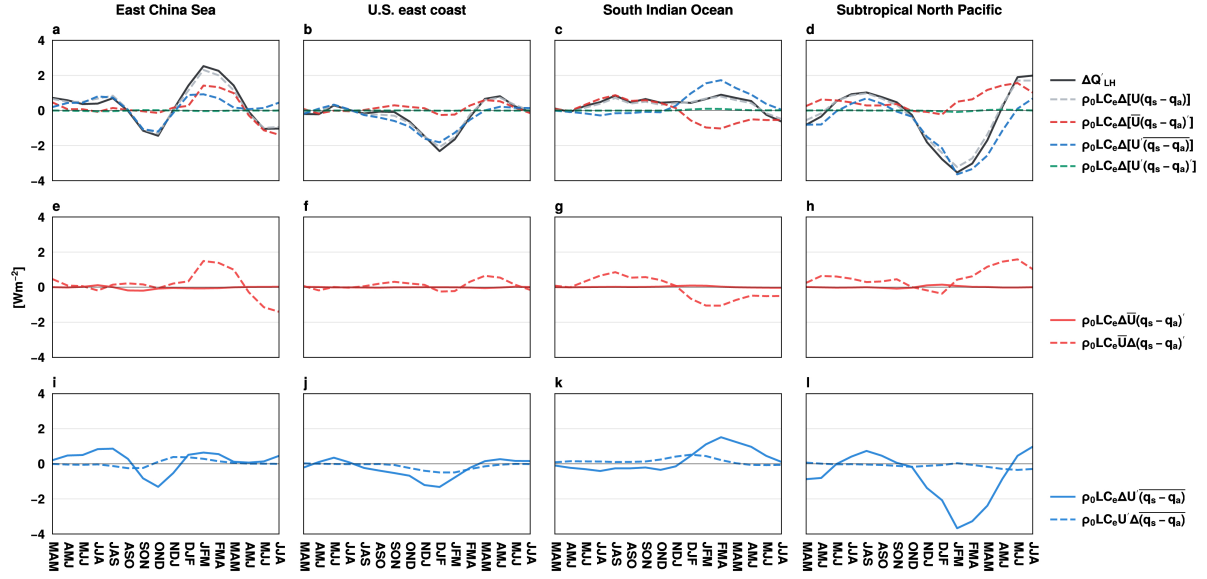
Supplementary Figure 7 | The changes in contributors of the global El Niño impacts on SST at each region. a, b, e and f Same as Figure 2b but the integrated term before multiplied by the sign of SST_{TOT} ($\Delta SST_{SFC+MLD}$, ΔSST_{SFC} , and ΔSST_{MLD}) and ΔSST_{TOT} is not absolute value (see Methods for details) for each region: **a** East China Sea (125°E–145°E, 20°N–35°N), **b** U.S. east coast (60°W–80°W, 25°N–40°N), **e** South Indian Ocean (50°E–90°E, 40°S–20°S), and **f** the subtropical North Pacific (150°E–165°W, 12°N–22°N). **c, d g and h** Same as Fig. 2c but but the integrated term before multiplied by the sign of SST_{TOT} for each region: **c** East China Sea, **d** U.S. east coast, **g** South Indian Ocean, and **h** the subtropical North Pacific rather than global mean. All error bars are calculated at the 95% confidence level.



Supplementary Figure 8 | The changes in El Niño-induced wind at each region. a-d Regression coefficient of January-March(1) (JFM(1)), but December(0)-February(1) (D(0)JF(1)) in **b**, 850 hPa geopotential height (shading; m K^{-1}) and wind (vector; $\text{m s}^{-1} \text{K}^{-1}$) onto D(0)JF(1) Niño3.4 sea surface temperature (SST) anomaly in based on Present-day (PD) simulation. **e-h** Changes in regression coefficient of JFM(1), but D(0)JF(1) in **f**, 850 hPa geopotential height (shading; m K^{-1}) and wind (vector; $\text{m s}^{-1} \text{K}^{-1}$) onto D(0)JF(1) Niño3.4 SST anomaly from PD to 2100. All figures show only statistically significant at the 95% confidence level using the bootstrap test.

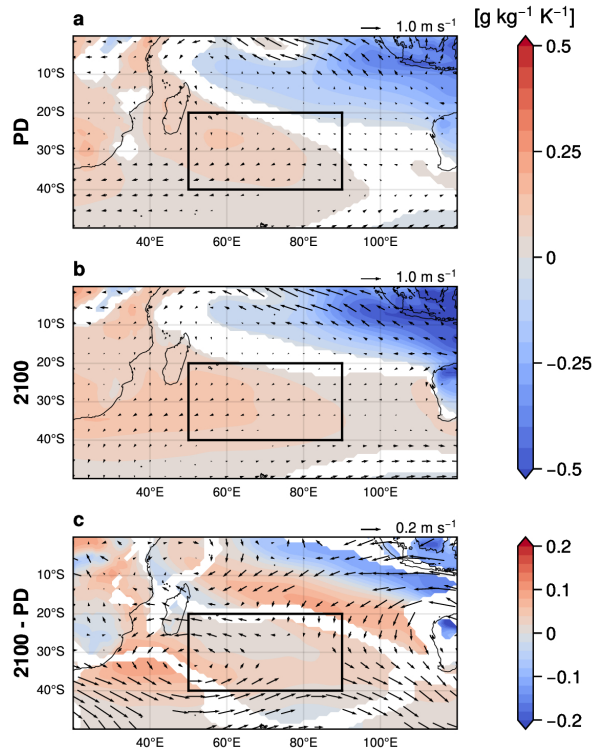


Supplementary Figure 9 | Decomposition of changes in ENSO related latent heat flux contribution to SST in four key regions. Panels show four regions: **a** East China Sea (125°E–145°E, 20°N–35°N), **b** U.S. east coast (60°W–80°W, 25°N–40°N), **c** South Indian Ocean (50°E–90°E, 40°S–20°S), and **d** the subtropical North Pacific (150°E–165°W, 12°N–22°N). Bars quantify the Present-day PD to 2085–2115 (2100) change in the contribution to El Niño–related latent heat flux-induced sea surface temperature; climatological wind speed (green), El Niño–induced specific-humidity gradient (blue), El Niño–induced wind speed (yellow), and climatological specific-humidity gradient (purple); the gray bar is the residual. Error bars denote 95% confidence intervals from bootstrap test.

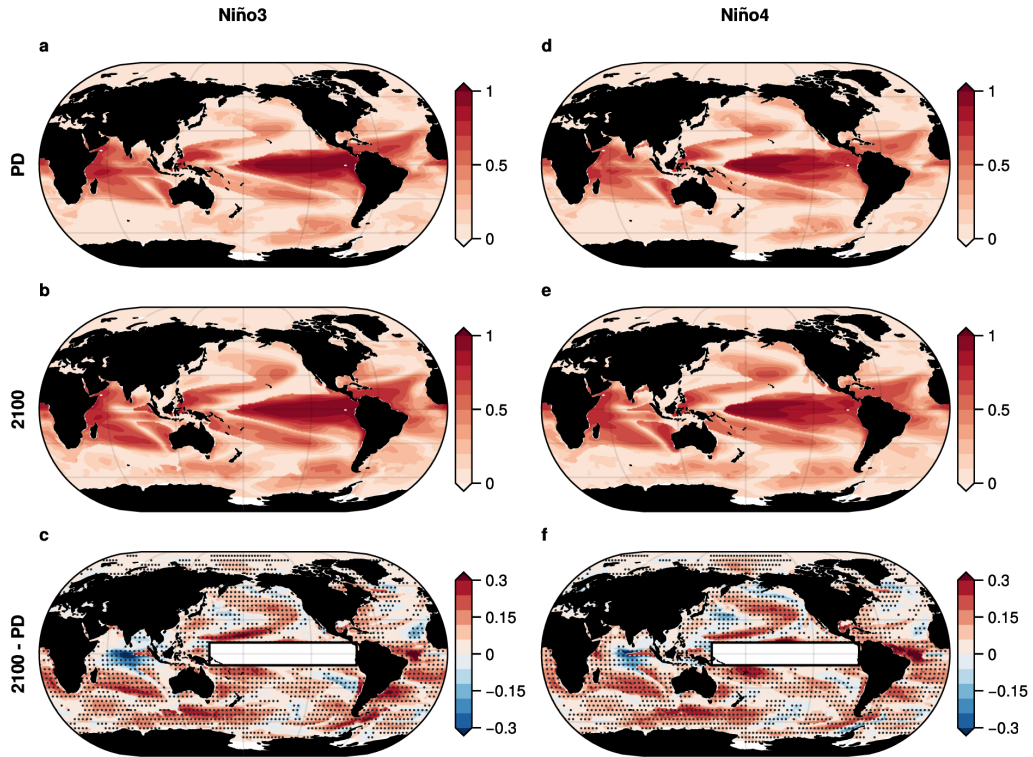


Supplementary Figure 10 | Time series of the changes in ENSO-induced latent heat flux.

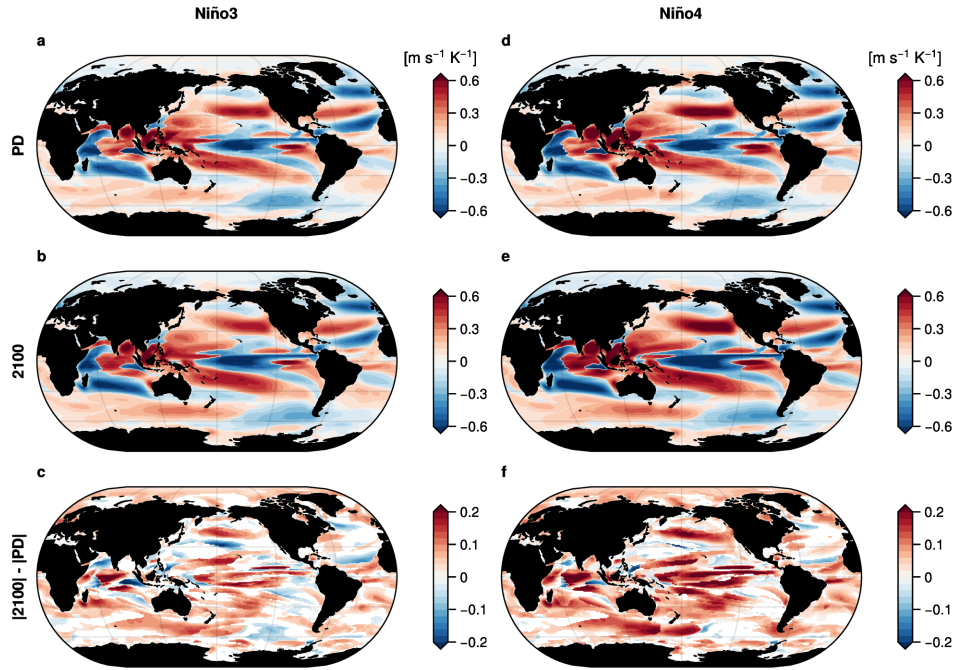
Seasonal evolution of the change in El Niño-Southern Oscillation (ENSO)-related latent heat flux anomalies from Present-day (PD) to 2085–2115 (2100) in CESM1 and its components for four regions: **a-d** East China Sea, U.S. East Coast, South Indian Ocean, and Subtropical North Pacific. The top row shows the total latent heat flux change (black) together with the reconstructed sum of components (gray dashed line). Red, blue, and green dashed line are each term of Eq. S4 (Supplementary Notes for details). **e-h** The middle row separates the two terms that contain the ENSO-driven humidity-gradient anomaly (solid line), and the change in the climatological wind speed (dashed line). **i-l** The bottom row separates the two terms that contain the ENSO-induced wind-speed (solid line) and the change in the climatological humidity difference (dashed line).



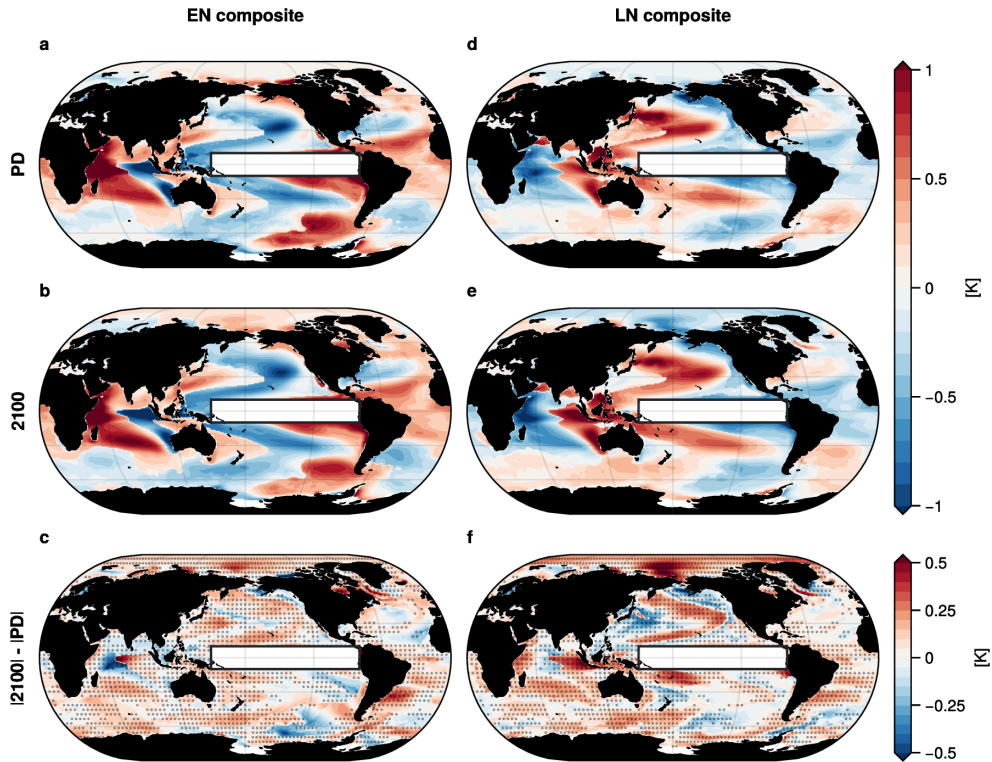
Supplementary Figure 11 | The change in surface specific humidity response to El Niño in SIO. a June-August(0) 10 m surface specific humidity (shade; $\text{g kg}^{-1} \text{K}^{-1}$) and 850 hPa wind (vector; $\text{m s}^{-1} \text{K}^{-1}$) regressed onto December(0)-February(1) Niño3.4 sea surface temperature anomaly in Present-day (PD) simulation with CESM1. **b** Same as **a** but in 2085–2115 (2100) of 1pctCO2 scenario. **c** The change in regression coefficient from PD to 2100. The black box indicates South Indian Ocean region (50°E – 90°E , 40°S – 20°S). All figures show only statistically significant at the 95% confidence level using the bootstrap test.



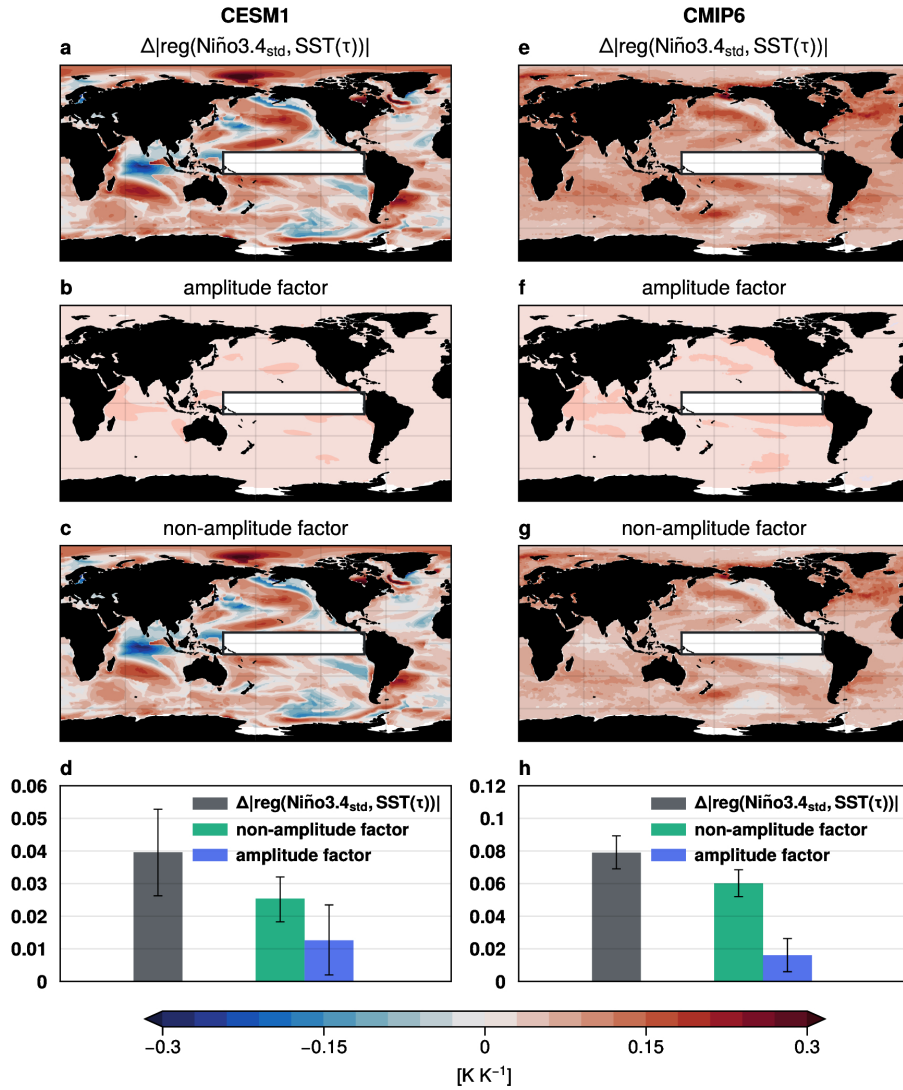
Supplementary Figure 12 | The changes in central Pacific and eastern Pacific El Niño impacts on remote SSTs. a-c and d-f Same as Figure 1a-c but explainable variance between sea surface temperature (SST) and December(0)-February(1) (D(0)JF(1)) Niño3 SST anomaly (left column, a-c) and Niño4 SST anomaly (right column, d-f) rather than Niño3.4. Stippling in c and f indicates regions that are statistically significant at the 95% confidence level using the bootstrap test.



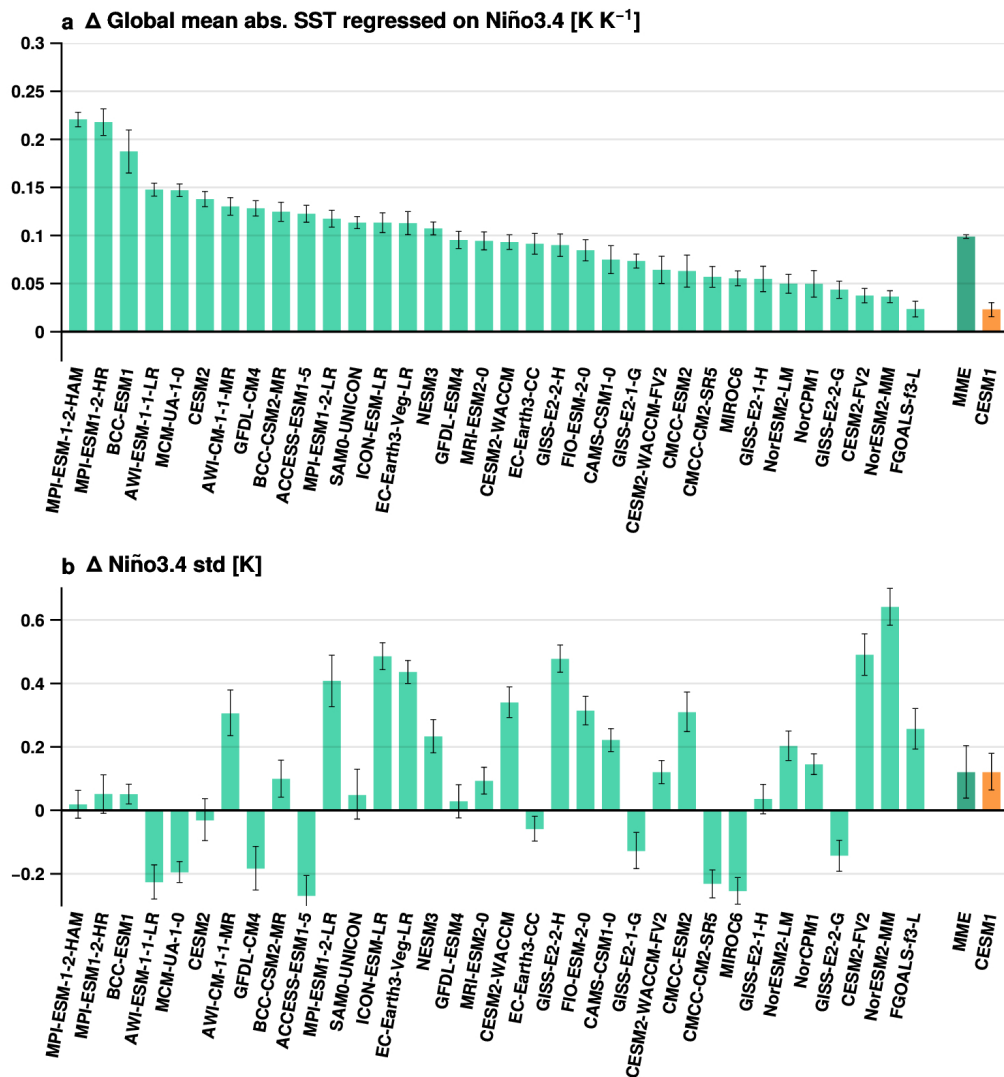
Supplementary Figure 13 | The changes in surface wind speed response to central Pacific and eastern Pacific El Niño. a-f Same as Figure 3a-c but surface wind speed regressed onto December(0)-February(1) Niño3 (left column; a-c) and Niño4 (right column; d-f) sea surface temperature anomaly rather than Niño3.4. **c** and **f** show only statistically significant at the 95% confidence level using the bootstrap test.



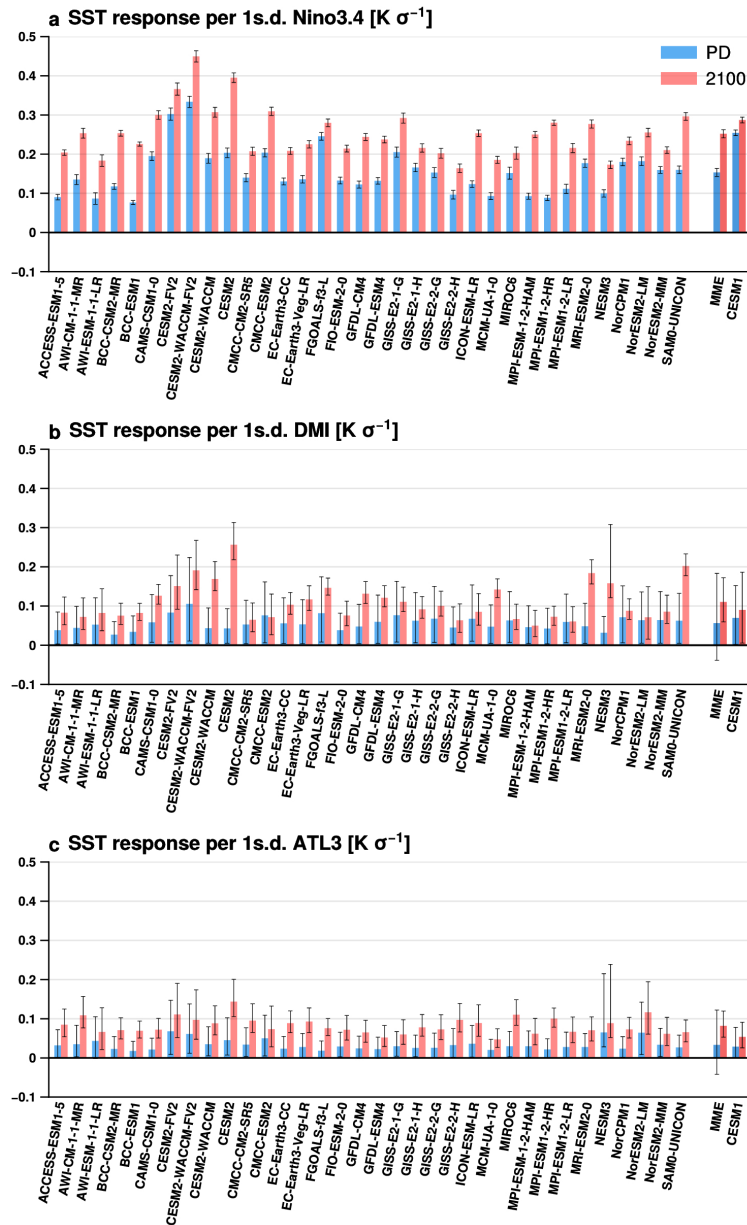
Supplementary Figure 14 | Changes in El Niño and La Niña impacts on SST. a-c El Niño composites for Present-day (PD), 2085–2115 (2100), and the change in absolute magnitude ($|2100| - |PD|$), taking the absolute maximum over the June-August(0) (JJA(0)) to JJA(1). **d-f** As in a-c but for La Niña. Stippling denotes regions where the change in absolute amplitude is statistically significant at the 95% confidence level using a bootstrap test. The white box marks the equatorial Pacific region to exclude El Niño-Southern Oscillation sea surface temperature itself.



Supplementary Figure 15 | Decomposition of the changes in ENSO impacts on SST. **a** The changes in absolute values of sea surface temperature anomaly(τ) (SSTA(τ)) regressed onto December(0)-February(1) (D(0)JF(1)) Niño3.4 SSTA from the Present-day (PD) period to 2085–2115 (2100). The contribution of **b** amplitude factor and **c** non-amplitude factor. **d** Global mean of (1) the changes in absolute values of SSTA(τ) regressed onto D(0)JF(1) Nino3.4 SSTA from the PD period to 2100, (2) non-amplitude factor, and (3) amplitude factor. **e-h** are as same as a-d (respectively) but CMIP6 multi-model mean. All error bars are calculated at the 95% confidence level.



Supplementary Figure 16 | The changes in El Niño impacts on SSTs and Niño3.4 amplitude. **a** Same as Supplementary Figure 2a. **b** Difference in standard deviation of December(0)-February(1) Niño3.4 sea surface temperature anomaly between pre-industrial and 31-year period after 100 years in 1pctCO2 scenario (model years 2085-2115). All error bars are calculated at the 95% confidence level.



Supplementary Figure 17 | Strengthening of SST response to tropical variability modes under warming. **a** Same as Supplementary Figure 2a but for response to 1 standard deviation of December(0)-February(1) (D(0)JF(1)) Niño3.4 SST anomaly. **b** Indian Ocean Dipole effect, defined as the difference between the present-day (PD) and 2085–2115 climates in the global mean absolute regression coefficient of SST anomalies onto the standardized Dipole mode index (DMI) at the lag of maximum correlation (from June-August(0) to D(0)JF(1)). **c** Same as b but for the tropical Atlantic, using the ATL3 index (20°W–0°, 2.5°S–2.5°N; from March-May(0) to September-November(0)). For each 34 CMIP6 model, multi-model mean (MME) and CESM1. All error bars are calculated at the 95% confidence level.