Supplementary Information for

Tropical eastern Pacific cooling trend reinforced by human activity

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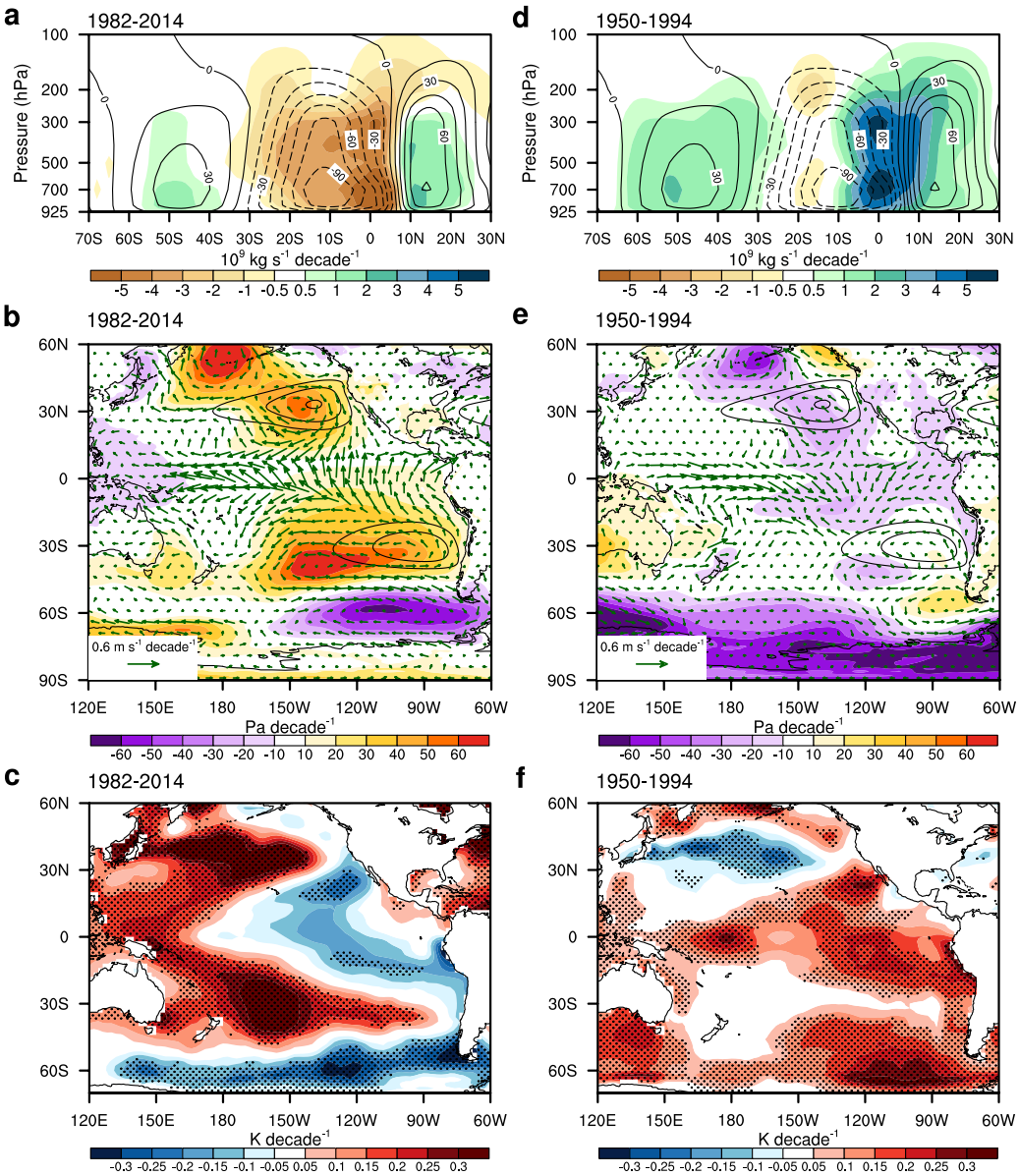
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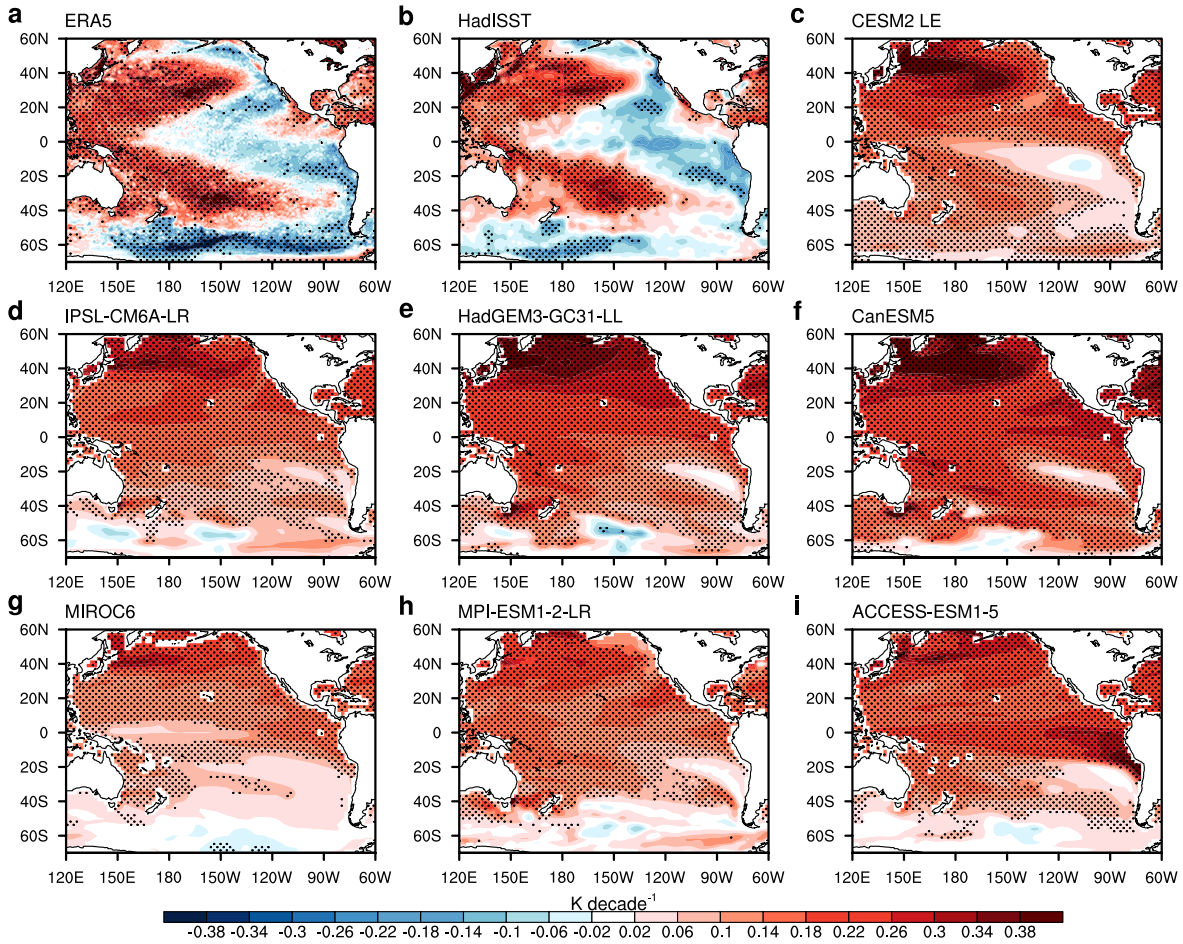
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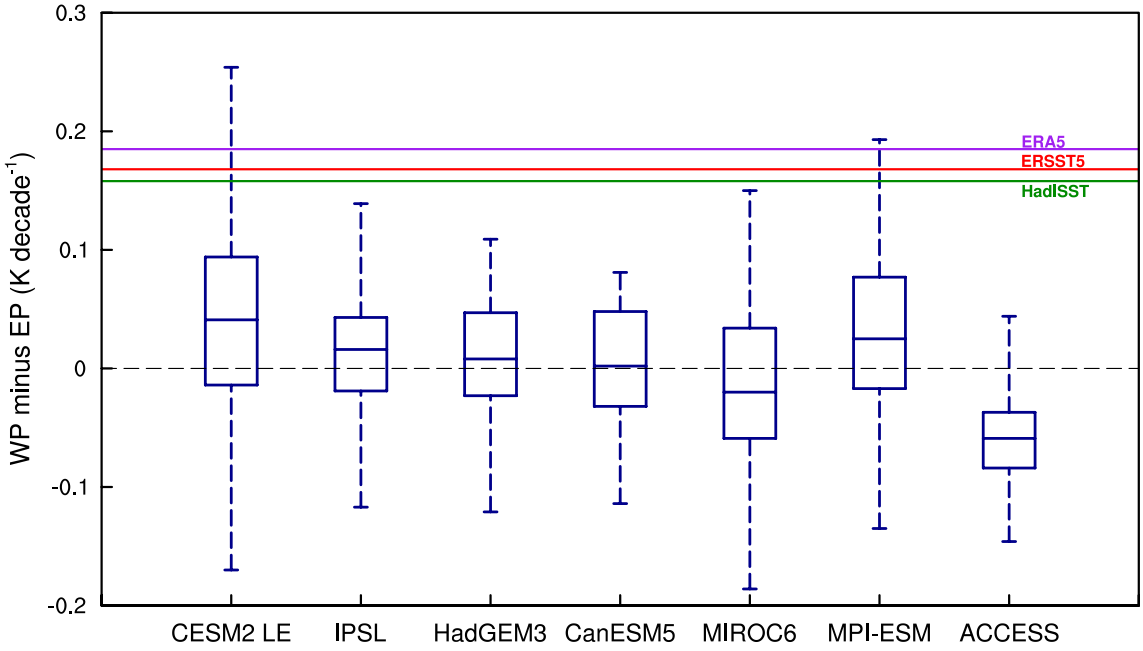
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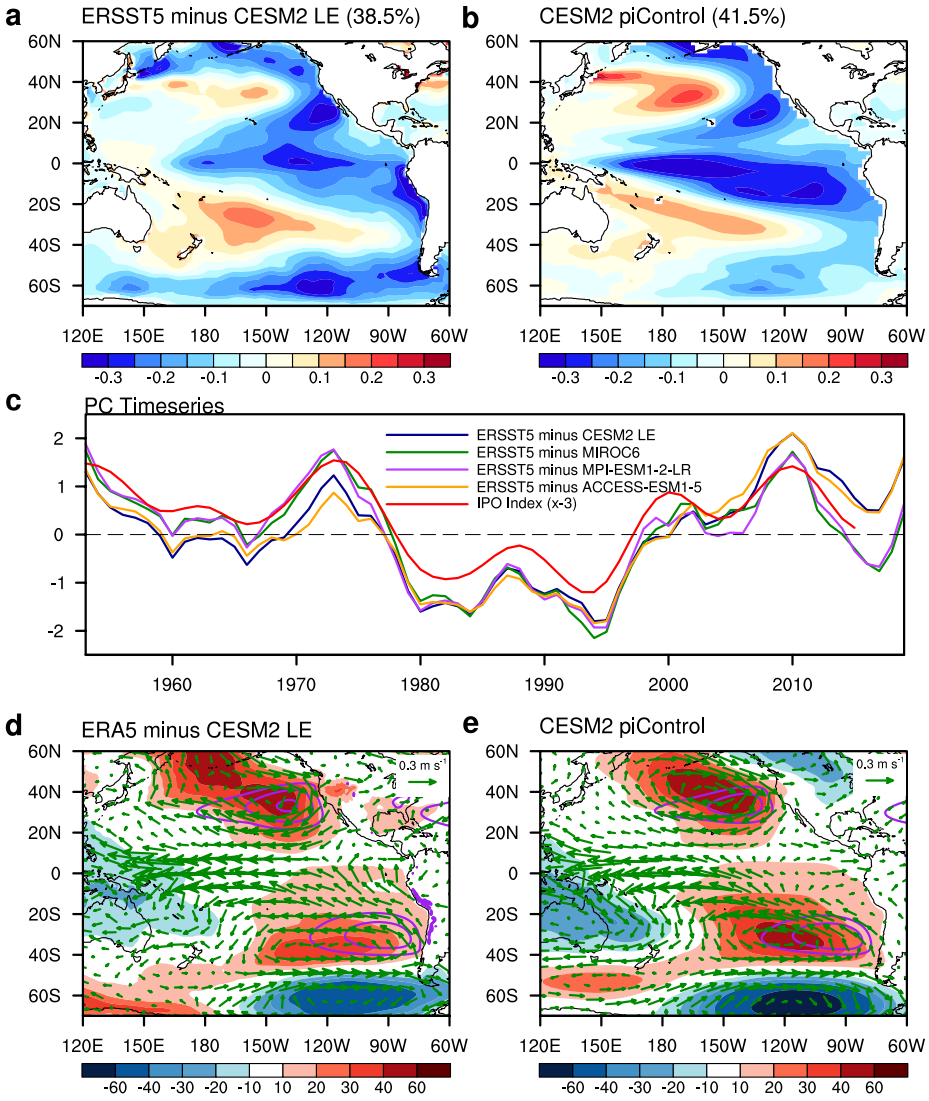
Supplementary Fig. 1: Sensitivity of the observed trends to analysis period. **a**, Annual-mean mass streamfunction trends over the period 1982–2014 from ERA5. Black contours represent the climatology over the period 1950–2014 (unit: 10^9 kg s^{-1}) with positive and negative values denoting clockwise and counter-clockwise circulation, respectively. **b**, Same as in **a**, but for trends in sea level pressure (shading) and surface winds (vectors). **c**, Same as in **a**, but for ERSST5 SST trends with stippling indicating statistical significance of the computed trends at the 95% confidence level. **d-f**, Same as in **a-c**, but over the period 1950–1994. In **b** and **e**, contours in black represent the climatological high-pressure regions.



Supplementary Fig. 2: Model-observation discrepancy in SST trends. **a**,**b**, Observed SST trends over the period 1979–2010 from ERA5 (**a**) and HadISST (**b**), with stippling indicating statistical significance of the computed trends at the 95% confidence level. **c-i**, Ensemble-mean SST trends over the same period for the CESM2 LE (**c**), IPSL-CM6A-LR (**d**), HadGEM3-GC31-LL (**e**), CanESM5 (**f**), MIROC6 (**g**), MPI-ESM1-2-LR (**h**), and ACCESS-ESM1-5 (**i**), with stippling denoting regions where more than 70% of the ensemble members exhibit the same sign.

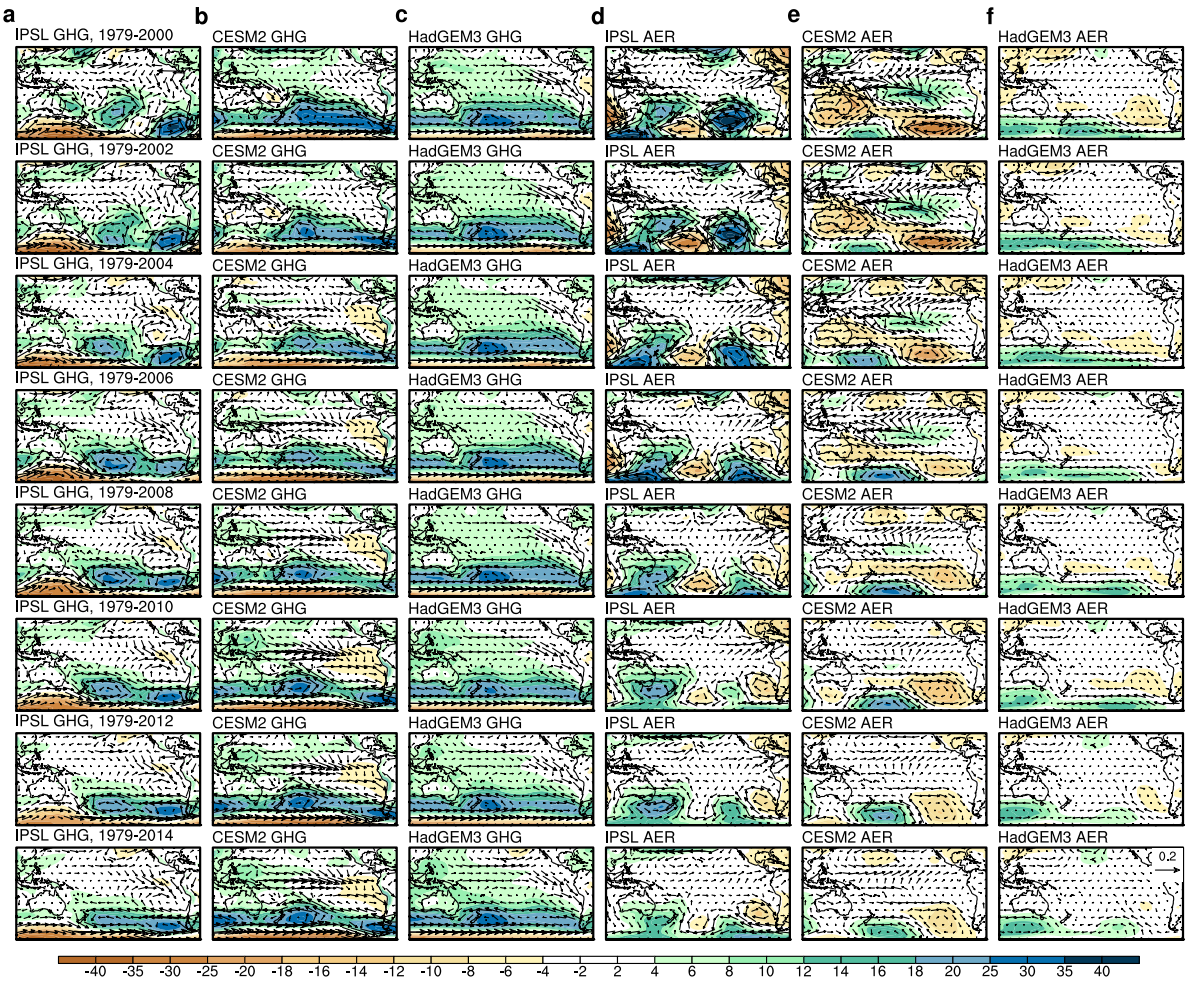


Supplementary Fig. 3: Observed and model-simulated changes in the tropical Pacific zonal SST gradient over the period 1979–2010, with the zonal SST gradient defined as the SST difference between the western Pacific (10ºS-10ºN, 110ºE-180º) and the eastern Pacific (10ºS-10ºN, 180º-80ºW). Boxes cover the inter-quartile range of trends for large ensemble model simulations with the line inside the box representing the ensemble-mean of a given model (i.e., CESM2 LE, IPSL-CM6A-LR, HadGEM3-GC31-LL, CanESM5, MIROC6, MPI-ESM1-2-LR, and ACCESS-ESM1-5) and whiskers denoting the entire inter-ensemble range. Horizontal lines denote the observed trends estimated from ERSST5 (red), HadISST (green), and ERA5 (purple).

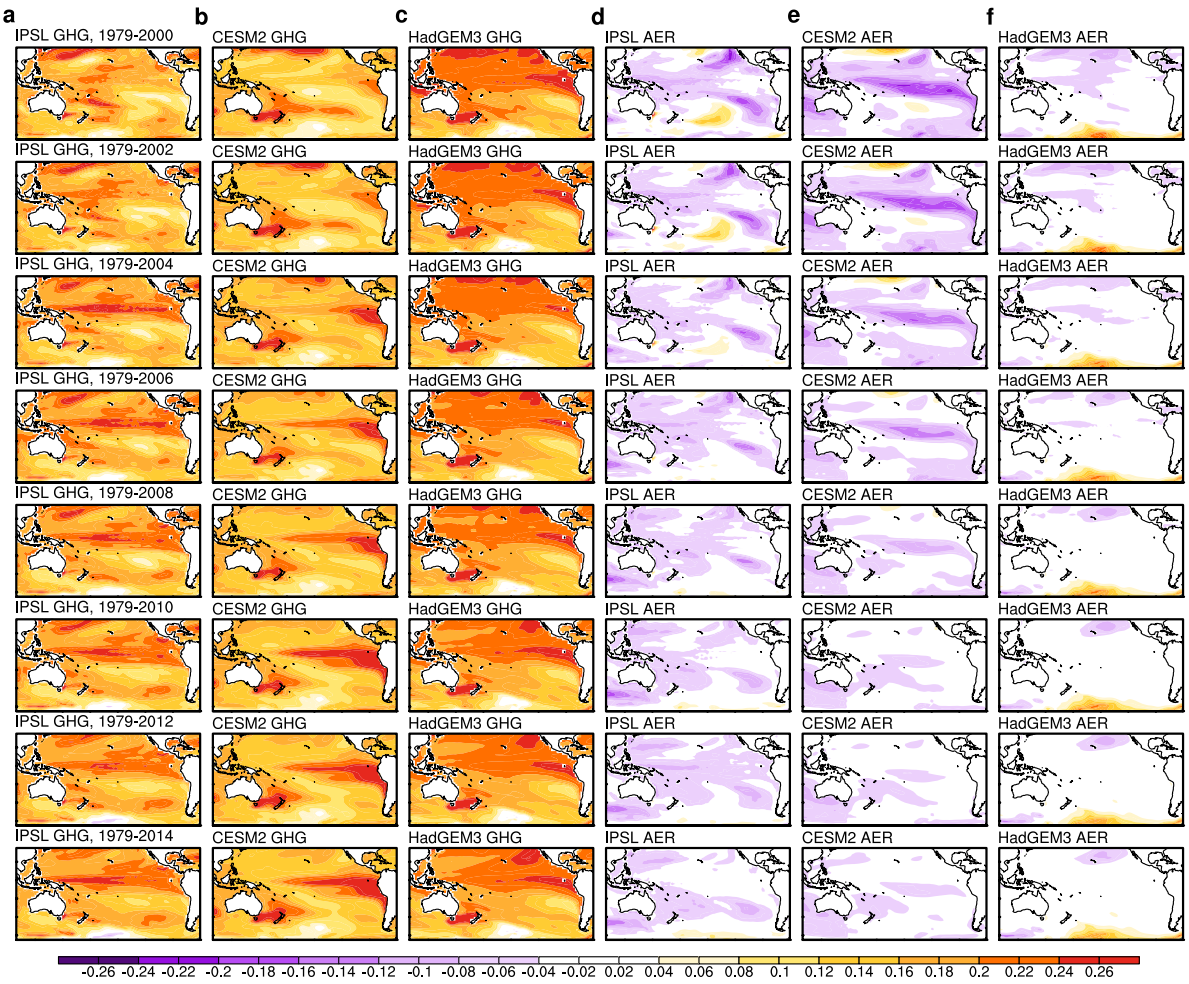


Supplementary Fig. 4: Potential role of internal climate variability in La Niña-like SST trend pattern. **a**, Spatial pattern of the first EOF mode analyzed in the Pacific (70ºS-60ºN, 120ºE-60ºW) for the 7-yr running-mean difference between ERSST5 and the CESM2 LE ensemble mean in annual-mean SST anomaly relative to the 1950–2022 means. **b**, Same as in **a**, but for an EOF analysis with 7-yr running-mean, annual-mean SST anomaly from CESM2 pre-industrial control simulation. **c**, Time series of the standardized PC values corresponding to the first EOF mode shown in **a**. Also presented are PC time series computed with the ensemble-mean SST anomaly of MIROC6, MPI-ESM1-2-LR, and ACCESS-ESM1-5 along with ERSST5. The red line denotes the observed time series of low-pass filtered IPO index multiplied by -3. **d**, 7-yr running-mean differences between ERA5 and the CESM2 LE ensemble mean in annual-mean sea level pressure (shading) and 850-hPa wind (vectors) anomalies regressed onto the standardized PC1 shown in **c**. **e**, 7-yr running-mean annual-mean sea level pressure (shading) and 850-hPa wind (vectors) anomalies regressed onto the

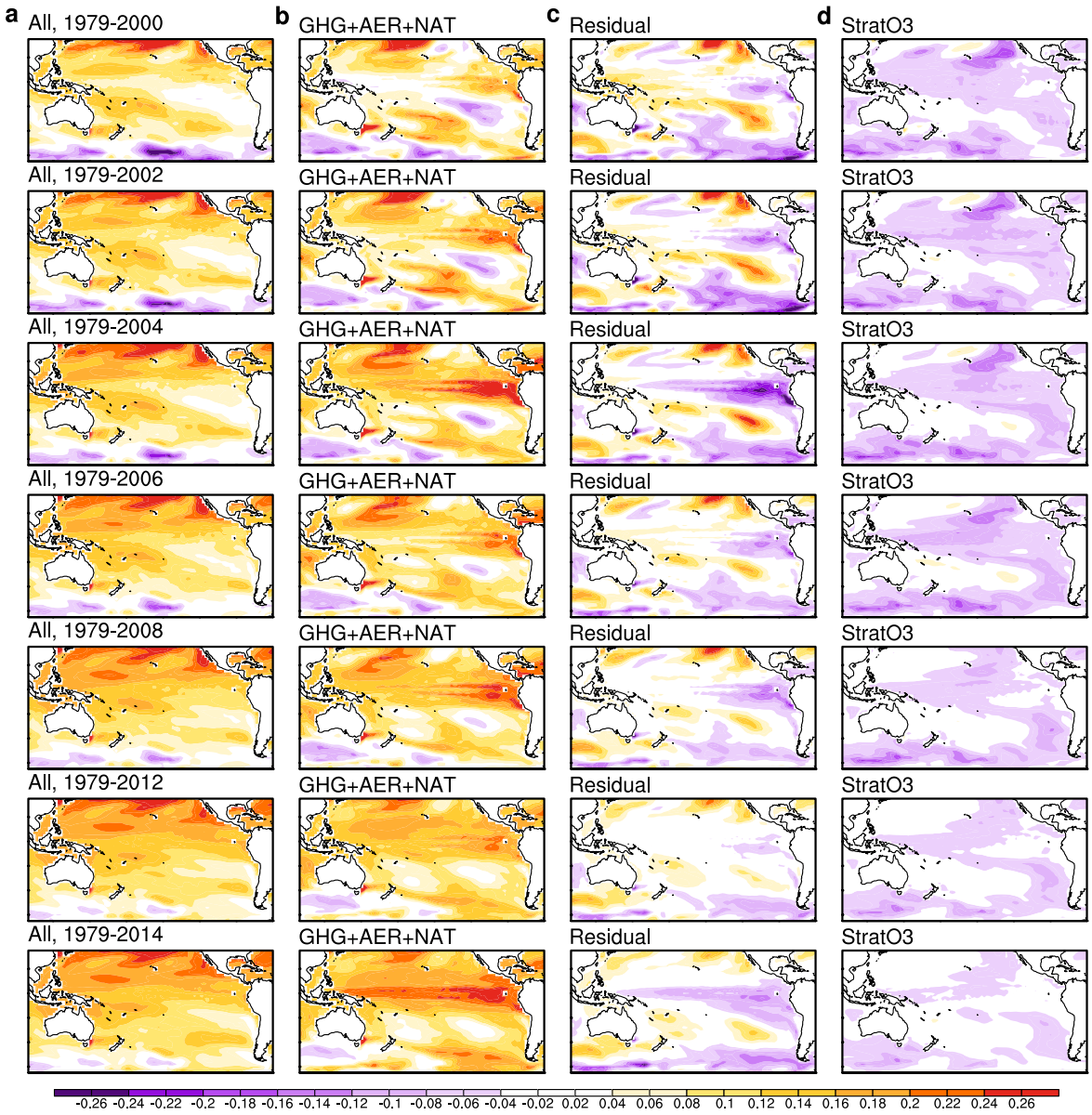
standardized PC1 for CESM2 pre-industrial control simulation. Contours in purple represent the climatological high-pressure regions in observation (**d**) and in the CESM2 pre-industrial control simulation (**e**).



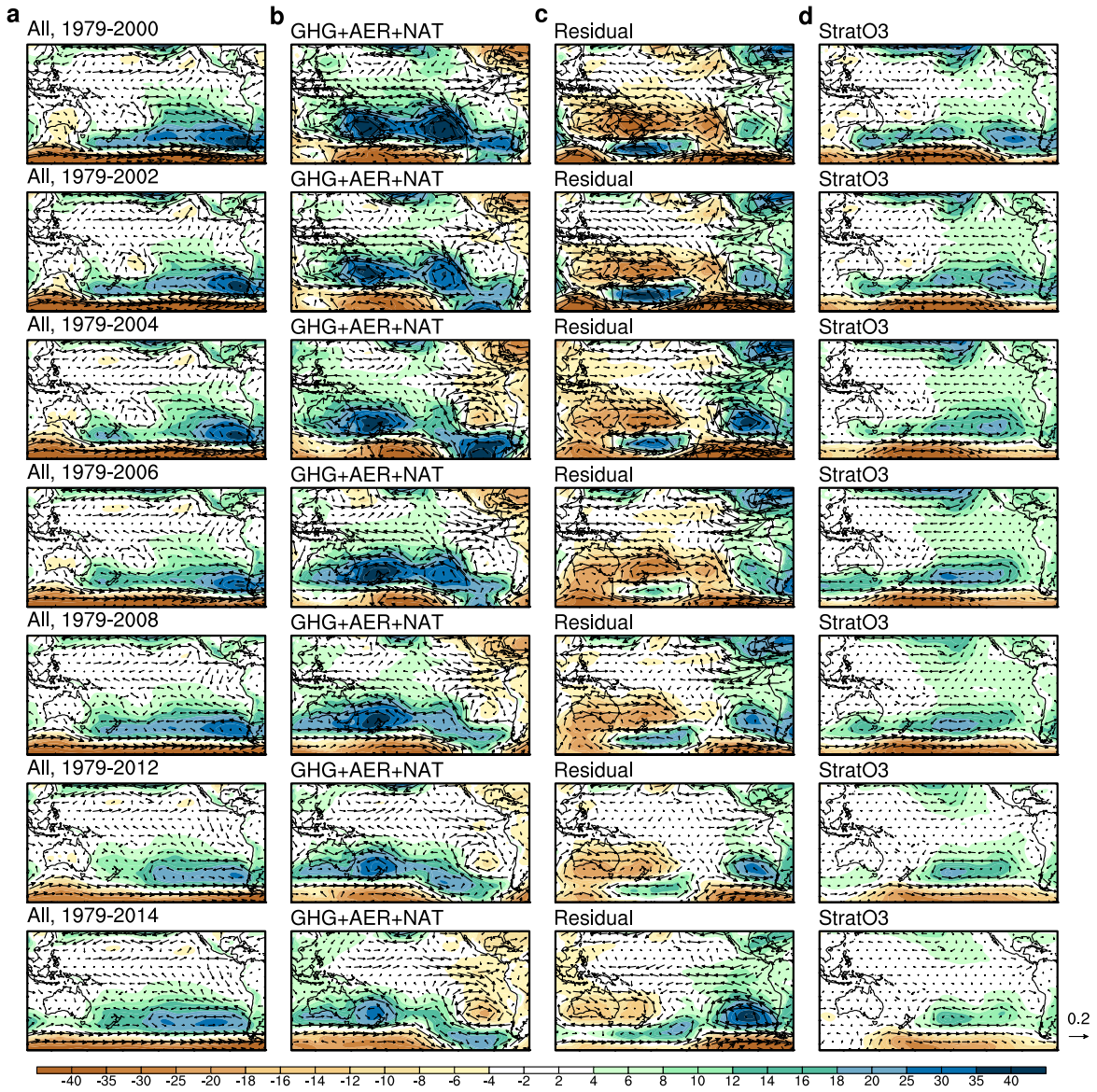
Supplementary Fig. 5: Impact of external forcing agents on atmospheric circulation over the Pacific. **a**, Ensemble-mean trends for sea level pressure (shading, unit: Pa decade^{-1}) and 850-hPa winds (vectors, unit: m s^{-1} decade^{-1}) over various periods for IPSL-CM6A-LR under greenhouse gas-only scenario. **b**, Same as in **a**, but for the CESM2 Single Forcing Large Ensemble Project. **c**, Same as in **a**, but for HadGEM3-GC31-LL. **d**-**f**, Same as in **a**-**c**, but for anthropogenic aerosol-only experiment.



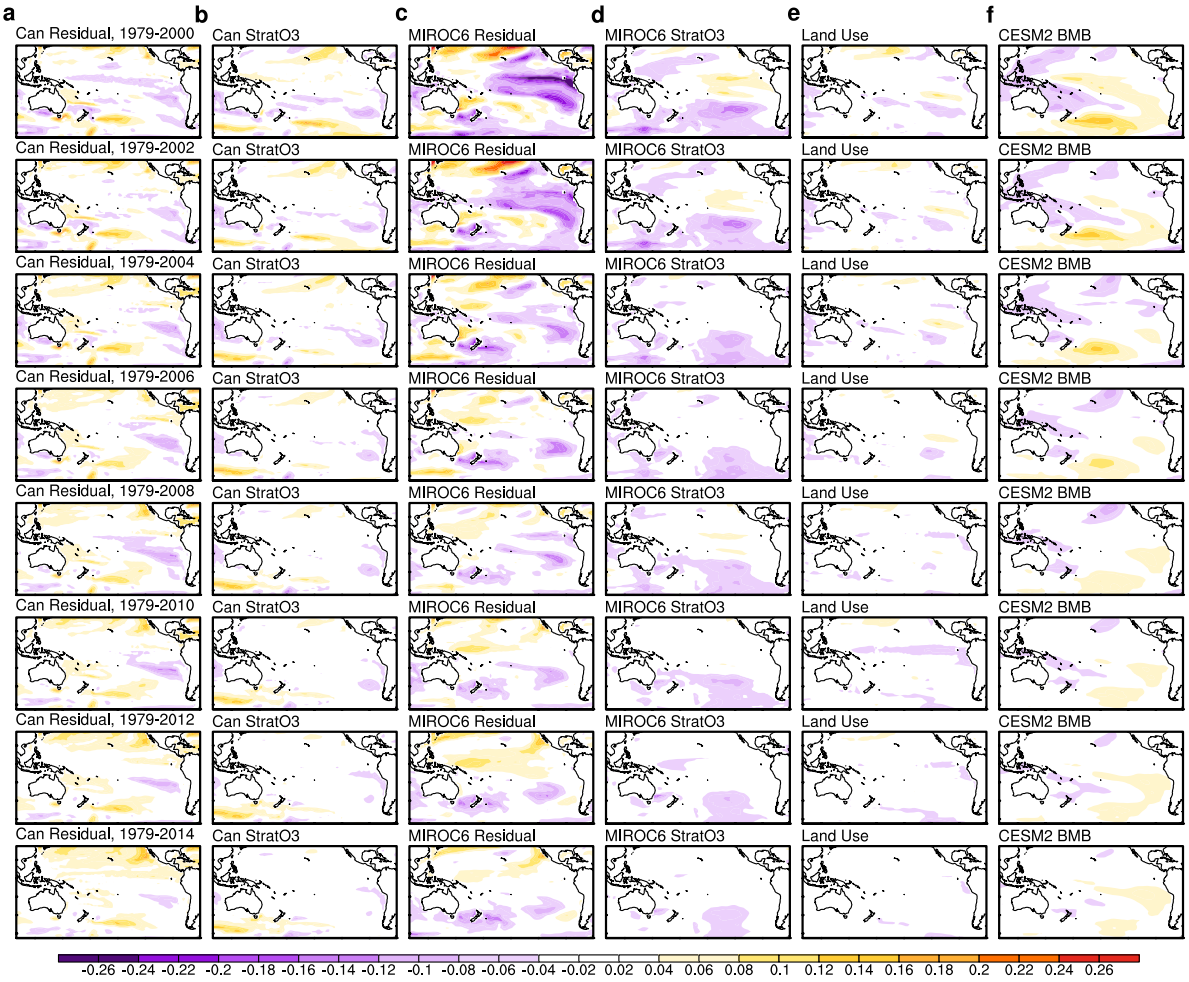
Supplementary Fig. 6: Impact of external forcing agents on SST over the Pacific. **a**, Ensemble-mean SST trends (unit: K decade^{-1}) over various periods for IPSL-CM6A-LR under greenhouse gas-only scenario. **b**, Same as in **a**, but for the CESM2 Single Forcing Large Ensemble Project. **c**, Same as in **a**, but for HadGEM3-GC31-LL. **d**-**f**, Same as in **a**-**c**, but for anthropogenic aerosol-only experiment.



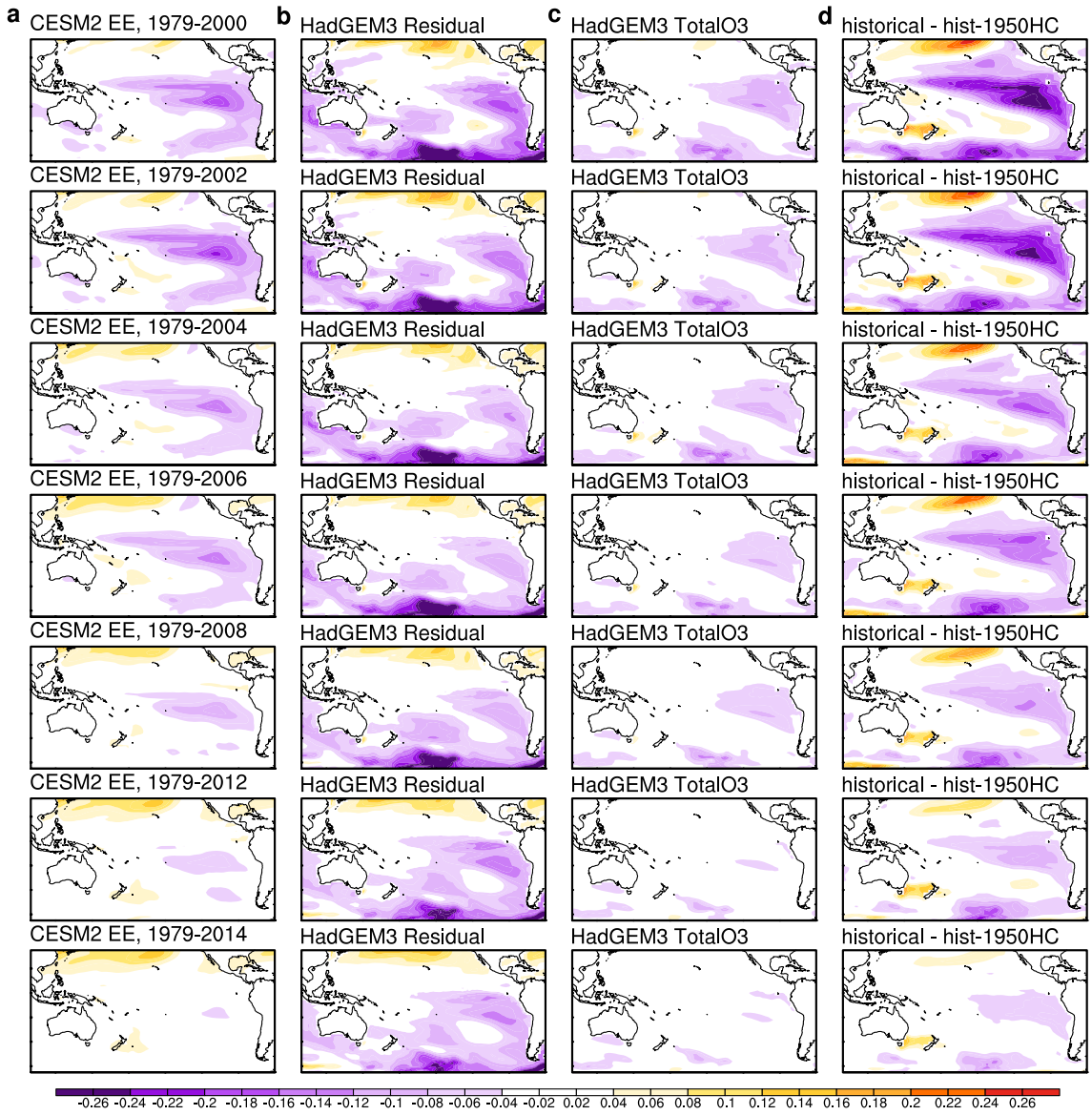
Supplementary Fig. 7: Impact of stratospheric ozone forcing on SST over the Pacific. **a**, Ensemble-mean SST trends (unit: K decade^{-1}) over various periods for IPSL-CM6A-LR in response to all forcing agents. **b**, Same as in **a**, but for the sum of SST trends for the corresponding greenhouse gas-only (GHG), anthropogenic aerosol-only (AER) and natural forcing-only (NAT) experiments. **c**, Difference between **a** and **b**. **d**, Same as in **a**, but for the corresponding stratospheric ozone-only (StratO3) experiment.



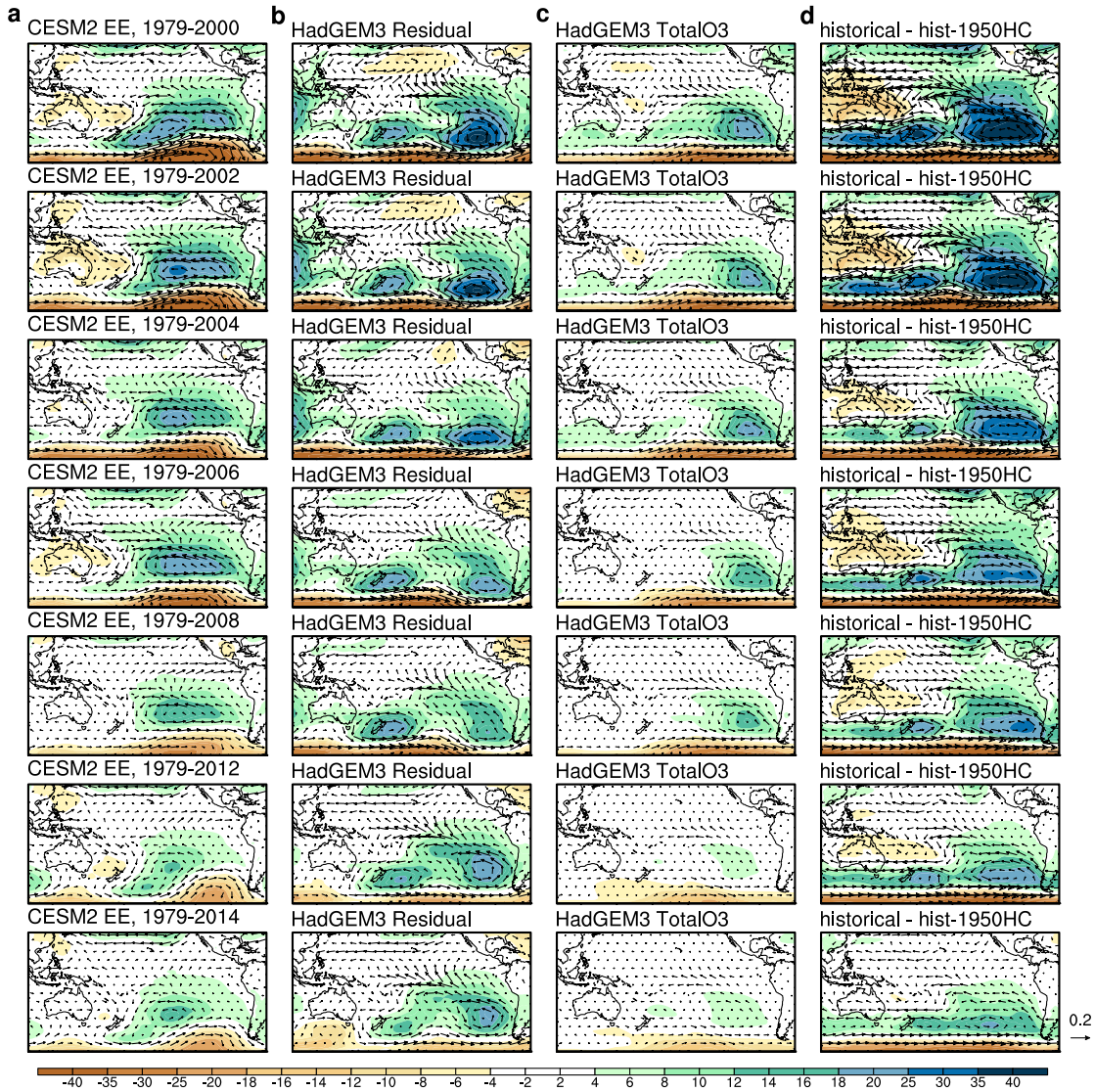
Supplementary Fig. 8: Impact of stratospheric ozone forcing on atmospheric circulation over the Pacific. **a**, Ensemble-mean trends for sea level pressure (shading, unit: Pa decade^{-1}) and 850-hPa winds (vectors, unit: m s^{-1} decade^{-1}) over various periods for IPSL-CM6A-LR in response to all forcing agents. **b**, Same as in **a**, but for the sum of the trends for the corresponding greenhouse gas-only (GHG), anthropogenic aerosol-only (AER) and natural forcing-only (NAT) experiments. **c**, Differences between **a** and **b**. **d**, Same as in **a**, but for the corresponding stratospheric ozone-only (StratO3) experiment.



Supplementary Fig. 9: Impact of external forcing agents on SST over the Pacific. **a**, Ensemble-mean difference in SST trend (unit: K decade^{-1}) over various periods between the all-forcing experiment and the sum of the corresponding greenhouse gas-only, anthropogenic aerosol-only and natural forcing-only simulations for CanESM5. **b**, Similar to **a**, but for stratospheric ozone-only experiment. **c**,**d**, Same as in **a** and **b**, but for MIROC6. **e**, Similar to **a**, but for the multi-model, multi-ensemble-mean SST trend difference between the historical and hist-noLu simulations, which represents the impact of land-use changes. **f**, Same as in **b**, but for the CESM2 Single Forcing Large Ensemble Project BMB (biomass burning emission) experiment.



Supplementary Fig. 10: Potential role of the stratospheric ozone depletion in a cooling trend over the tropical eastern Pacific. **a**, Ensemble-mean SST trends (unit: K decade^{-1}) over various periods for the CESM2 Single Forcing Large Ensemble Project EE (everything else except for greenhouse gases, anthropogenic aerosols and biomass burning emissions) experiment. **b**, Similar to **a**, but for the SST trend difference between the all-forcing experiment and the sum of the corresponding greenhouse gas-only, anthropogenic aerosol-only and natural forcing-only simulations for HadGEM3-GC31-LL. **c**, Same as in **a**, but for the HadGEM3-GC31-LL total (tropospheric plus stratospheric) ozone forcing-only experiment. **d**, Similar to **a**, but for the multi-model, multi-ensemble SST trend difference between the historical and hist-1950HC simulations, which represents the impact of time-varying ozone depleting substances and resultant stratospheric ozone concentration changes.



Supplementary Fig. 11: Potential role of the stratospheric ozone depletion in a strengthening of the Pacific trade winds. **a**, Ensemble-mean trends for sea level pressure (shading, unit: Pa decade^{-1}) and 850-hPa winds (shading, unit: m s^{-1} decade^{-1}) over various periods for the CESM2 Single Forcing Large Ensemble Project EE (everything else except for greenhouse gases, anthropogenic aerosols and biomass burning emissions) experiment. **b**, Similar to **a**, but for the trend differences between the all-forcing experiment and the sum of the corresponding greenhouse gas-only, anthropogenic aerosol-only and natural forcing-only simulations for HadGEM3-GC31-LL. **c**, Same as in **a**, but for the HadGEM3-GC31-LL total (tropospheric plus stratospheric) ozone forcing-only experiment. **d**, Similar to **a**, but for the multi-model, multi-ensemble trend differences between the historical and hist-1950HC simulations, which represent the impact of time-varying ozone depleting substances and resultant stratospheric ozone concentration changes.

Supplementary Table 1: Information on the model simulations analyzed in this study. Numerals indicate the number of ensemble members for a given forcing scenario.

Scenario / Model	historical (historical + SSP370 or SSP245)	hist-GHG or GHG	hist-aer or AAER	hist-nat	historical & hist-noLu	hist-stratO3 or hist-totalO3	historical & hist-1950HC	EE (BMB)
ACCESS-ESM1-5	(40)				10			
BCC-CSM2-MR					1			
CanESM5	50 (50)	50	30	50	10	10		
CESM2					3			
CESM2 LE	50 (50)	15	20					15 (15)
CESM2-WACCM							1	
CMCC-ESM2					1			
CNRM-ESM2-1					3		2	
GISS-E2-1-G							5	
HadGEM3-GC31-LL	50 (50)	50	50	50		50		
IPSL-CM6A-LR	33 (11)	10	10	10	4	10		
MIROC-ES2L					1			
MIROC6	50 (50)	50	10	50		10		
MPI-ESM1-2-LR	(30)				1			
MRI-ESM2-0							6	
NorESM2-LM					1			
UKESM1-0-LL					4		3	