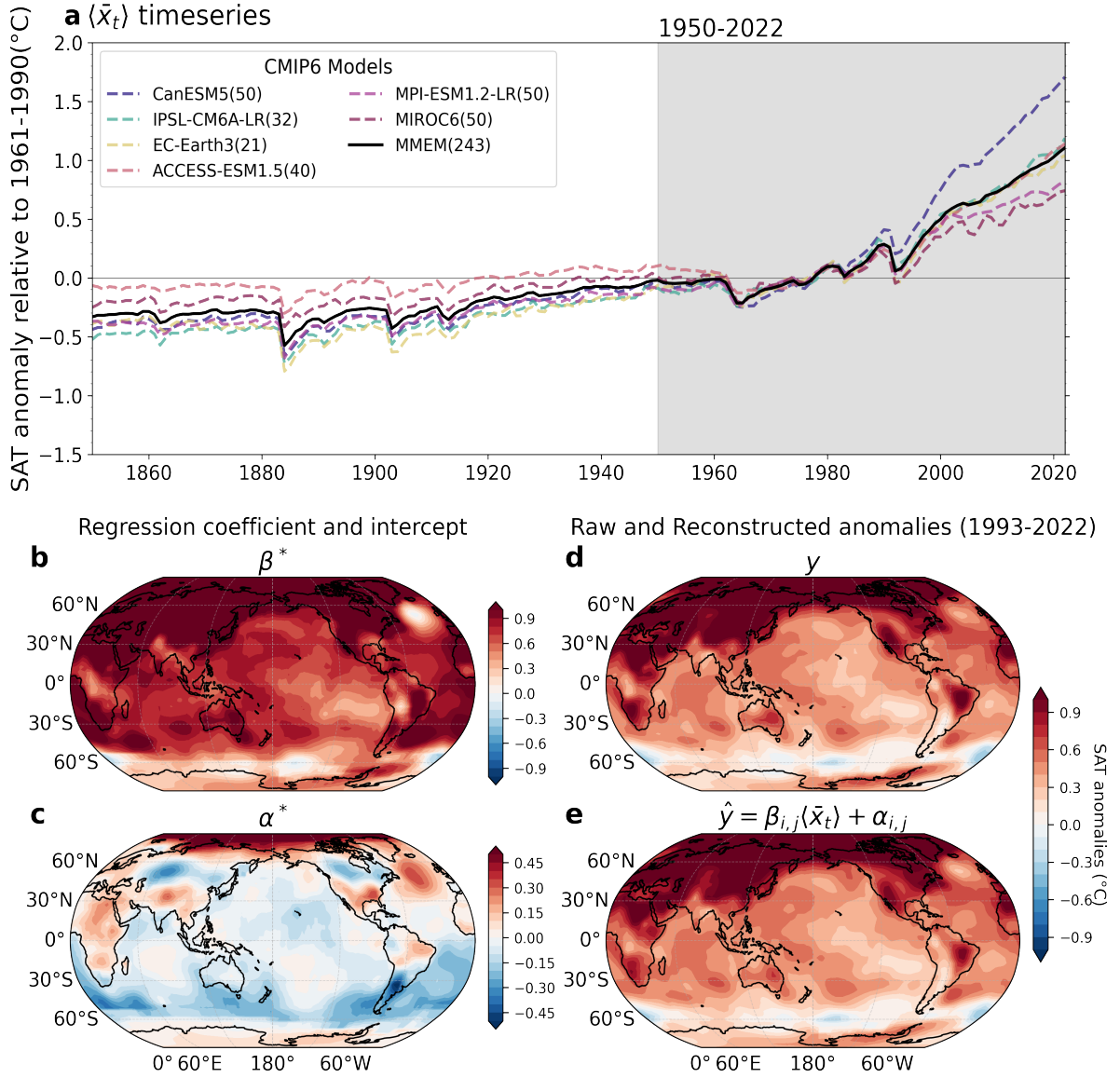


Supplementary Information:

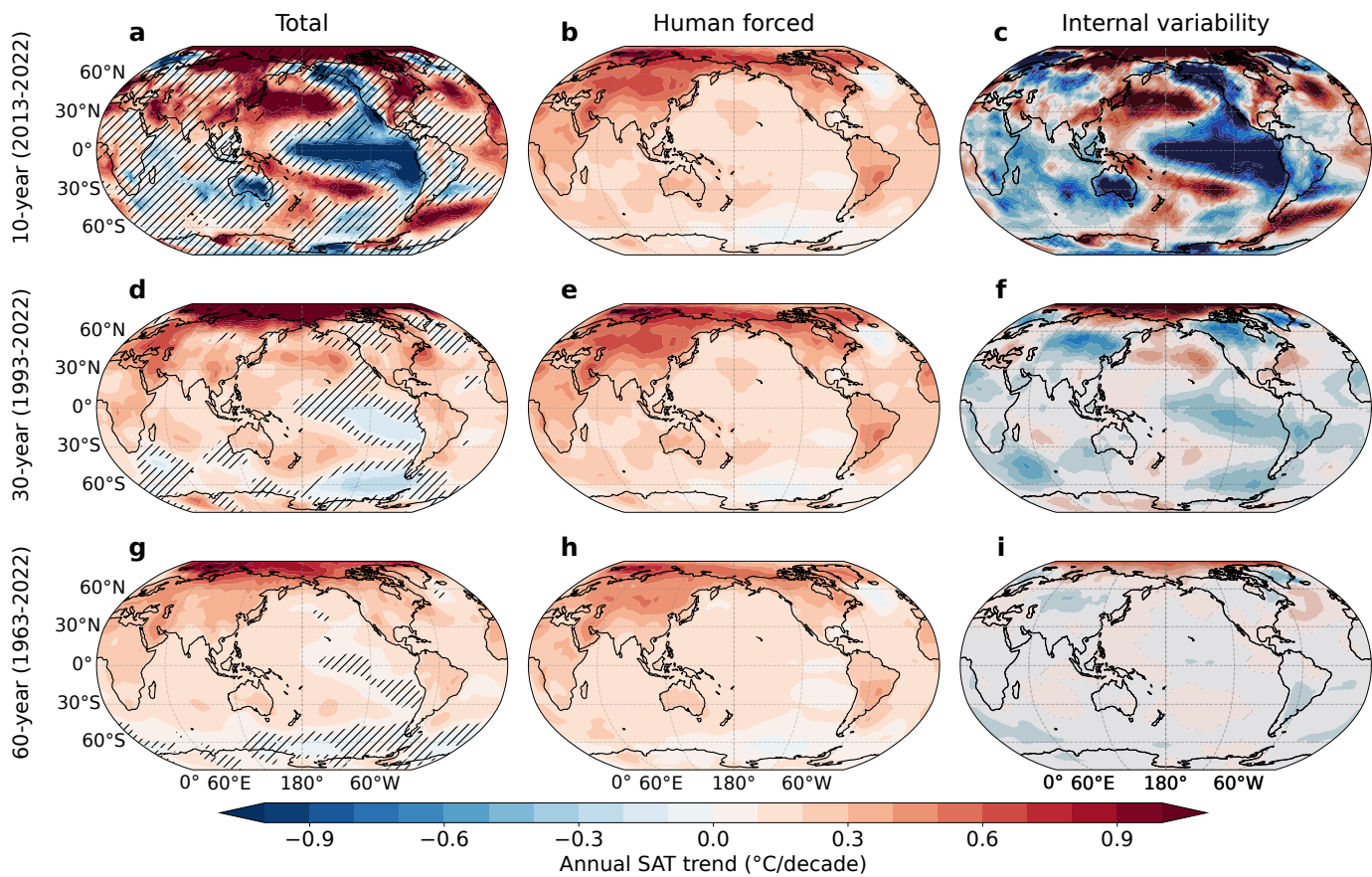
¹ **Observed fingerprint of global warming**

² Hasi Aru¹⁺, Dirk Olonscheck¹, Jochem Marotzke¹, Chao Li¹⁺

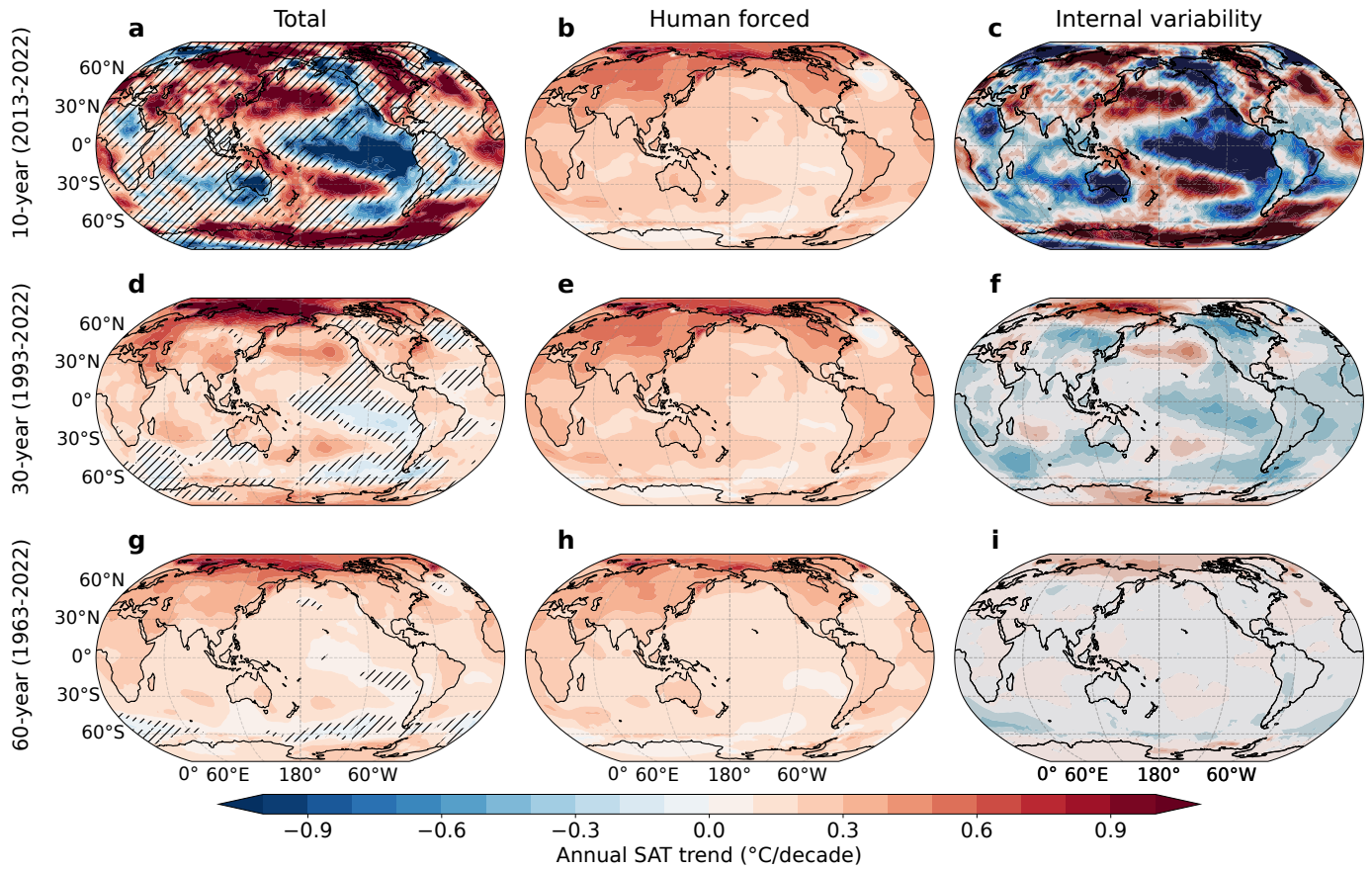
³ ¹*Max Planck Institute for Meteorology, Hamburg, Germany*



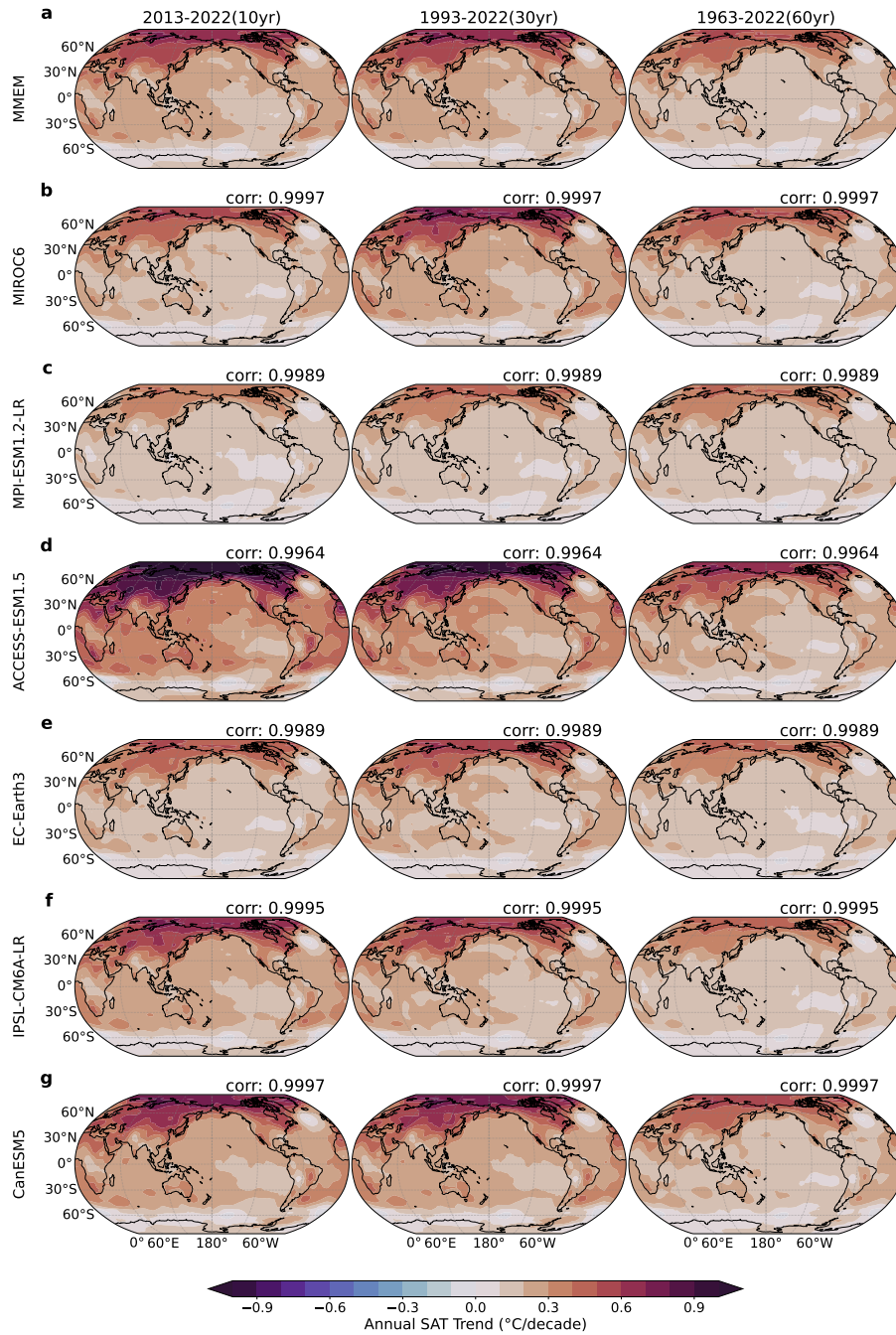
Extended Data Fig.1|Illustration of the methodology employed in this study. **a**, Time series of globally averaged annual mean SAT anomalies from 1850 to 2022, as represented by the MMEM and individual trajectory from large ensembles, each depicted with distinct colored lines. Spatial patterns of **b**, anthropogenic fingerprint and **c**, regression intercepts for observational annual mean SAT anomalies (1850-2022) relative to the MMEM globally averaged annual mean SAT time series $\langle \bar{x}_t \rangle$. Spatial patterns of **d**, raw observational and **e**, reconstructed SAT annual mean anomalies for the period 1993-2022.



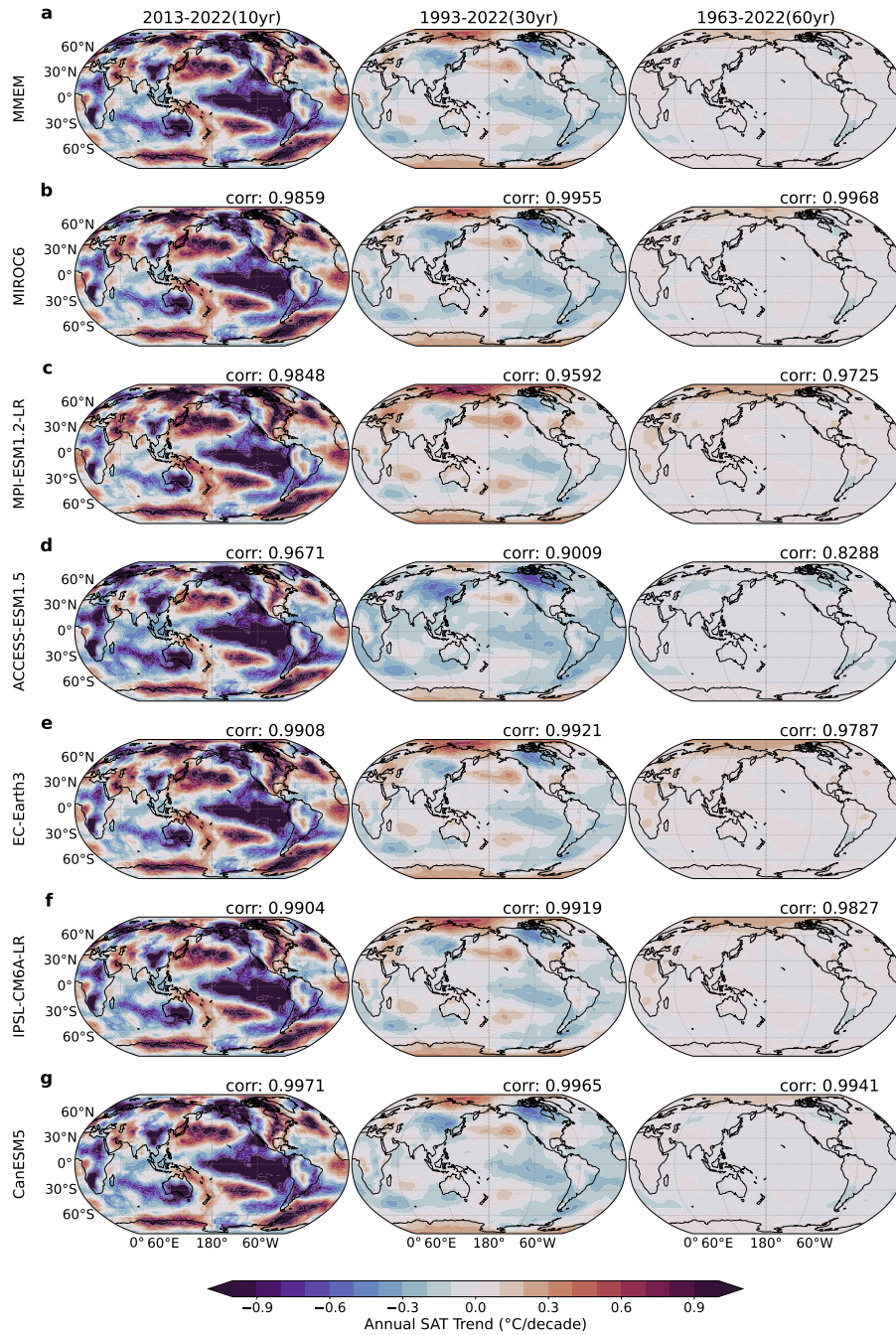
Extended Data Fig.2|Partitioning of observed SAT trend patterns to human forcing and internal variability. This figure follows the same methodology as Fig. 1, but is based on the NOAA GlobalTemp data.



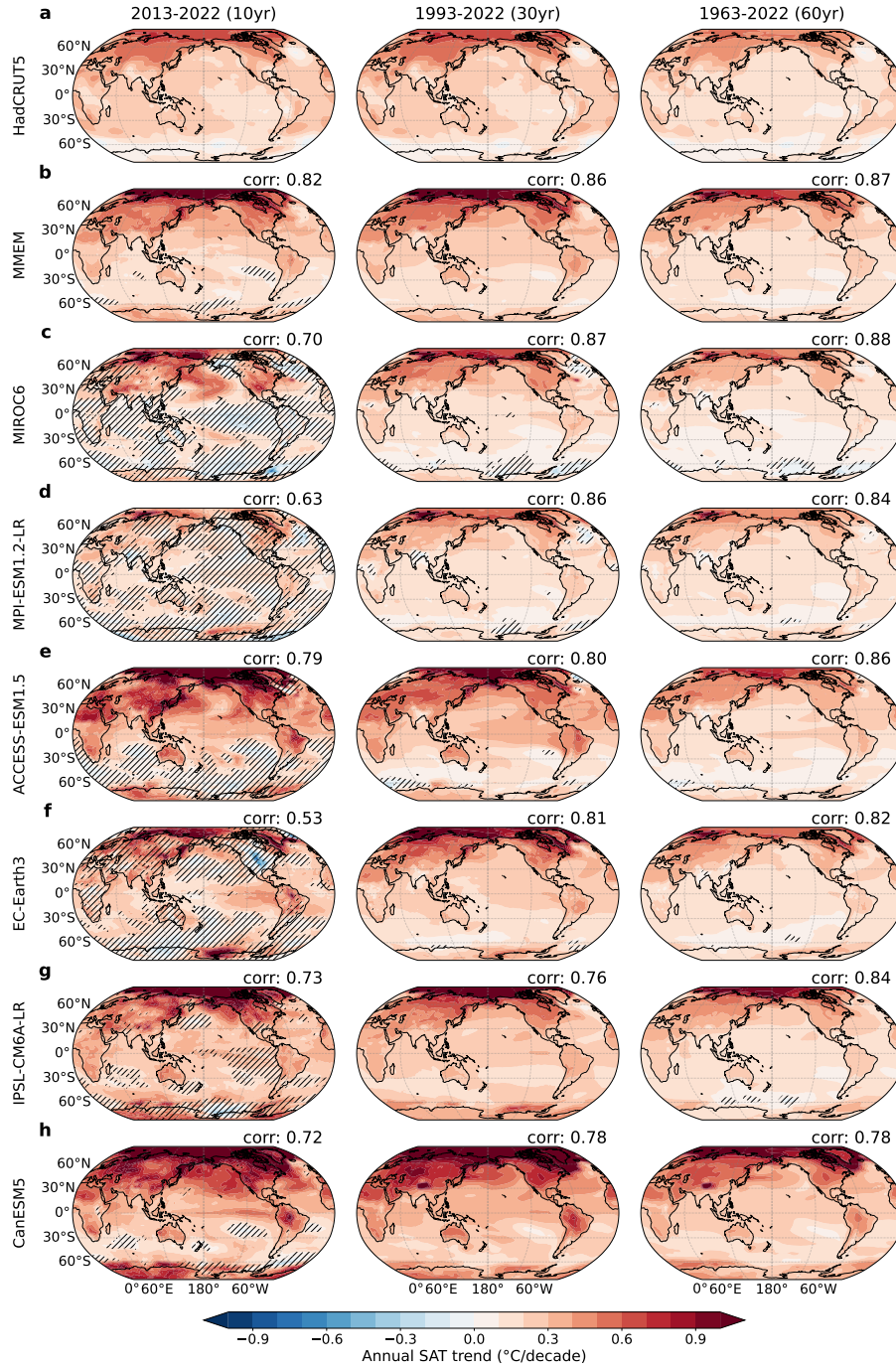
Extended Data Fig.3|Partitioning of observed SAT trend patterns to human forcing and internal variability. This figure follows the same methodology as Fig. 1, but is based on the Berkeley Earth Surface Temperature data.



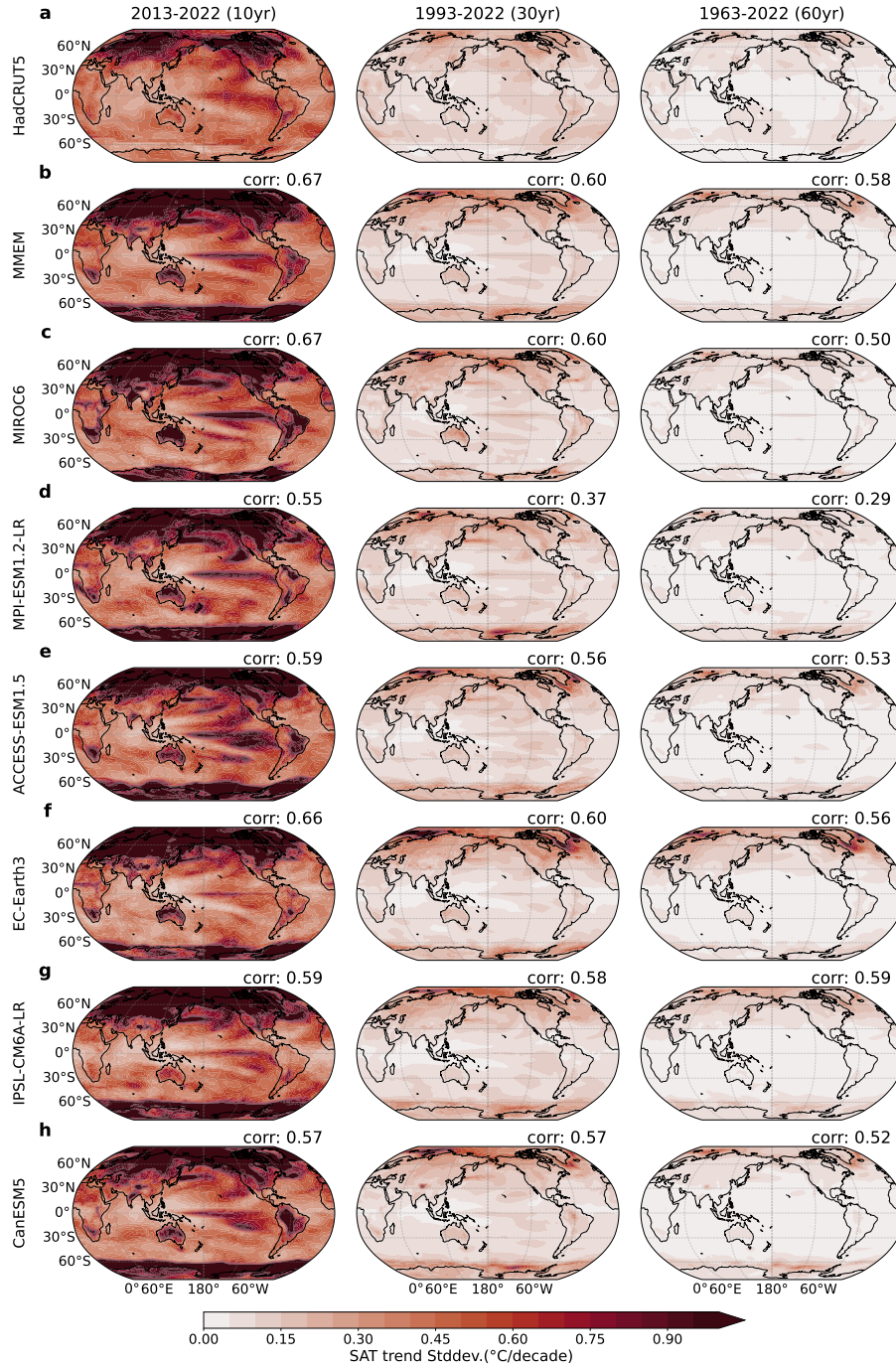
Extended Data Fig.4|Geographical patterns of observed human-forced SAT trend patterns relative to MMEM and various large ensemble climate models. Observed human-forced SAT trend patterns are shown relative to **a**, the MMEM, **b**, CanESM5, **c**, IPSL-CM6A-LR, **d**, EC-Earth3, **e**, ACCESS-ESM1.5, **f**, MPI-ESM1.2-LR and **g**, MIROC6 ensemble mean globally averaged annual mean SAT time series, derived using the observed fingerprint method (Methods). Columns (from left to right) correspond to the 10-year (2013-2022), 30-year (1993-2022) and 60-year (1963-2022) periods. Pearson correlation coefficients between the MMEM-based and large ensemble-based observed human-forced SAT patterns are indicated in the upper right corner of each panel.



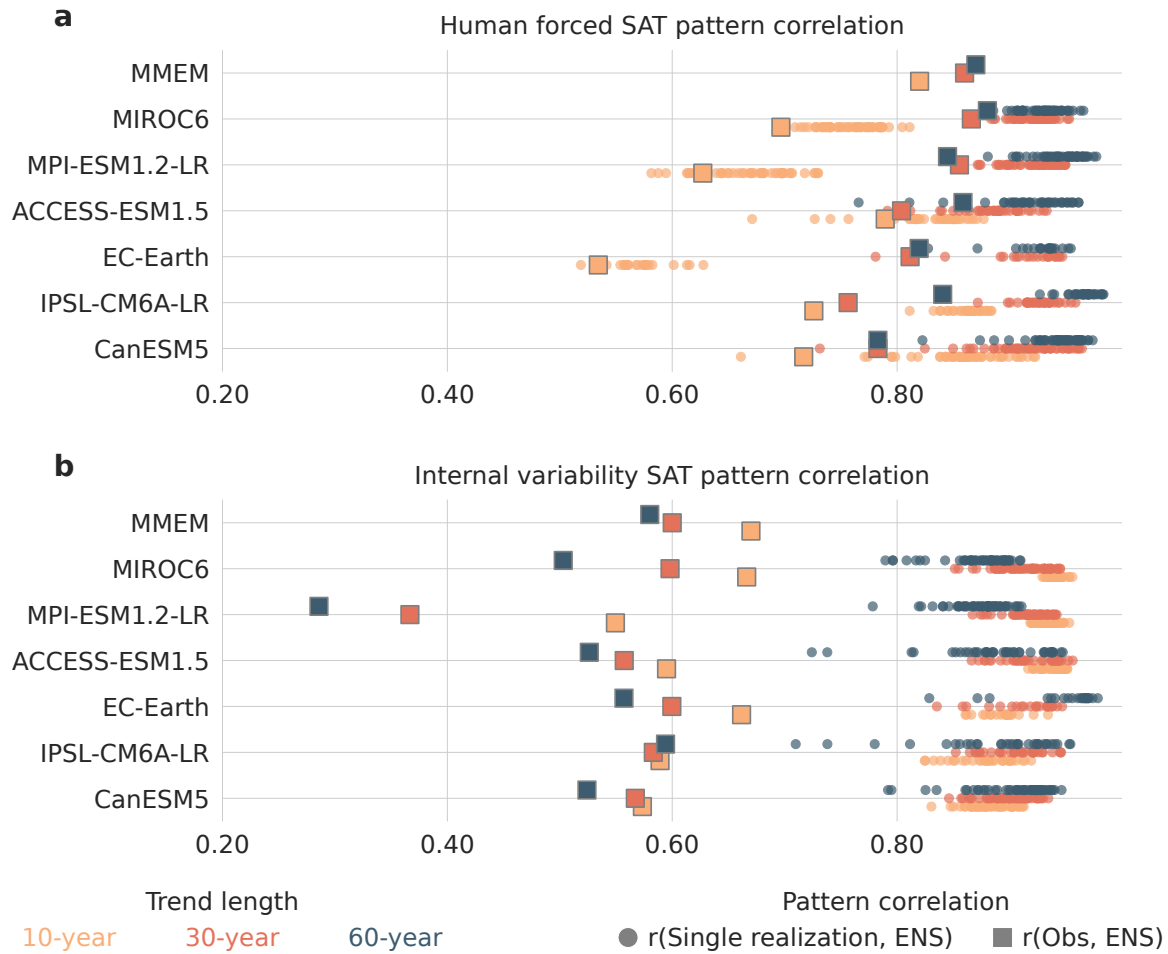
Extended Data Fig.5|Geographical patterns of observed internal variability SAT trends relative to MMEM and various large ensemble climate models. Observed internal variability SAT trend patterns are shown relative to **a**, the MMEM, **b**, CanESM5, **c**, IPSL-CM6A-LR, **d**, EC-Earth3, **e**, ACCESS-ESM1.5, **f**, MPI-ESM1.2-LR and **g**, MIROC6 ensemble mean globally averaged annual mean SAT time series, derived using the observed fingerprint method (Methods). Columns (from left to right) correspond to the 10-year (2013-2022), 30-year (1993-2022) and 60-year (1963-2022) periods. Pearson correlation coefficients between the MMEM-based and large ensemble-based observed internal variability SAT patterns are indicated in the upper right corner of each panel.



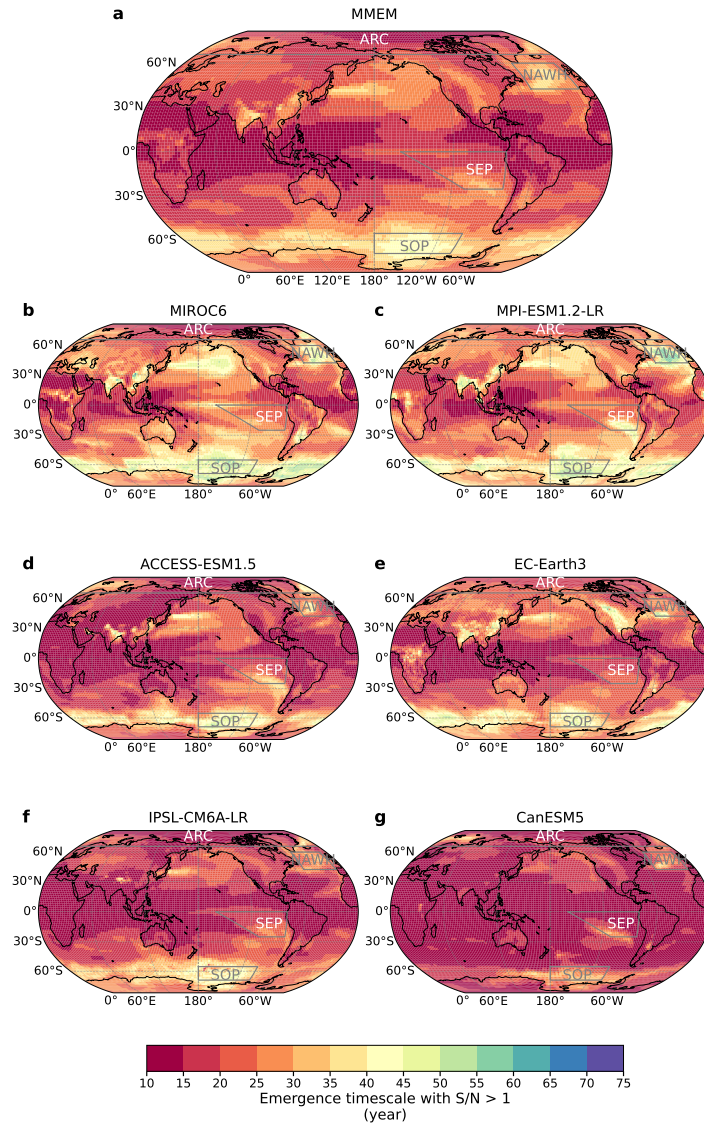
Extended Data Fig.6|Geographical patterns of annual mean human-forced SAT trend patterns. The human-forced SAT trend pattern obtained in **a**, observation, **b**, MMEM, **c**, MIROC6, **d**, MPI-ESM1.2-LR, **e**, ACCESS-ESM1.5, **f**, EC-Earth3, **g**, IPSL-CM6A-LR and **h**, CanESM5. Columns (from left to right) correspond to the 10-year (2013-2022), 30-year (1993-2022) and 60-year (1963-2022) periods. Regions where the identified trends are not statistically significant at the 95% confidence level are marked with hatching.



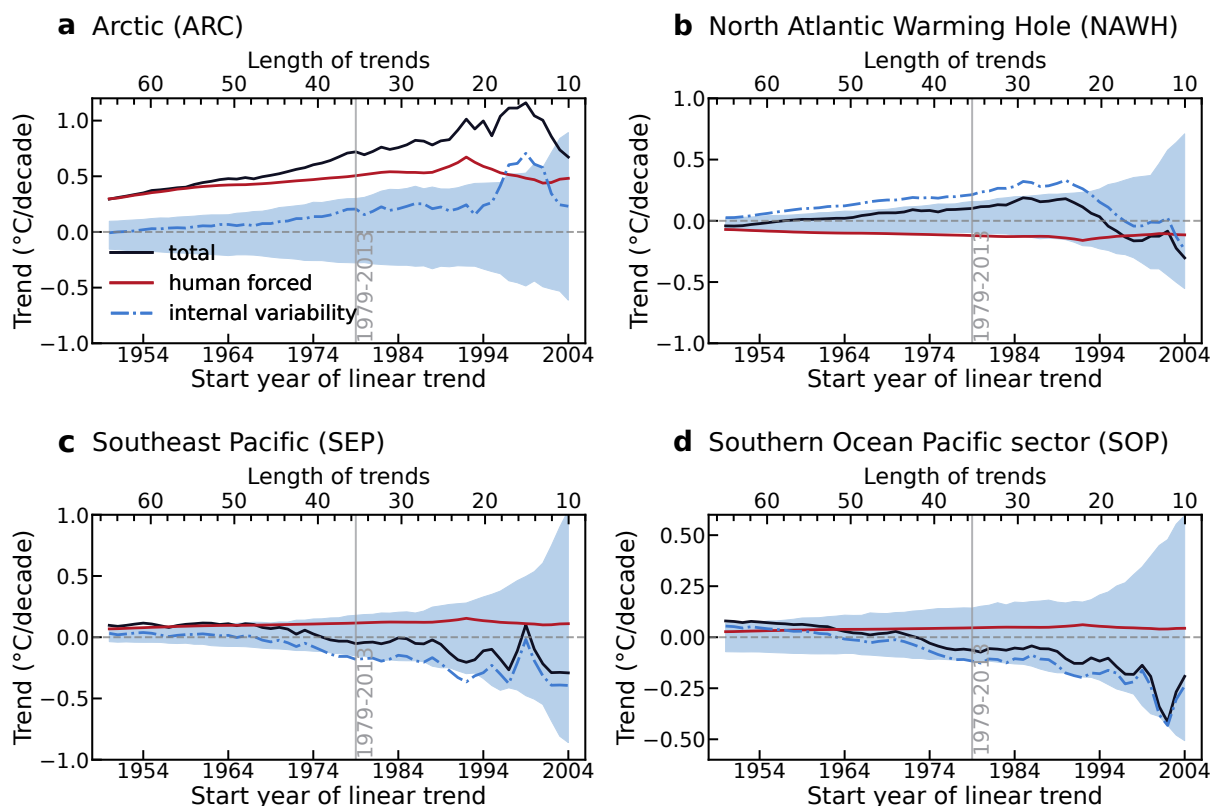
Extended Data Fig.7|Geographical patterns of annual mean internal variability SAT trend patterns. The standard deviation of the internal variability SAT patterns in **a**, observation data and ensemble spread in **b**, MMEM, **c**, MIROC6, **d**, MPI-ESM1.2-LR, **e**, ACCESS-ESM1.5, **f**, EC-Earth3, **g**, IPSL-CM6A-LR and **h**, CanESM5. Columns (from left to right) correspond to the 10-year (2013-2022), 30-year (1993-2022) and 60-year (1963-2022) periods.



Extended Data Fig. 8 | Pattern correlations between observed and simulated SAT patterns. Correlation coefficients of **a**, simulated human-forced SAT patterns from each ensemble member and the ensemble mean pattern, **b**, simulated internal variability SAT patterns from each ensemble member and the ensemble spread (see Methods). Circles denote the correlation coefficients between the simulated pattern of a single ensemble member and **(a)** the ensemble mean and **(b)** the ensemble spread pattern derived from the observed fingerprinting method, respectively. Squares denote the correlation coefficients between the observed **(a)** human-forced and **(b)** internal variability patterns and **(a)** ensemble mean and **(b)** ensemble spread simulated patterns. 10-year trends (2013-2022) are shown in orange, 30-year trends (1993-2022) in red, and 60-year trends (1963-2022) in blue. Models are ordered by ECS values, listed in descending order from bottom to top (details see the Extended Data Table 1)



Extended Data Fig. 9 | Emergence timescale of simulated SAT trends during the historical period (1950-2022). Emergence timescale of **a**, MMEM and **b**, MIROC6, **c**, MPI-ESM1.2-LR, **d**, ACCESS-ESM1.5, **e**, EC-Earth3, **f**, IPSL-CM6A-LR and **g**, CanESM5 simulated SAT trends. The emergence timescale represents the first trend length at each grid point where the signal-to-noise ratio (S/N) exceeds 1 (Methods). Colored regions indicate where anthropogenic warming signals emerged from internal variability within 10- to 73-year trends. Grey boxes highlight regions referenced in the main text Fig. ???: Arctic (ARC, 66.5°N poleward), North Atlantic warming hole (NAWH, 42°N-60°N, 50°W-10°W), Southeastern Pacific (SEP), Southern Ocean Pacific sector (SOP, 70°S-55°S, 180°-100°W).



Extended Data Fig.10|Evolution of total, human-forced, and internal variability SAT trends over four key regions during 1950-2013. The total (black solid line), human-forced (red solid line) and internal variability (blue dash-dot line) SAT variations are obtained by dissecting the total and partitioned SAT trends in one-year increments over a rolling window from 1950-2022, with the end year fixed at 2013. The light blue shading denotes the observed internal variability distribution quantified as the 5th and 95th percentile range of all possible internal variability estimates, constructed from samples of each trend length over 1850-2022 (Methods). The grey vertical line represents the 35-year trend during the 1979-2013 period.

Extended Data Table1|List of the CMIP6 large ensemble models referenced in the main text, specifying the scenarios used up to the year 2022. ‘ECS’ indicates the effective climate sensitivity in K, while ‘N’ refers to the number of ensemble members for each model.

Models	Variable	ECS	N	Institution	Source
ACCESS-ESM1.5	tas, Historical, SSP2-4.5	3.9	40 (r1i1p1f1)	Commonwealth Scientific and Industrial Research Organization, Bureau of Meteorology (BOM), Australia	Ziehn et al. 2020
CanESM5	tas, Historical, SSP2-4.5	5.6	50 (r1i1p1f1, r1i1p2f1)	Canadian Center for Climate Modeling and Analysis (CCCma), Canada	Swart et al. 2019
EC-Earth3	tas, Historical, SSP2-4.5	4.3	21(r1i1p1f1)	EC-Earth-Consortium (27 European institutes)	Döscher et al. 2022
IPSL-CM6A-LR	tas, Historical, SSP2-4.5	4.7	32 (r1i1p1f1)	Institute Pierre-Simon Laplace Climate Modelling Centre, France	Boucher et al. 2020
MIROC6	tas, Historical, SSP2-4.5	2.6	50 (r1i1p1f1)	Japan Agency for Marine-Earth Science and Technology; Atmosphere and Ocean Research Institute, The University of Tokyo; National Institute for Environmental Studies; RIKEN Center for Computational Science, Japan	Tatebe et al. 2019
MPI-ESM1.2-LR	tas, Historical, SSP2-4.5	2.8	50 (r1i1p1f1)	Max Planck Institute for Meteorology, Germany	Olonscheck et al. 2023