

Supplementary Information for

**Reducing forced-signal uncertainty in the INM RAS climate models using a
pattern-recognition based approach**

Sergey Kravtsov,^{a, b} Andrey Gritsun^c

^a *University of Wisconsin-Milwaukee, Milwaukee, WI*

^b *Shirshov Institute of Oceanology of Russian Academy of Sciences, Moscow, Russia*

^c *Institute of Numerical Mathematics of Russian Academy of Sciences, Moscow, Russia*

Corresponding author: Sergey Kravtsov, kravtsov@uwm.edu

To be submitted to *Climate Dynamics*

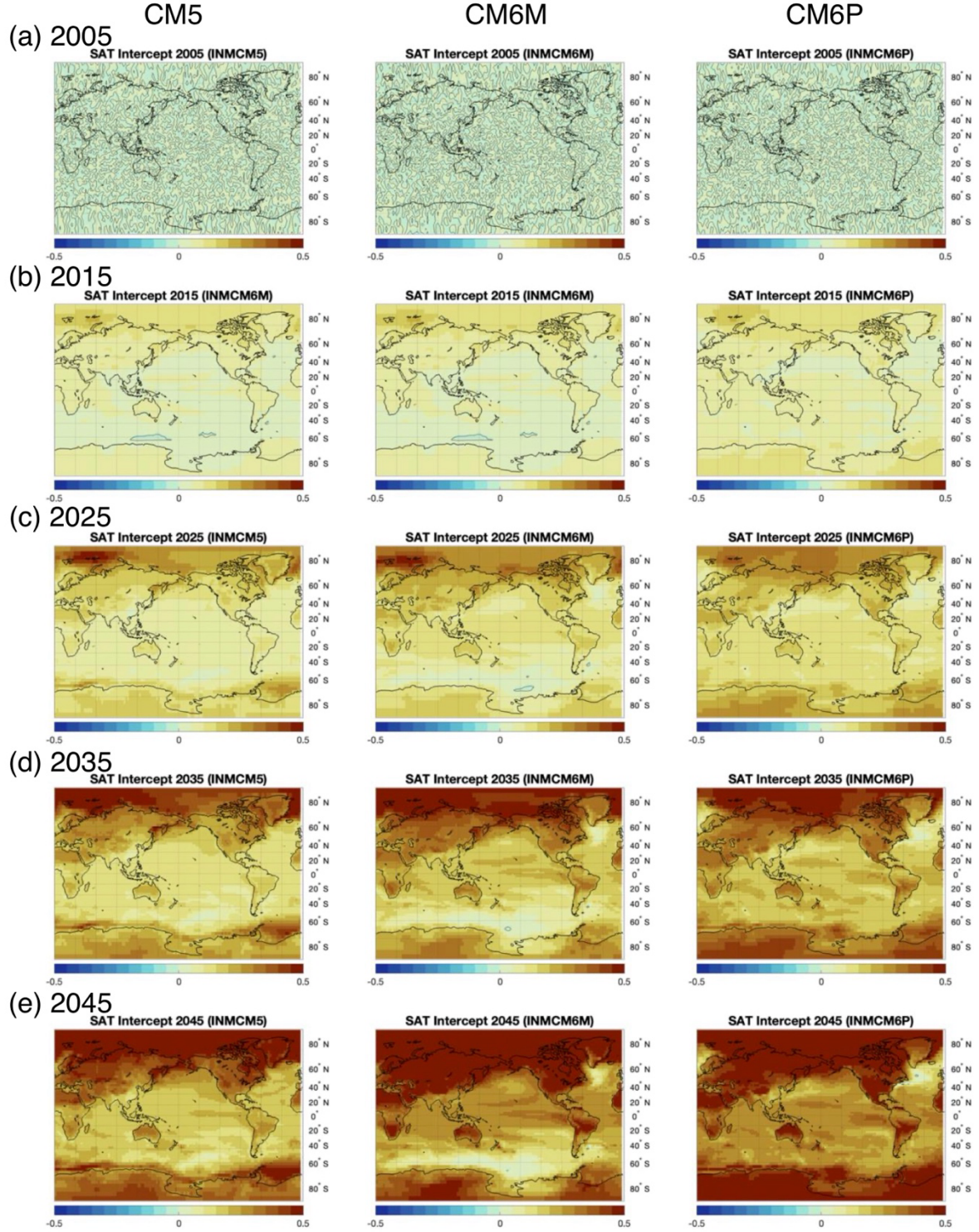


Fig. S1 The intercept (time-mean) SAT anomaly patterns (with respect to the 1880–2005 climatology) *INT* computed over the training periods starting at 1880 and ending at: (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045, for INMCM5 (left), INMCM6M (middle column), and INMCM6P (right column) historical simulations.

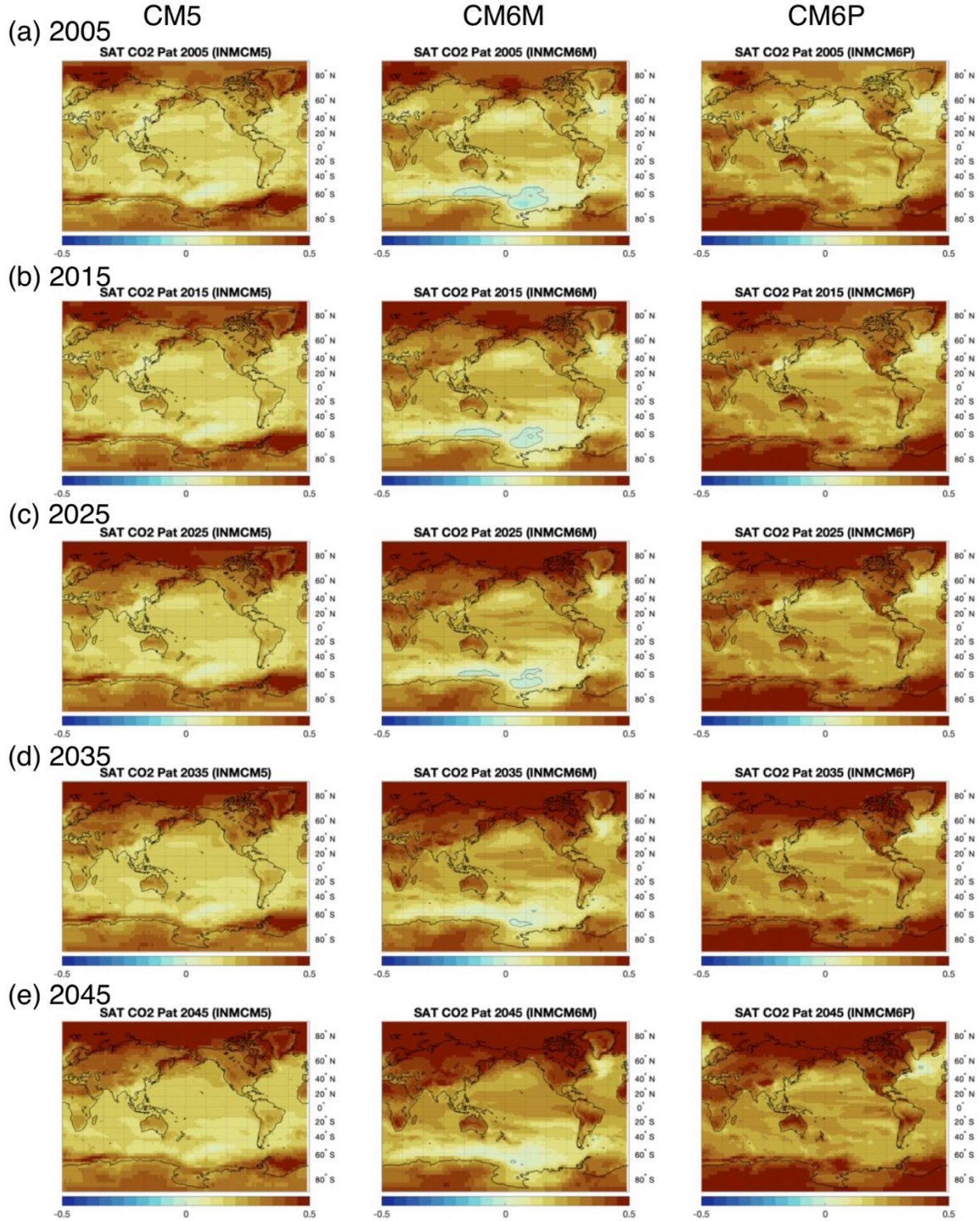


Fig. S2 The CO₂-congruent SAT anomaly regression patterns (with respect to the 1880–2005 climatology) *PAT* computed over the training periods starting at 1880 and ending at: (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045, for INMCM5 (left), INMCM6M (middle column), and INMCM6P (right column) historical simulations. The top-row patterns are identical to those shown in Figs. 1d–f of the main text.

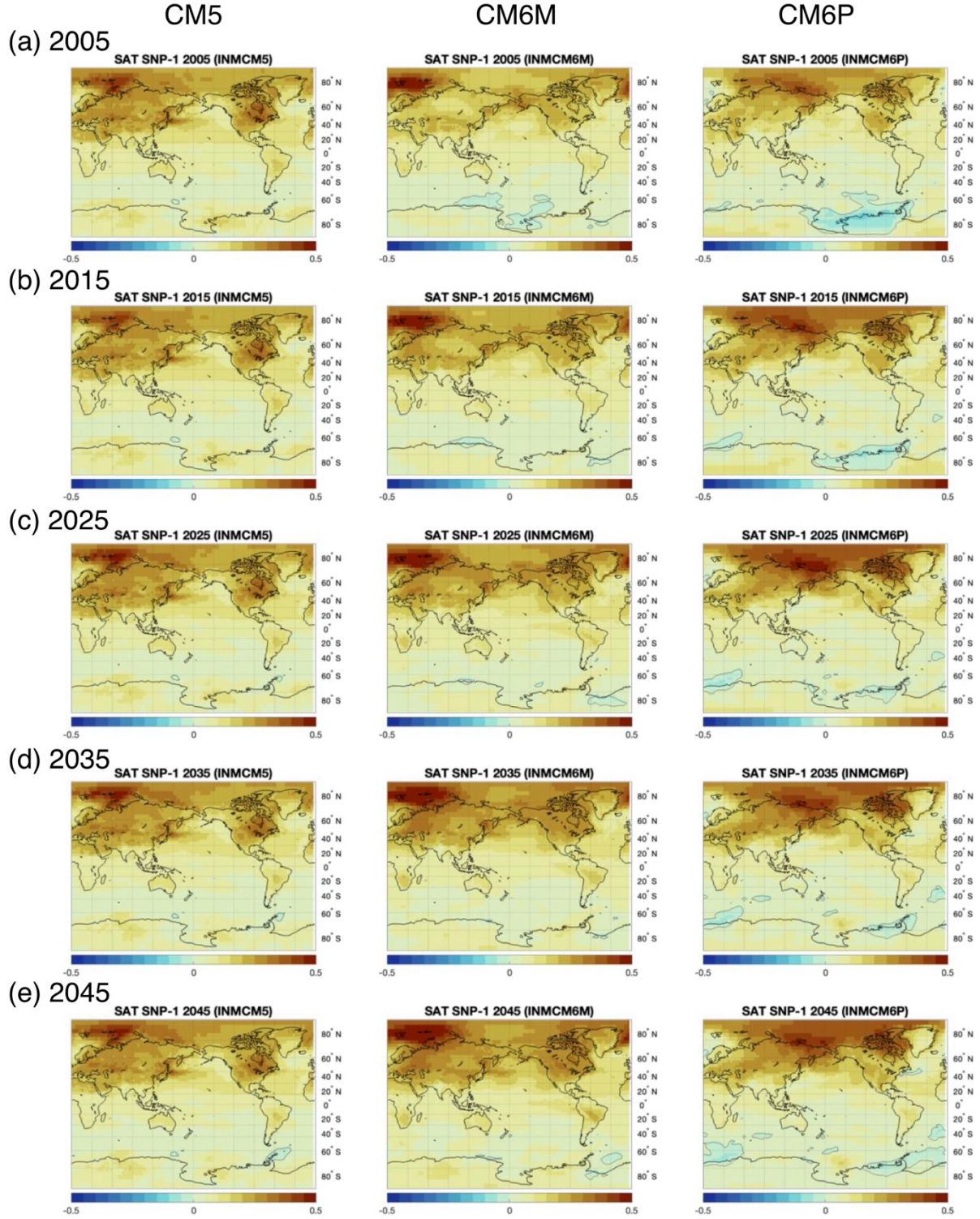


Fig. S3 S/NP pattern 1 of the CO₂-detrended SAT data for the INMCM5 (left column), INMCM6M (middle column), and INMCM6P (right column) historical simulations and different training periods, starting at 1880 and going through one of the end dates: 2005, 2015, 2025, 2035, and 2045 (panels a–e, respectively). The patterns correspond to the components shown in Fig. 2a of the main text.

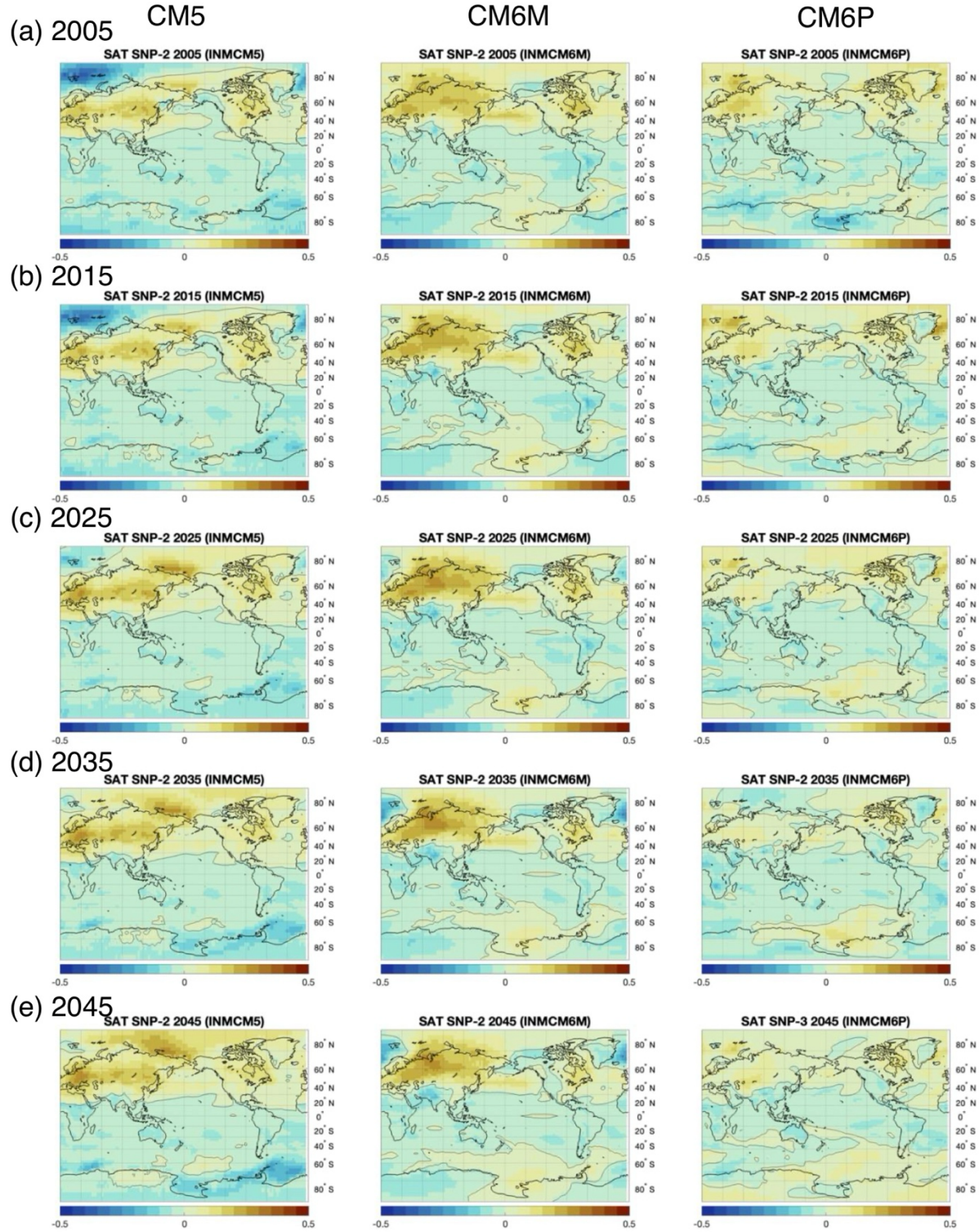


Fig. S4 S/NP pattern 2 of the CO₂-detrended SAT data for the INMCM5 (left column), INMCM6M (middle column), and INMCM6P (right column) historical simulations and different training periods, starting at 1880 and going through one of the end dates: 2005, 2015, 2025, 2035, and 2045 (panels a–e, respectively). The patterns correspond to the components shown in Fig. 2b of the main text.

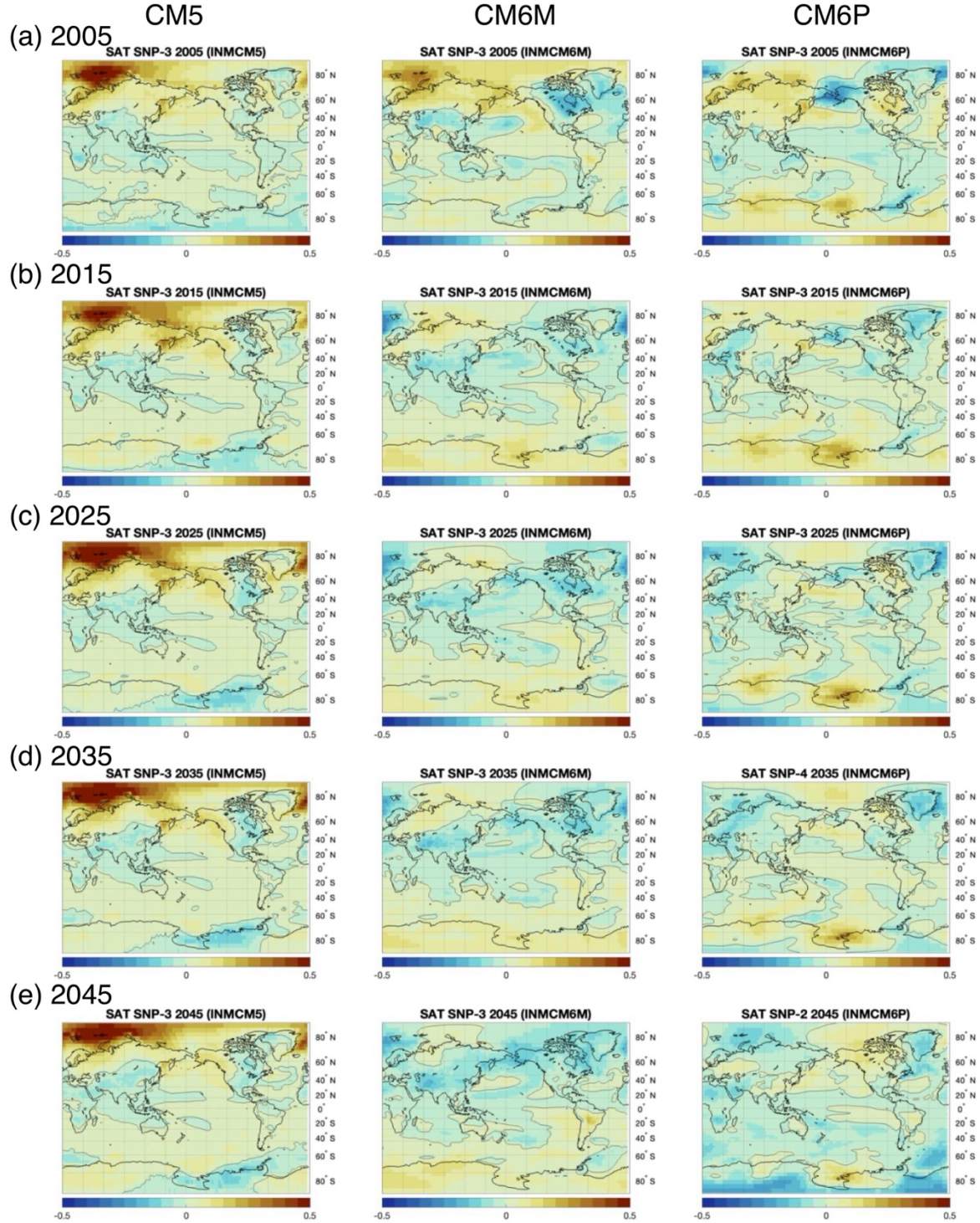


Fig. S5 S/NP pattern 3 of the CO₂-detrended SAT data for the INMCM5 (left column), INMCM6M (middle column), and INMCM6P (right column) historical simulations and different training periods, starting at 1880 and going through one of the end dates: 2005, 2015, 2025, 2035, and 2045 (panels a–e, respectively). The patterns correspond to the components shown in Fig. 2c of the main text.

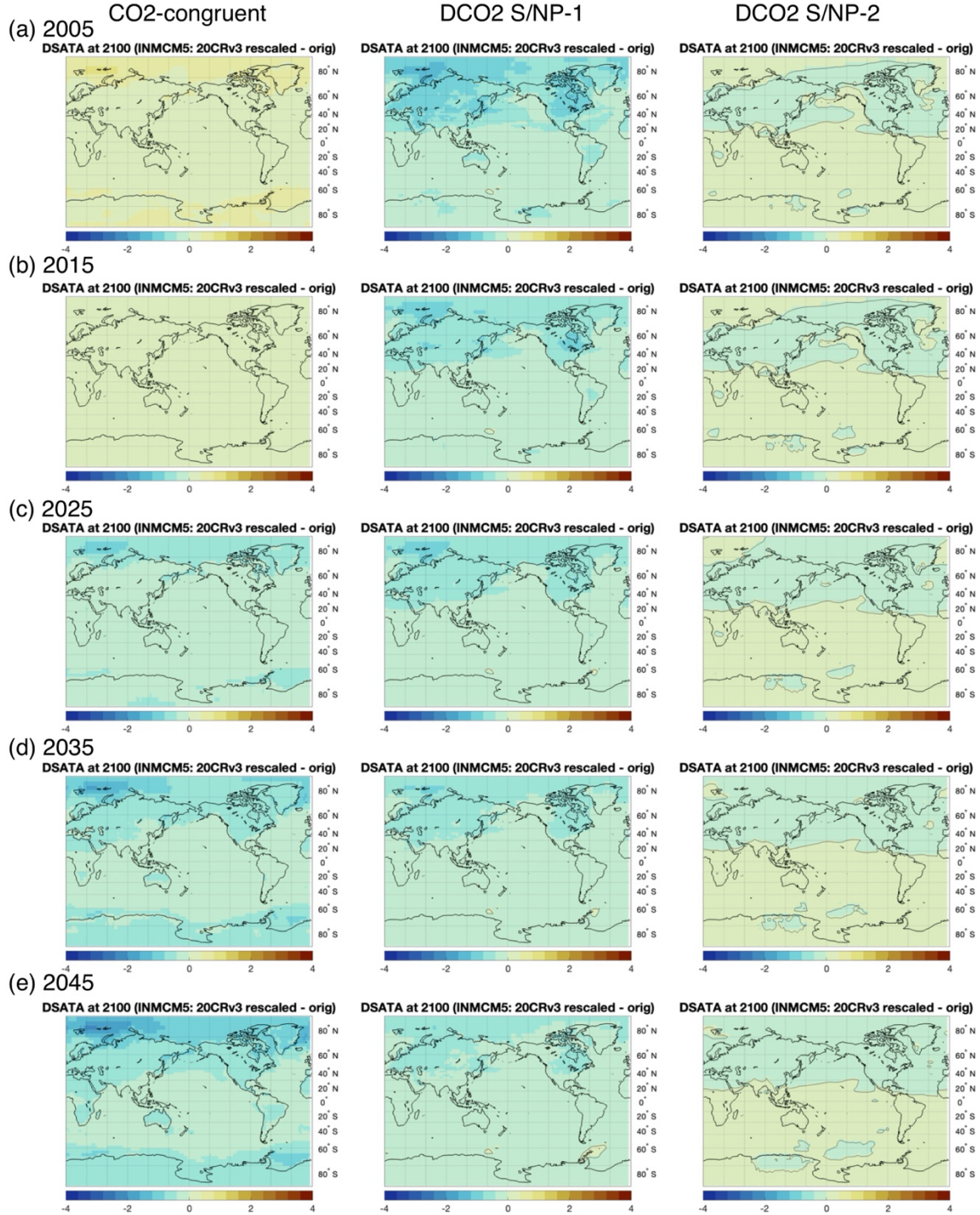


Fig. S6 The contributions to the INMCM5's 20CRv3-based rescaling signals shown in Fig. 7 of the main text (left column) from the CO₂-congruent component (left column), S/NP-1 component (middle column), and S/NP-2 component (right column). The rescaling parameters were estimated using the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045. The sum of patterns across each row equals the pattern shown in the corresponding row of the left column of Fig. 7 of the main text. Analogous to Fig. 8 of the main text for the INMCM6M model.

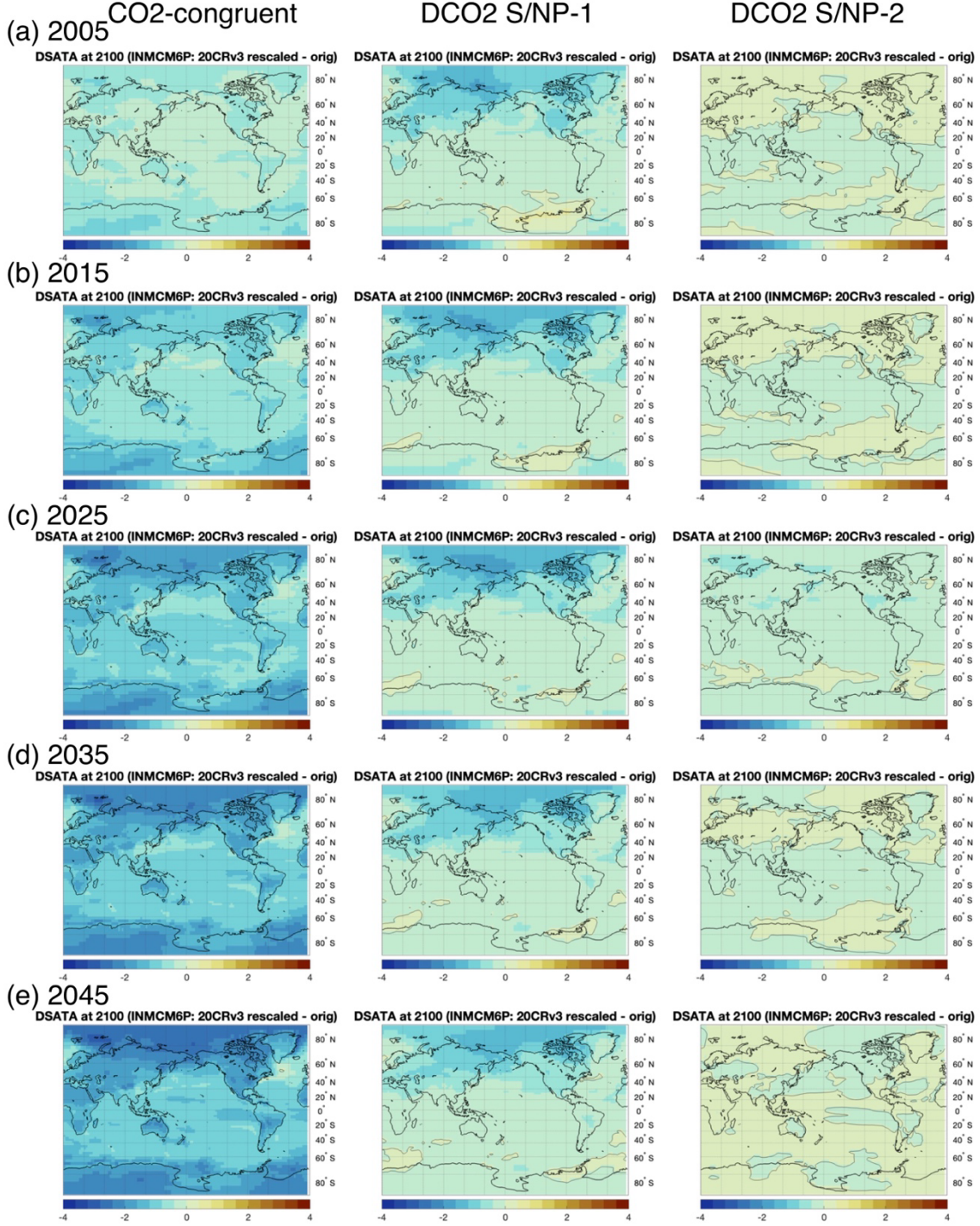


Fig. S7 The contributions to the INMCM6P's 20CRv3-based rescaling signals shown in Fig. 7 of the main text (right column) from the CO₂-congruent component (left column), S/NP-1 component (middle column), and S/NP-2 component (right column). The rescaling parameters were estimated using the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045. The sum of patterns across each row equals the pattern shown in the corresponding row of the right column of Fig. 7 of the main text. Analogous to Fig. 8 of the main text for the INMCM6M model.

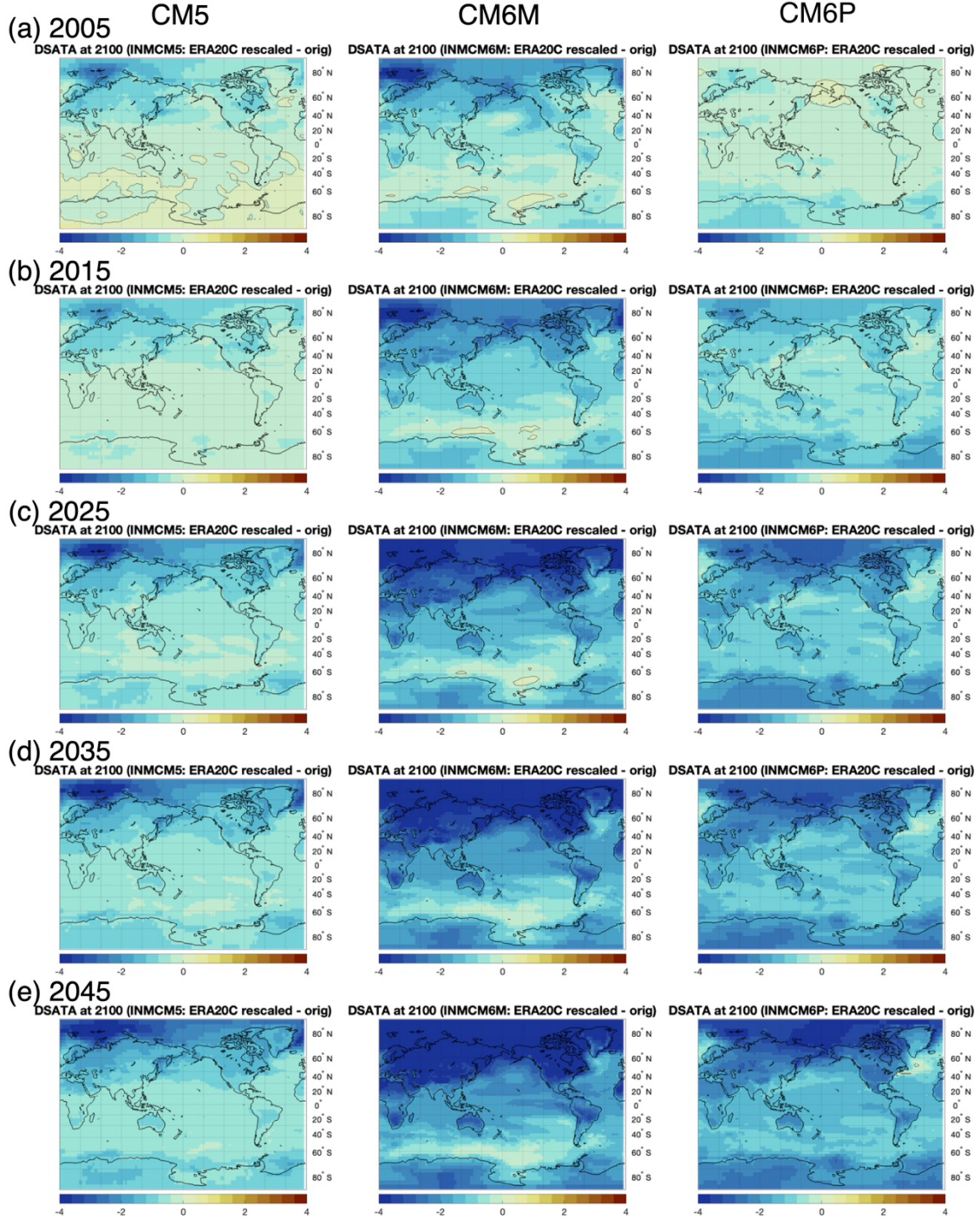


Fig. S8 Rescaling ‘signal’ measured at year 2100 as the difference between the original and rescaled forced-signal temperature anomaly (with respect to the 1880–2005 mean) (degrees C) for the ERA20C-based rescaling and INMCM5 (left column), INMCM6M (middle column), and INMCM6P (right column) models. The rescaling parameters were estimated using the CO₂-congruent SAT component and DCO2 SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045. Analogous to Fig. 7 of the main text for the 20CrV3-based rescaling.

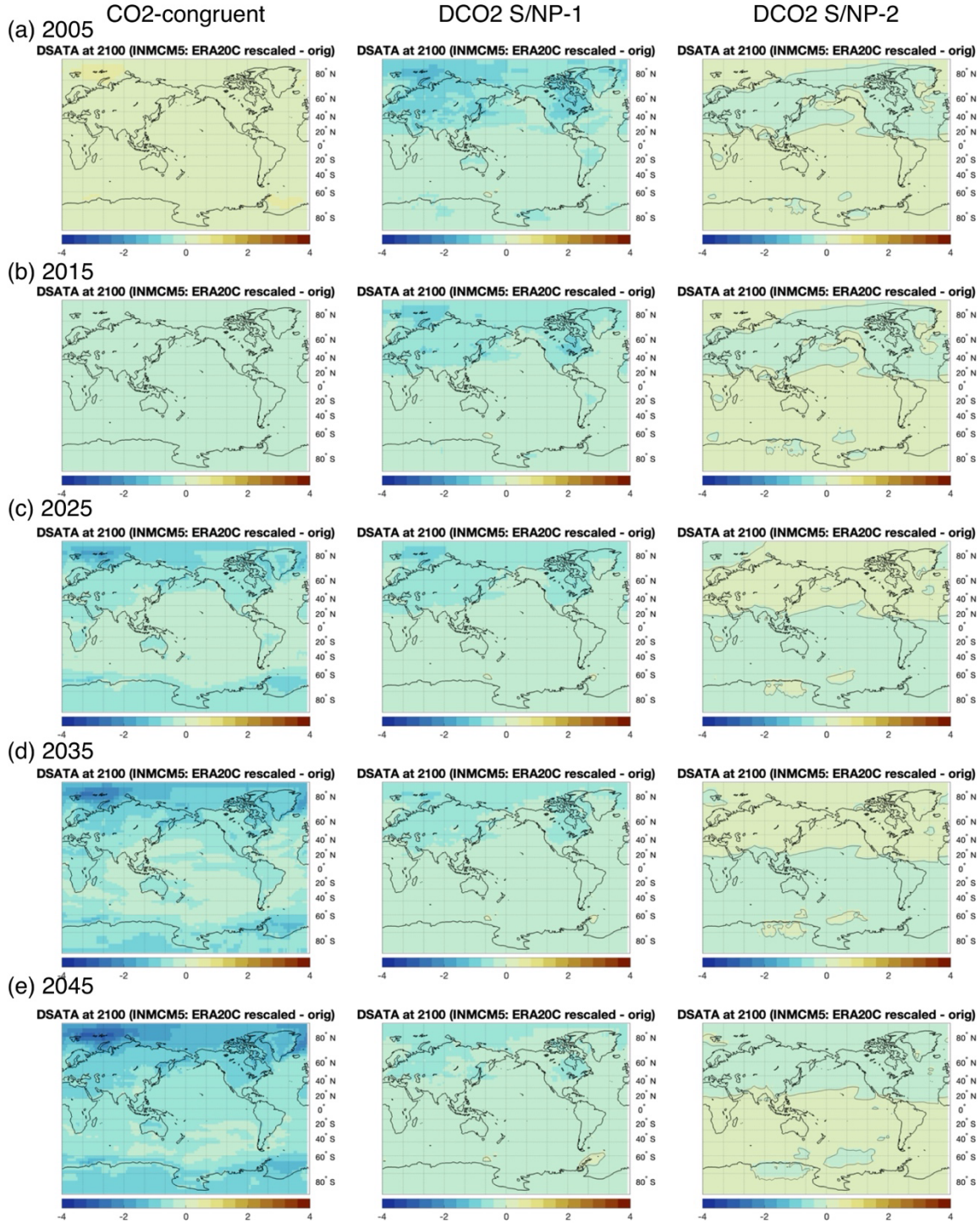


Fig. S9 The contributions to the INMCM5's ERA20C-based rescaling signals shown in Fig. S8 above (left column) from the CO₂-congruent component (left column), S/NP-1 component (middle column), and S/NP-2 component (right column). The rescaling parameters were estimated using the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045. The sum of patterns across each row equals the pattern shown in the corresponding row of the left column of Fig. S8. Analogous to Fig. S6 above for the 20CRv3-based rescaling.

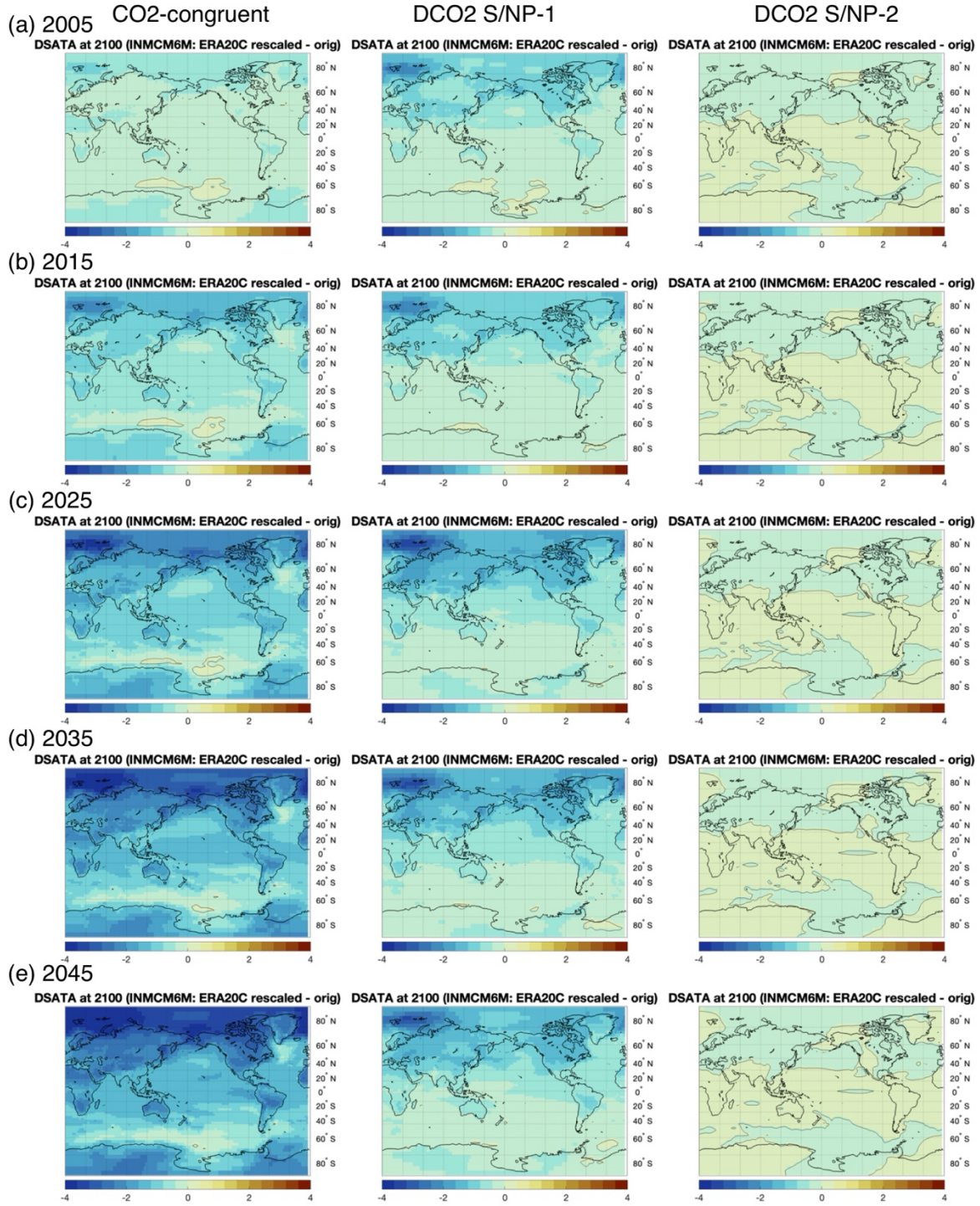


Fig. S10 The contributions to the INMCM6M's ERA20C-based rescaling signals shown in Fig. S8 above (middle column) from the CO₂-congruent component (left column), S/NP-1 component (middle column), and S/NP-2 component (right column). The rescaling parameters were estimated using the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045. The sum of patterns across each row equals the pattern shown in the corresponding row of the middle column of Fig. S8. Analogous to Fig. 8 of the main text for the 20CRv3-based rescaling.

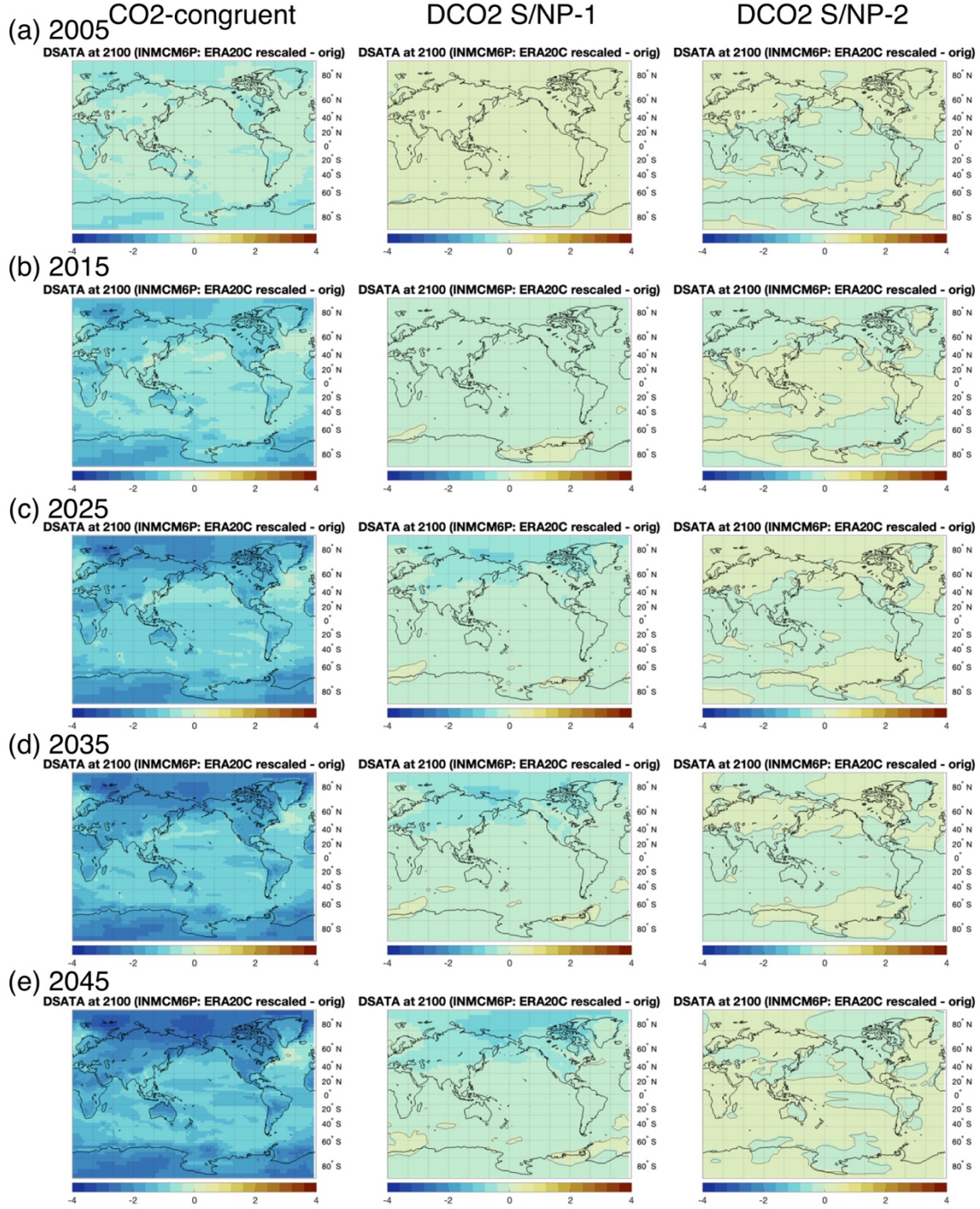


Fig. S11 The contributions to the INMCM6P's ERA20C-based rescaling signals shown in Fig. S8 above (right column) from the CO₂-congruent component (left column), S/NP-1 component (middle column), and S/NP-2 component (right column). The rescaling parameters were estimated using the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045. The sum of patterns across each row equals the pattern shown in the corresponding row of the right column of Fig. S8. Analogous to Fig. S7 above for the 20CRv3-based rescaling.

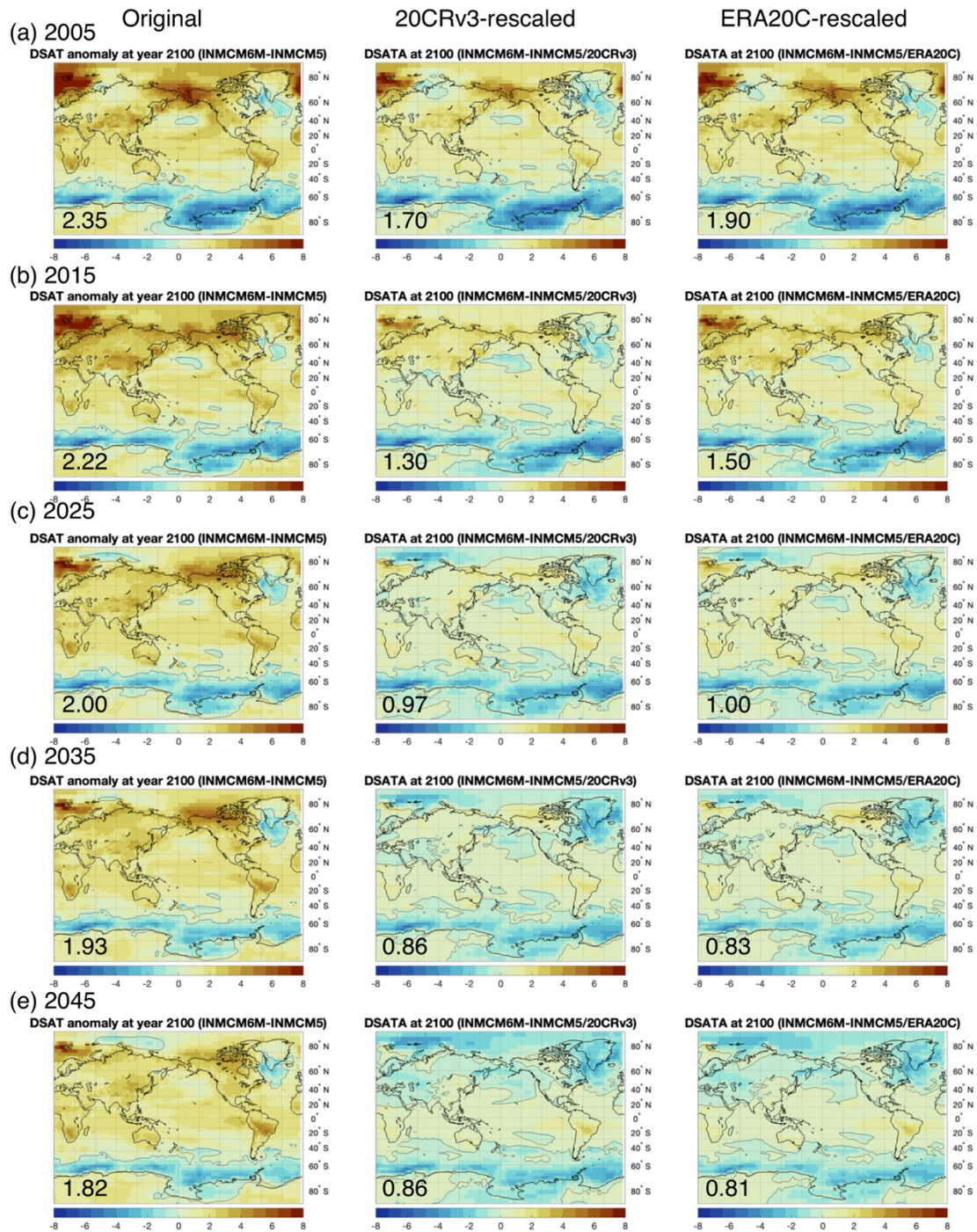


Fig. S12 (Climate projection) model uncertainty, as measured by the difference between the year 2100 (estimated forced signal) SAT anomalies of the INMCM6M and INMCM5 models. These differences are shown for: unscaled anomalies (left column), 20CRv3 rescaled anomalies (middle column), and ERA-20C anomalies (right column). The number at the lower-left corner of each of the left panels shows the global root-mean-square difference (degrees C) between the corresponding model pairs. The results are based on the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045.

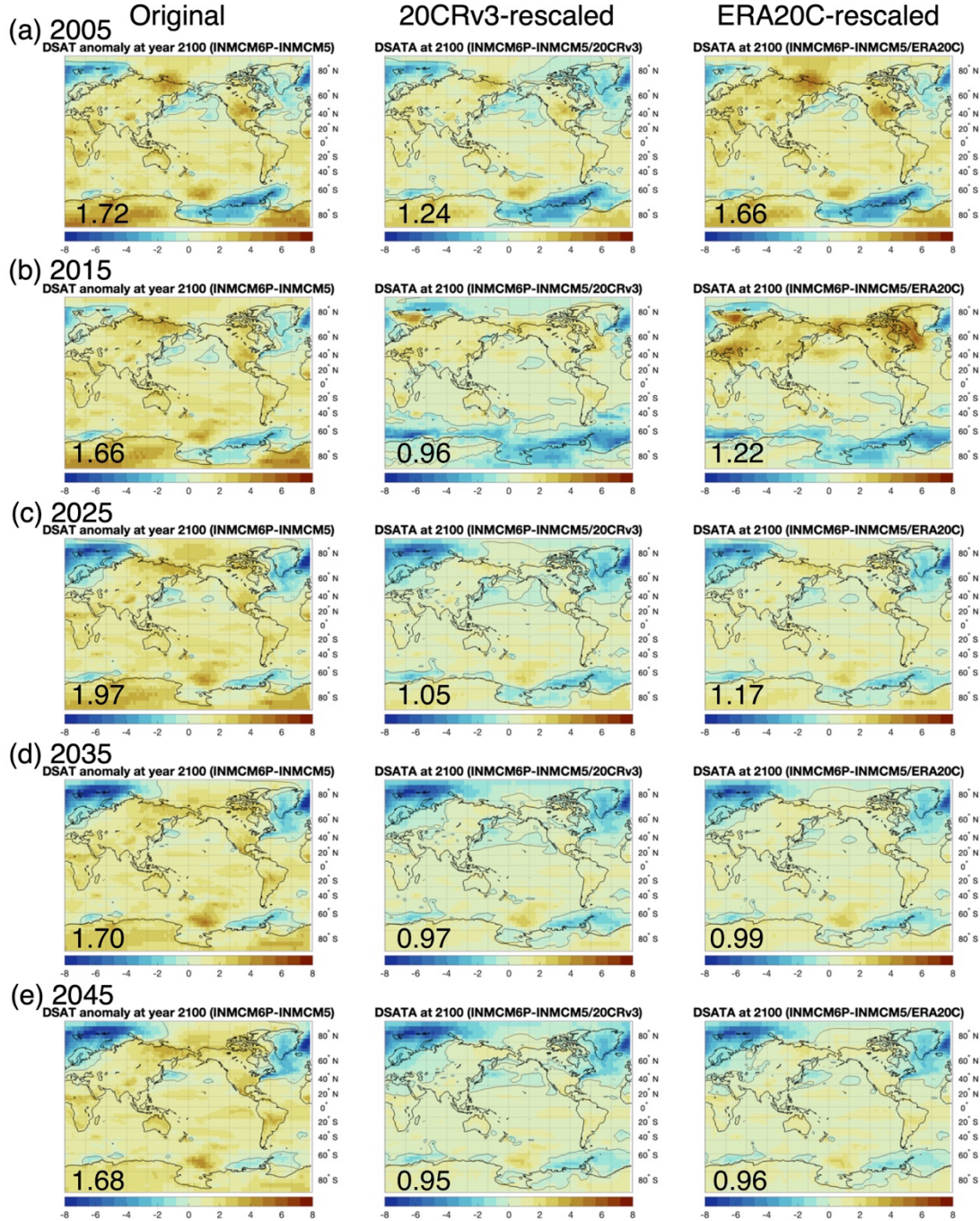


Fig. S13 (Climate projection) model uncertainty, as measured by the difference between the year 2100 (estimated forced signal) SAT anomalies of the INMCM6P and INMCM5 models (analogous to Fig. S12 above for the INMCM6M–INMCM5 differences). These differences are shown for: unscaled anomalies (left column), 20CRv3 rescaled anomalies (middle column), and ERA-20C anomalies (right column). The number at the lower-left corner of each of the left panels shows the global root-mean-square difference (degrees C) between the corresponding model pairs. The results are based on the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045.

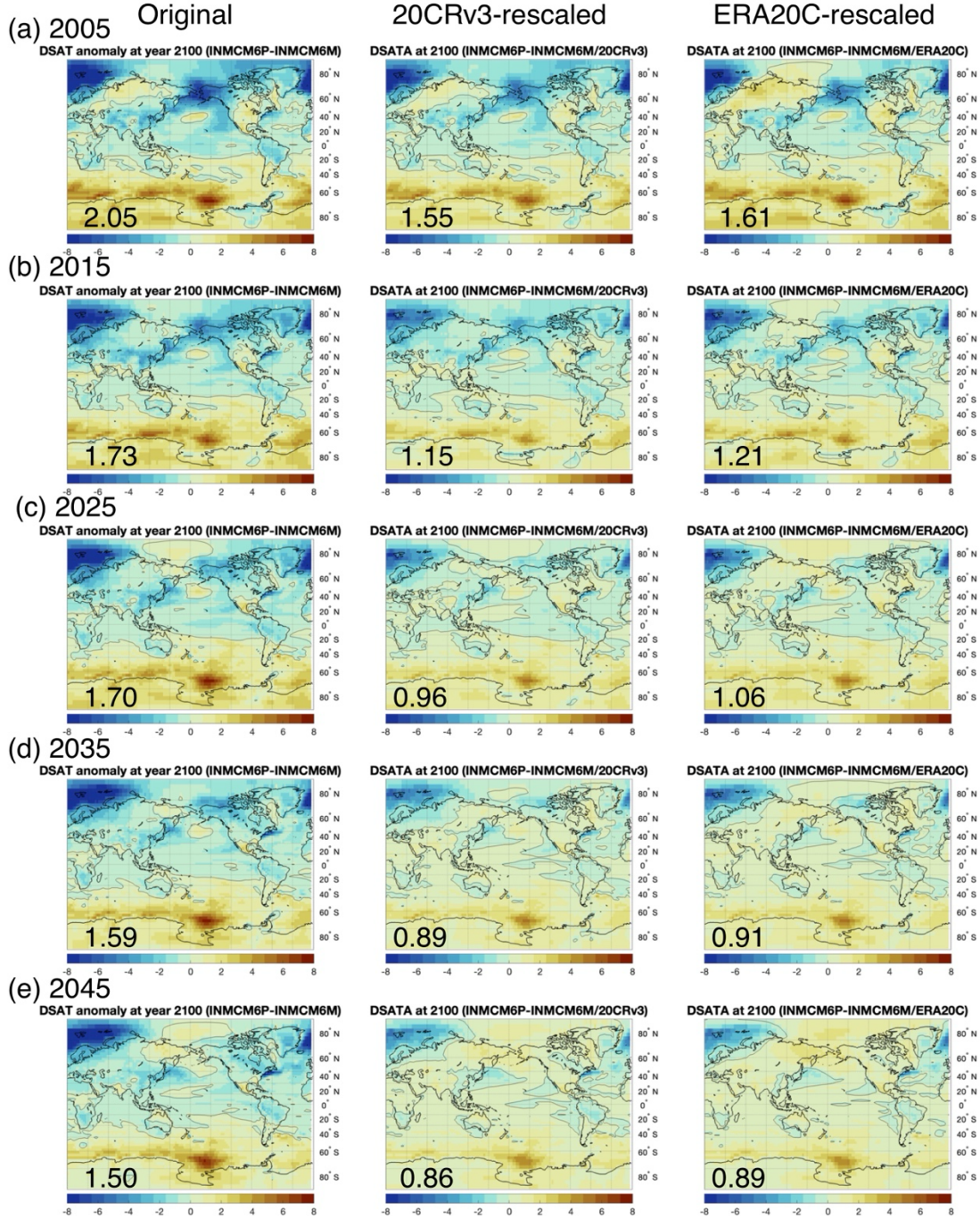


Fig. S14 (Climate projection) model uncertainty, as measured by the difference between the year 2100 (estimated forced signal) SAT anomalies of the INMCM6P and INMCM6M models (analogous to Fig. S12 and S13 above for the INMCM6M–INMCM5 and INMCM6P–INMCM5 differences). These differences are shown for: unscaled anomalies (left column), 20CRv3 rescaled anomalies (middle column), and ERA-20C anomalies (right column). The number at the lower-left corner of each of the left panels shows the global root-mean-square difference (degrees C) between the corresponding model pairs. The results are based on the CO₂-congruent SAT component and DCO₂ SAT S/NP components computed over the training periods starting at 1880 and ending in (a) 2005; (b) 2015; (c) 2025; (d) 2035; and (e) 2045.

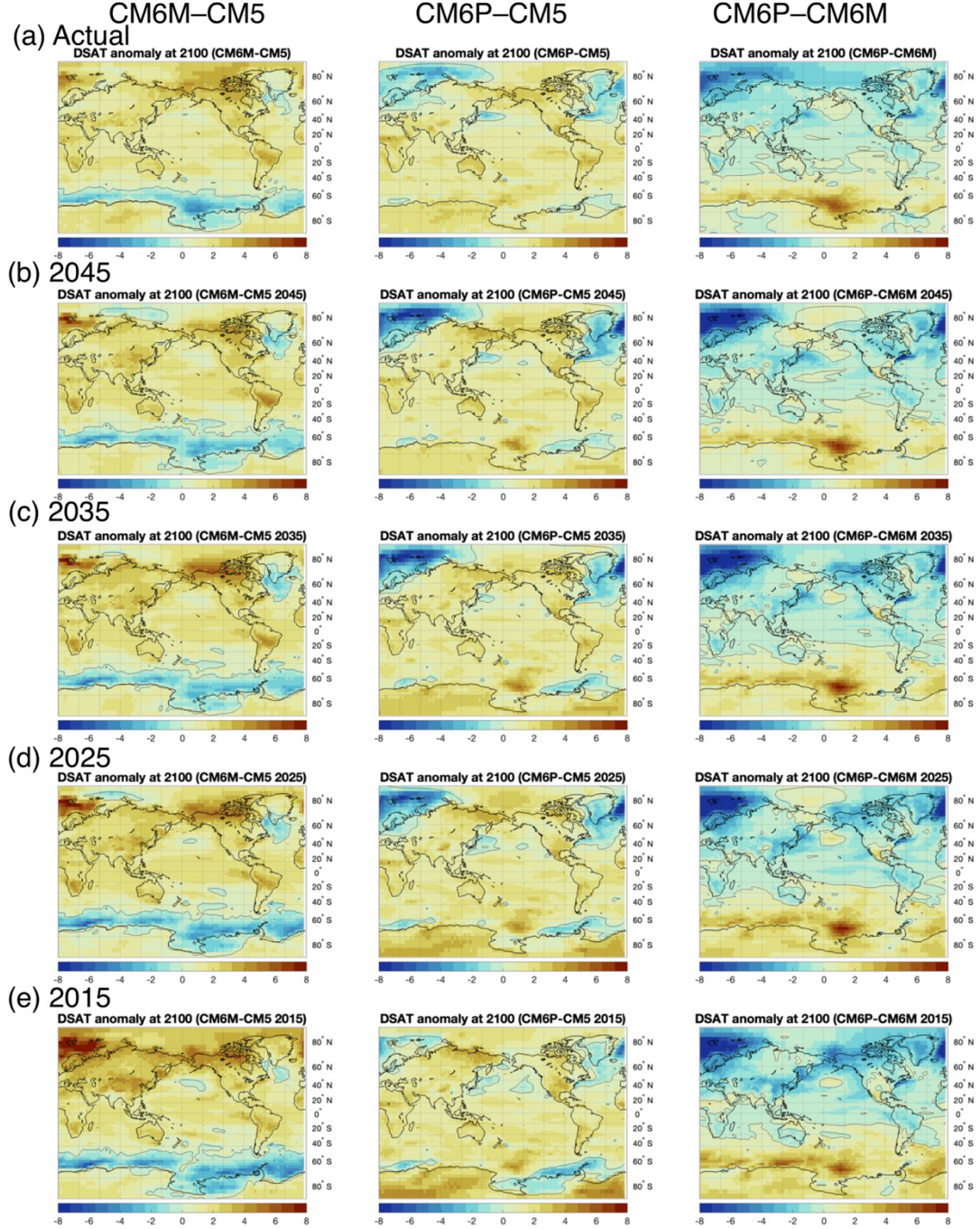


Fig. S15 SAT differences at 2100 between different INM RAS models: CM6M–CM5 (left column); CM6P–CM5 (middle column); CM6P–CM6M (right column), for (a) full model simulations (ensemble mean) smoothed by the 5-yr boxcar running-average filter, $T_{actual}(x, y, t)$; (b–e): Pattern-based forced-signal estimates $T_{predicted}(x, y, t)$ for the training periods ending in 2045, 2035, 2025, and 2015, respectively.

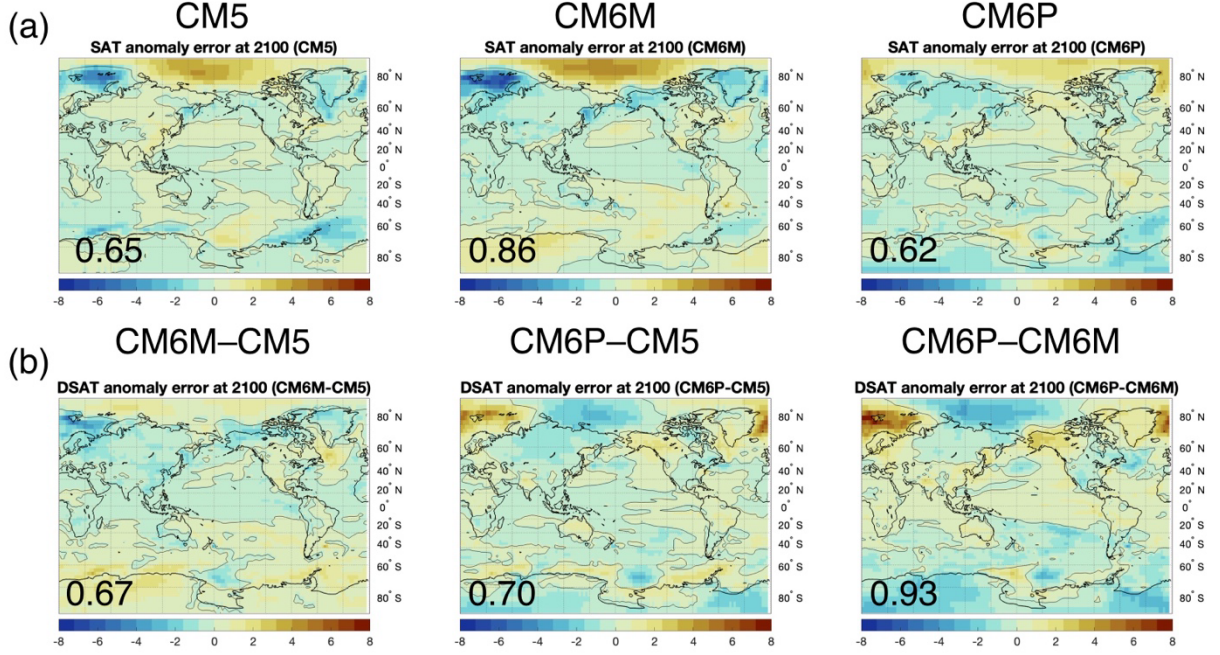


Fig. S16 Residual forced signal unaccounted for by the pattern-recognition based extrapolation: (a) SAT anomalies at year 100 for the (left-to-right) CM5, CM6M, and CM6P models; (b) SAT differences at 2100 between CM6M–CM5 (left column), CM6P–CM5 (middle column), and CM6P–CM6M (right column) model pairs. The residual forced signal was defined as the difference between the actual model simulations (ensemble mean) smoothed by the 5-yr boxcar running-average filter — $T_{actual}(x, y, t)$, — and the pattern-recognition based forced-signal extrapolation $T_{predicted}(x, y, t)$, associated here with the 1880–2025 training period.

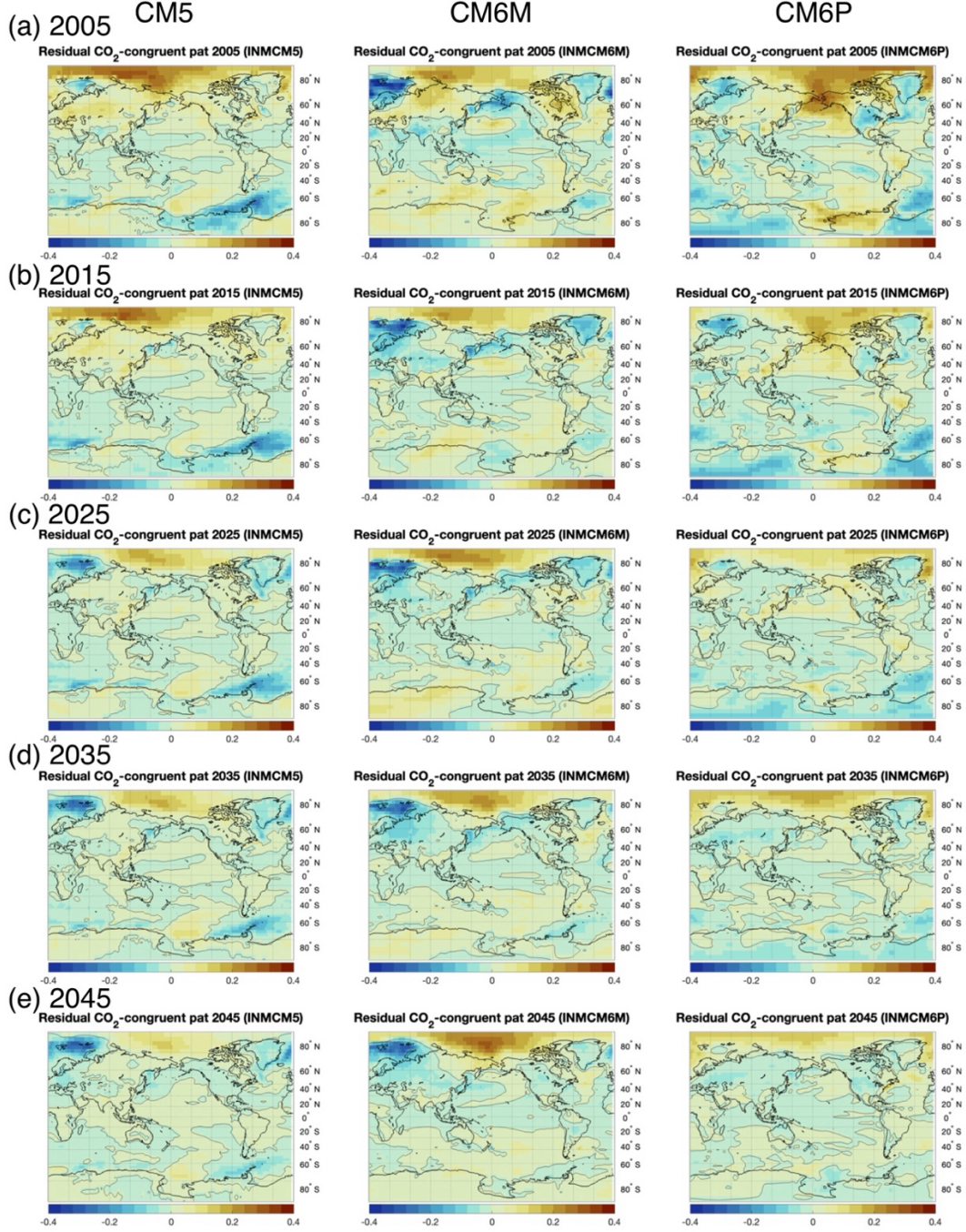


Fig. S17 Residual CO_2 -congruent SAT pattern data in the INMCM5 (left column), INMCM6M (middle column), and INMCM6P (right column) historical simulations and different training periods, starting at 1880 and going through one of the end dates: 2005, 2015, 2025, 2035, and 2045 (panels a–e, respectively). The patterns were computed by time averaging the scaled difference $(T_{\text{actual}}(x, y, t) - T_{\text{predicted}}(x, y, t))/p_{\text{CO}_2}(t)$ over the 2015–2100, 2025–2100, 2035–2100, 2045–2100, 2055–2100 periods (for the training-period end dates 2005, 2015, 2025, 2035, and 2045, respectively), where $T_{\text{actual}}(x, y, t)$ was defined as the 5-yr boxcar running-average ensemble-mean SAT in the actual model’s projection of the future climate. This scaled difference remained approximately constant across each validation period (see an example in Fig. 10 of the main text). The results shown in row (c) duplicate Fig. 11 of the main text.

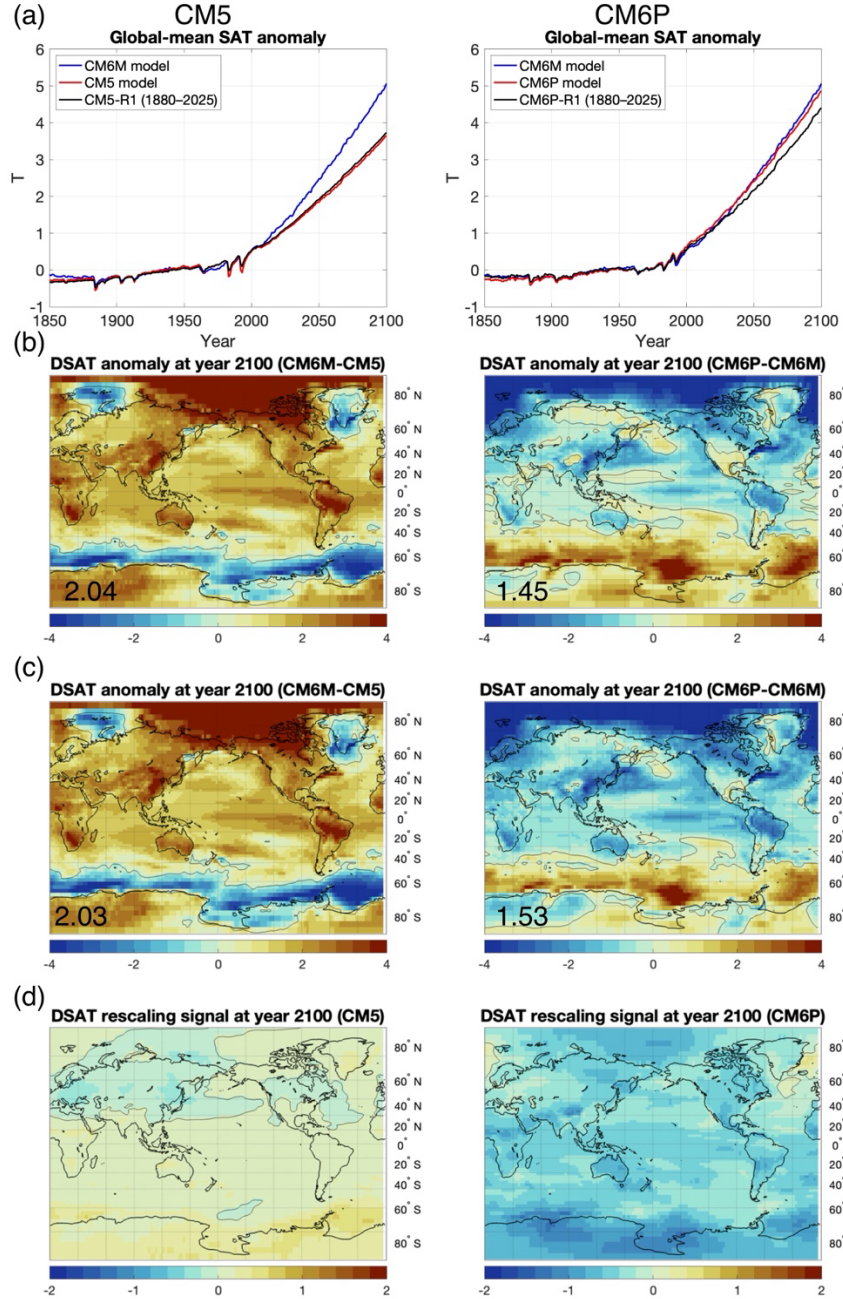


Fig. S18 Pattern-recognition based rescaling of the CM5 (left column) and CM6P (right column) model simulations using the CM6M simulated (historical and future) climates as ground truth: (a) unscaled and rescaled global-mean temperature anomaly time series [with respect to the 1880–2025 mean] (see legend for details); (b) the difference between the unscaled S/NP-extrapolated CM5 or CM6P forced-signal and the CM6M (ensemble-mean) temperature anomaly at year 2100; (c) the same as in (b) but using the rescaled forced signals; (d) the rescaling signal — the difference between rescaled and unscaled CM5 or CM6P temperature anomalies at year 2100. The rescaling here is based on the CO₂-congruent SAT signals and DCO₂ S/NP components computed over the 1880–2025 training period. The number at the lower-left corner of each panel shows the global root-mean-square value of the corresponding field. Units are degrees C. Analogous to Fig. 13 of the main text for the rescaling based on the CM5 “ground truth.”

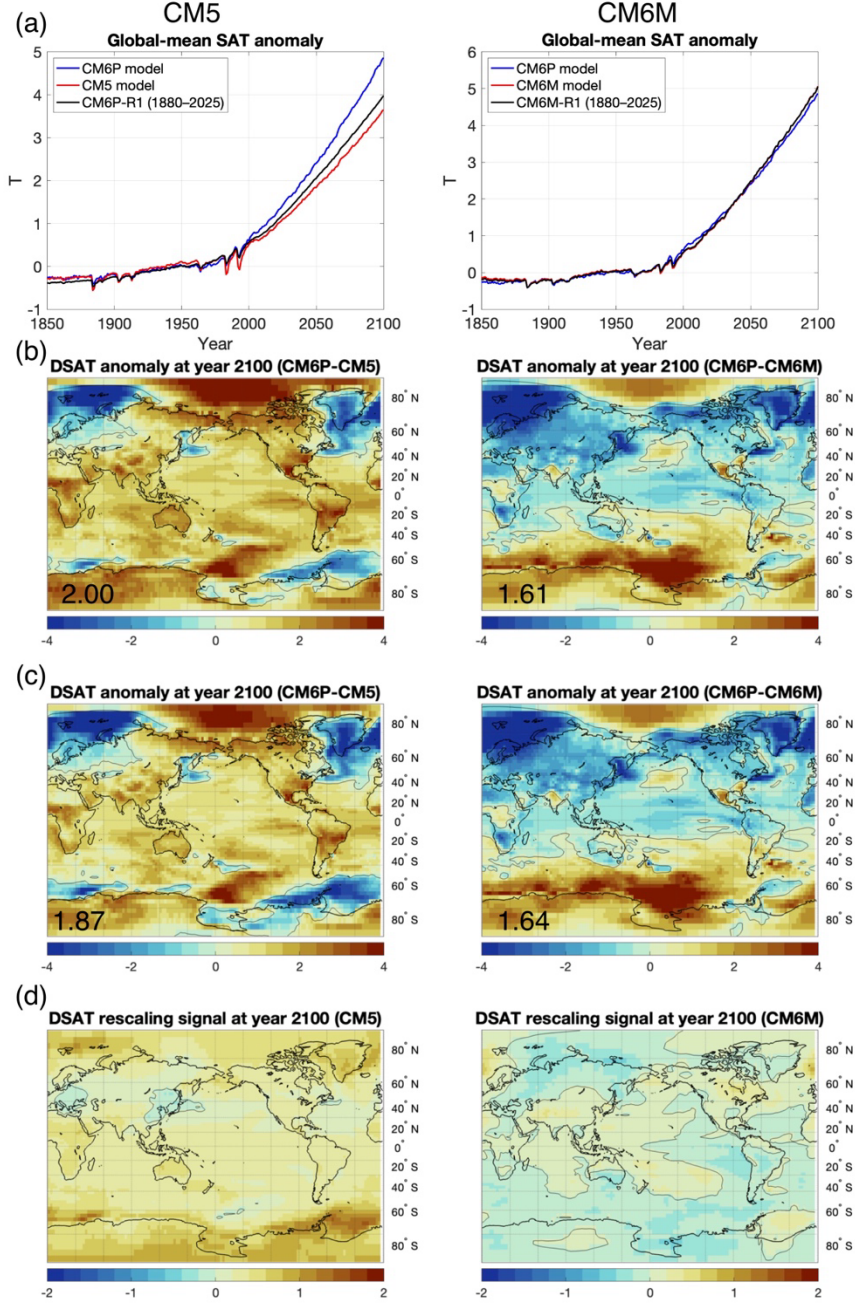


Fig. S19 Pattern-recognition based rescaling of the CM5 (left column) and CM6M (right column) model simulations using the CM6P simulated (historical and future) climates as ground truth: (a) unscaled and rescaled global-mean temperature anomaly time series [with respect to the 1880–2025 mean] (see legend for details); (b) the difference between the unscaled S/NP-extrapolated CM5 or CM6M forced-signal and the CM6P (ensemble-mean) temperature anomaly at year 2100; (c) the same as in (b) but using the rescaled forced signals; (d) the rescaling signal — the difference between rescaled and unscaled CM5 or CM6M temperature anomalies at year 2100. The rescaling here is based on the CO₂-congruent SAT signals and DCO₂ S/NP components computed over the 1880–2025 training period. The number at the lower-left corner of each panel shows the global root-mean-square value of the corresponding field. Units are degrees C. Analogous to Fig. 13 of the main text for the rescaling based on the CM5 “ground truth.”