

## Supplementary Materials for

### Past warming trend constrains future warming in CMIP6 models

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#### This PDF file includes:

Fig. S1. Estimated contribution of Pacific and Atlantic internal variability to GSAT in °C per decade during 1981–2014 and 1981–2017.

Fig. S2. Correlation of the simulated warming trend for the period 1981–2017 with TCR.

Fig. S3. Correlation of the simulated warming trend for the period 1981–2014 with TCR, showing different types of regression and methods of estimating the uncertainty of the regression.

Fig. S4. Correlations of future warming in CMIP5 and CMIP6 models (with respect to 1995–2014 baseline), with the simulated past warming trend (1981–2017).

Fig. S5. Correlations of future warming in CMIP6 models (with respect to 1995–2014 baseline), with the simulated past warming trend (1981–2017).

Fig. S6. Correlations of TCR and ECS with future warming in CMIP6 and CMIP5 models.

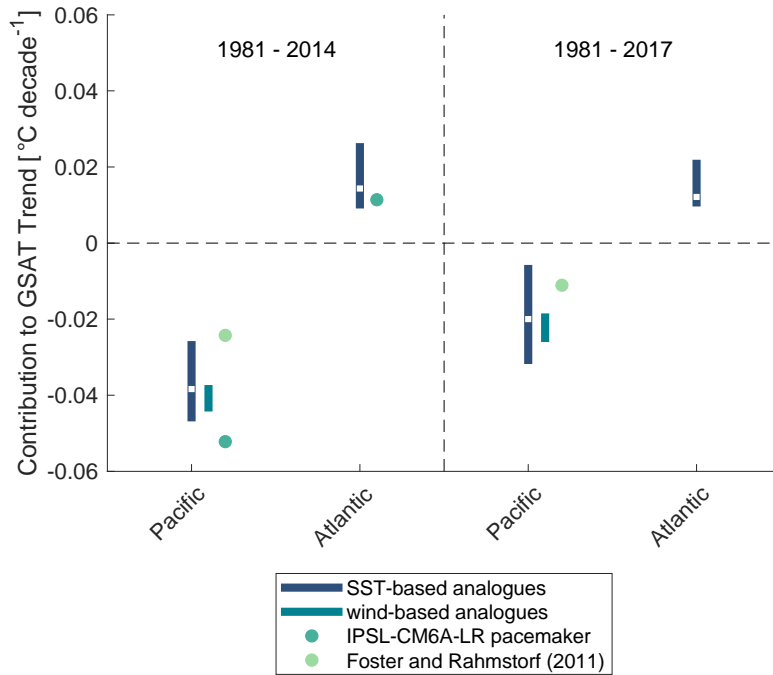
Table S1. CMIP6 models used in this study with their TCR and ECS values.

Table S2. GSAT trends for the periods 1981–2017 and 1981–2014 and estimates of the effect of internal variability of CMIP5 and CMIP6 models.

Table S3. TCR ranges (constrained and unconstrained) in CMIP6 and CMIP5 models.

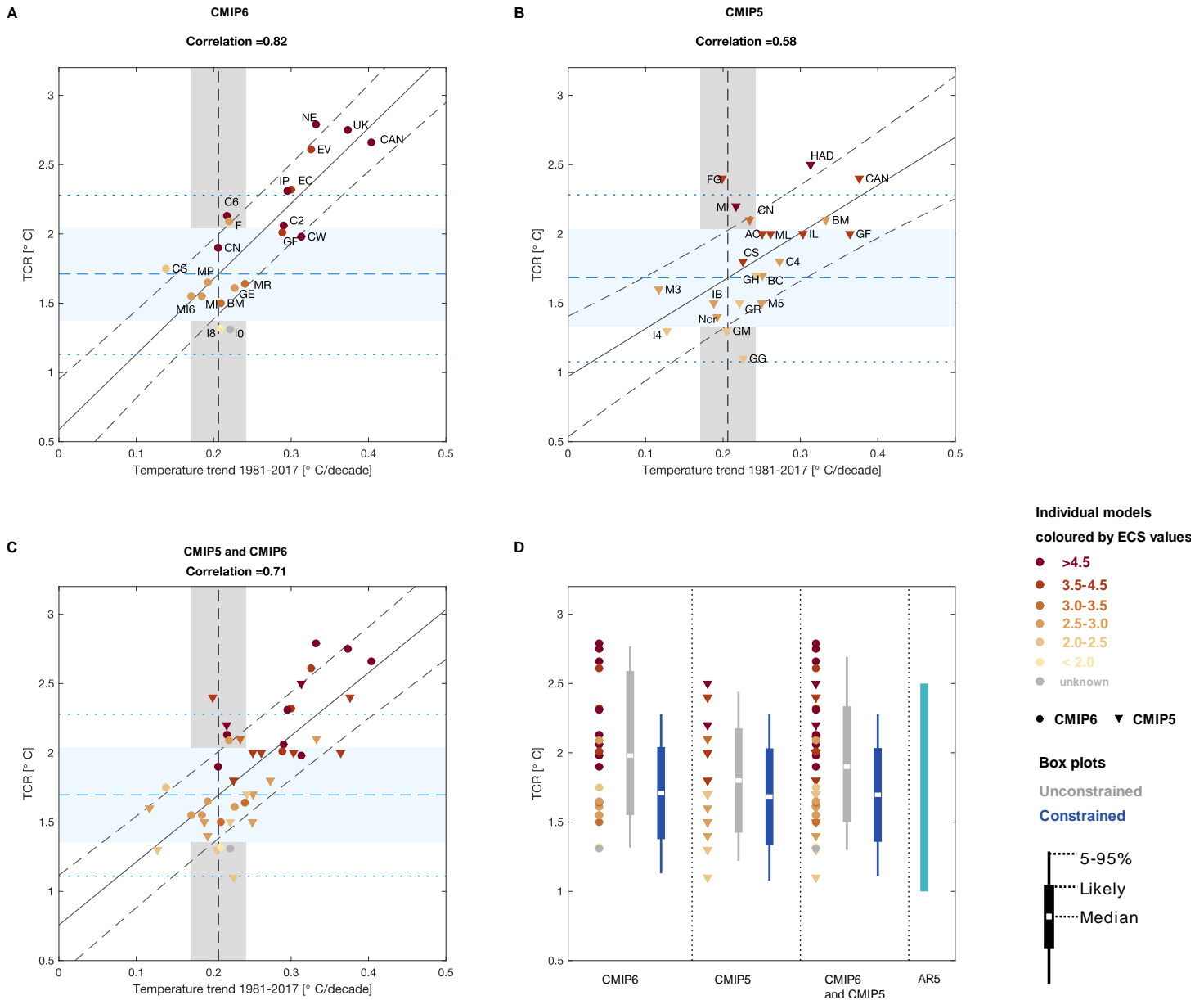
Table S4. Future warming (constrained and unconstrained) in CMIP6 models under different SSP scenarios, as labeled.

References (55, 56)

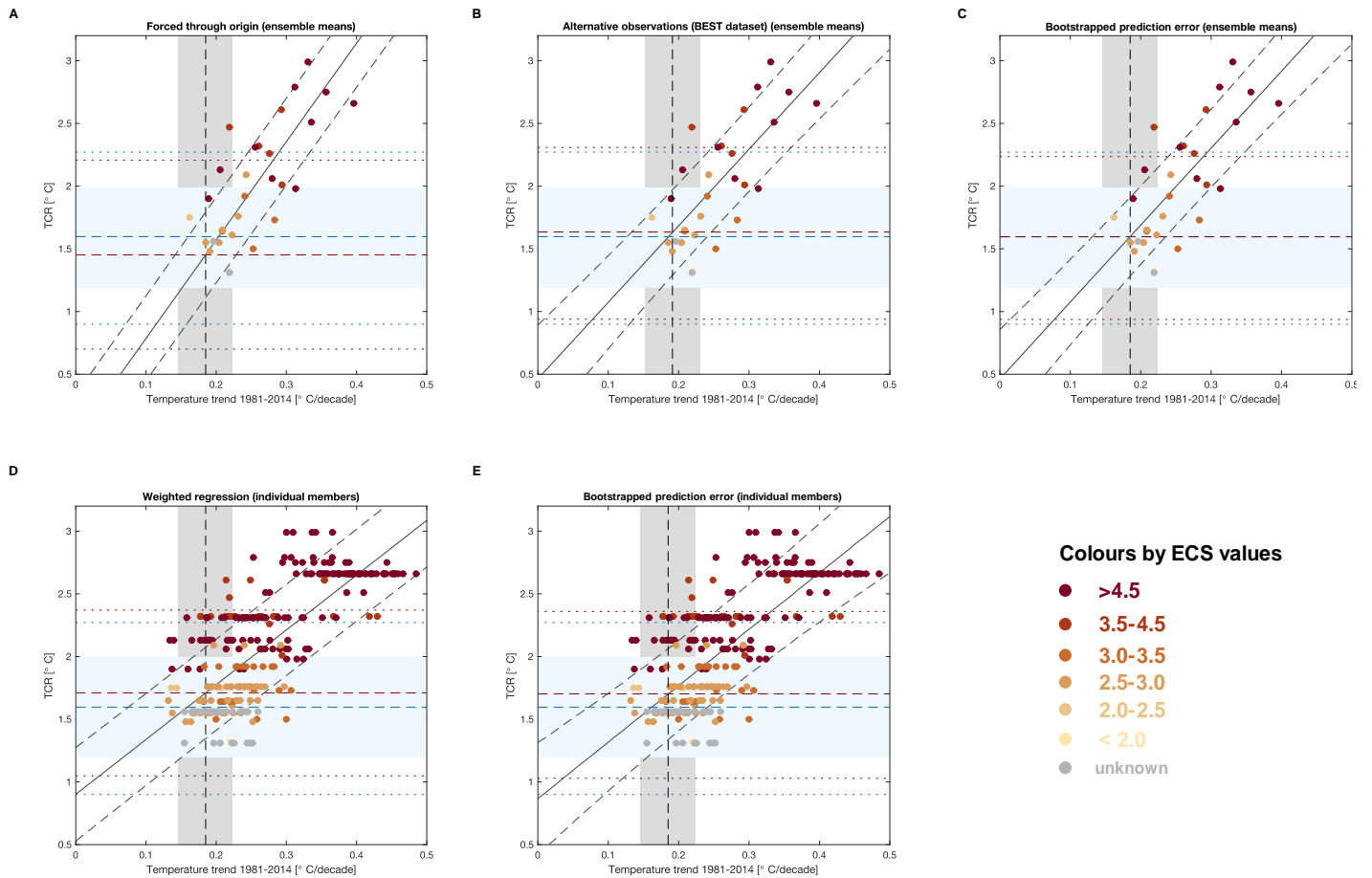


**Fig. S1. Estimated contribution of Pacific and Atlantic internal variability to GSAT in °C per decade during 1981–2014 and 1981–2017.** We report the minimum to maximum range across the different SST and wind stress datasets, and methods to remove the forced signal from observations (see Materials and Methods). For the SST-based analogues we show a best estimate based on removing the scaled CMIP6 multi-model mean GBST (historical extended with SSP5-8.5) from the observed time series of tropical Pacific and North Atlantic SST (white marker within blue bar). For the best estimate we report the mean of the COBE-SST2 and ERSSTv5 datasets. For 1981-2014, we estimate a Pacific contribution of  $-0.038$  °C per decade ( $-0.026$  to  $-0.047$  °C per decade range) and an Atlantic contribution of  $0.014$  °C ( $0.009$  to  $0.026$  °C) per decade, resulting in a slightly negative contribution from internal variability. For 1981-2017, we estimate a weaker Pacific contribution of  $-0.020$  °C per decade ( $-0.006$  to  $-0.032$  °C per decade) that is partly compensated by an Atlantic contribution of  $0.012$  °C per decade ( $0.010$  to  $0.022$  °C per decade). The combined influence of Pacific and Atlantic variability is by around  $0.016$  °C per decade smaller during 1981-2017 than during 1981-2014. This is consistent with the around  $0.02$  °C per decade larger observed GBST increase during 1981-2017 compared to 1981-2014 (the CMIP6 ensemble indicates nearly identical forced GSAT trends during the two periods).

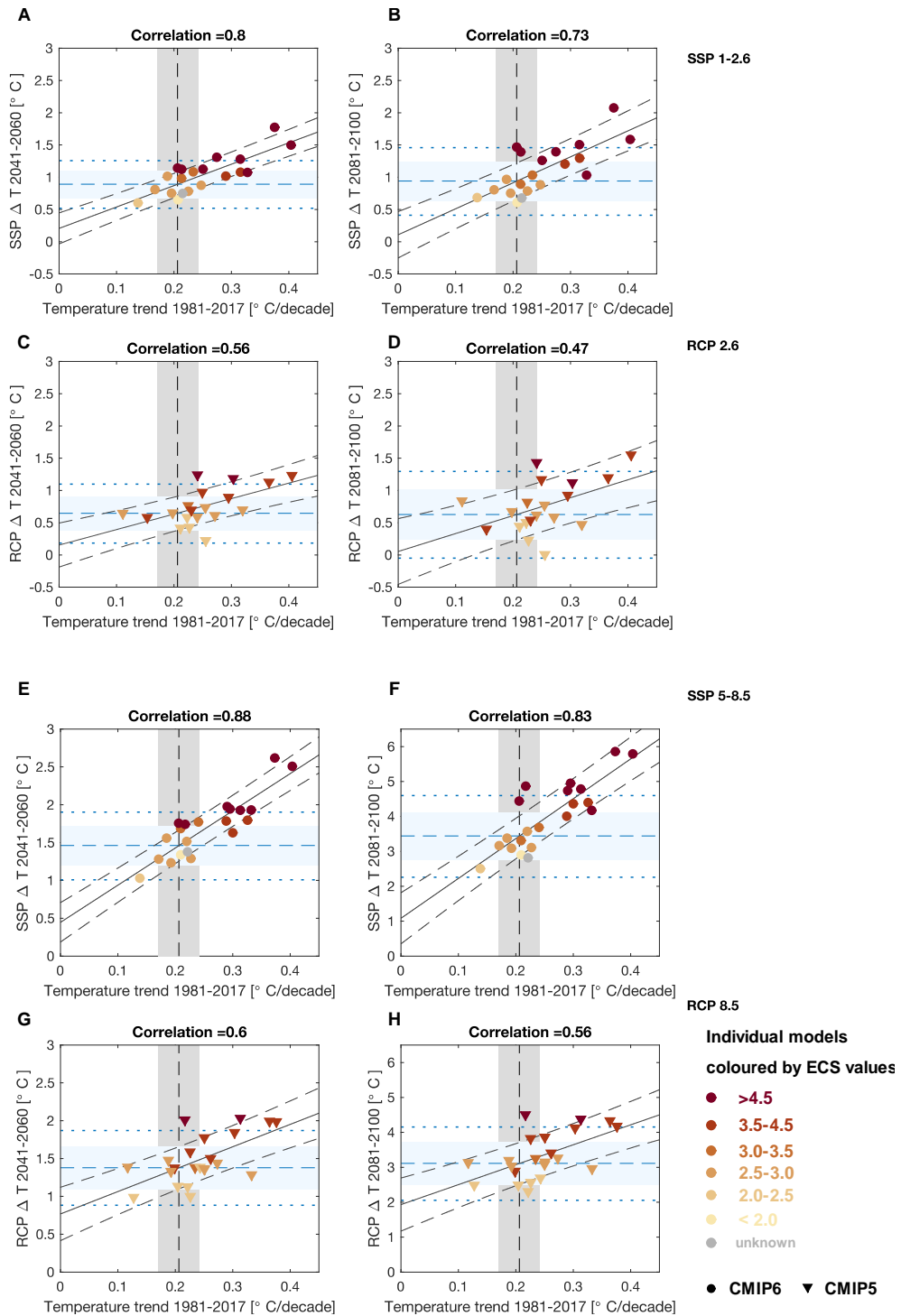
Also shown are the results of the IPSL-CM6A-LR pacemaker experiments where the model was nudged towards observed SST (ERSSTv4) over the tropical Pacific ( $15^{\circ}\text{S}$  -  $15^{\circ}\text{N}$ ,  $180^{\circ}\text{W}$  to American coast) and the North Atlantic ( $10^{\circ}\text{N}$  -  $65^{\circ}\text{N}$ )<sup>55</sup>. The Atlantic and Pacific contribution to GSAT is estimated as the difference between the historical and the nudged simulations of IPSL-CM6A-LR. For the Pacific contribution to GSAT we further show an updated estimate of Ref.<sup>56</sup>.



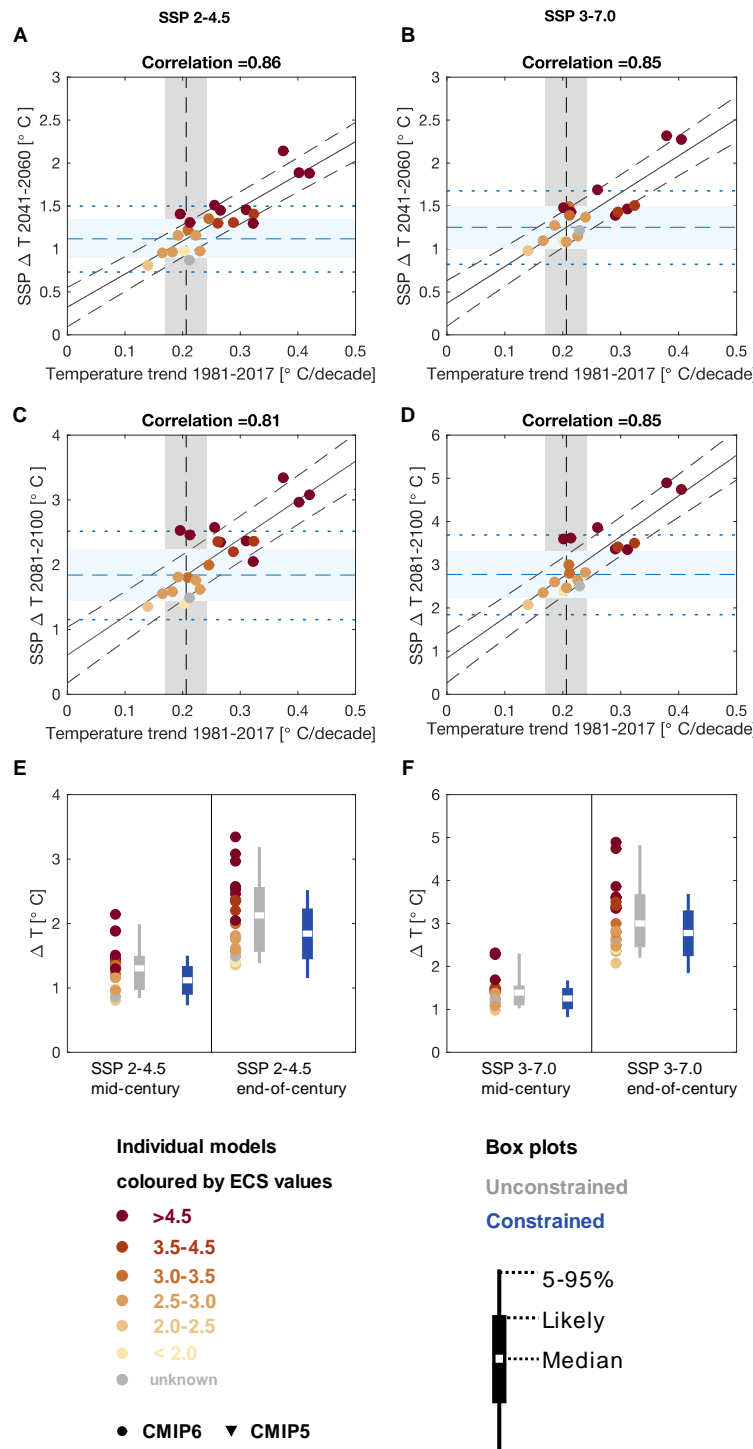
**Fig. S2. Correlation of the simulated warming trend for the period 1981–2017 with TCR.** (As Fig. 2, but for a longer period, with less CMIP6 models available). (A) based on CMIP6 models; (B) based on CMIP5 models; (C) based on the joint distribution of CMIP6 models (circles) and CMIP5 models (triangles). The emergent constraint is based on the Cowtan and Way<sup>27</sup> and GISTEMP<sup>28,29</sup> datasets, as in Fig. 2. If a model had more than one ensemble member, its ensemble mean is shown and was used in the regression. On panels a-c, grey rectangle shows observed trends for the period 1981-2017 (with the uncertainty range as in Fig. 2). Blue rectangle indicates the likely range (>66%) of the emergent constraint on future warming (TCR). Median value is shown by dashed blue lines, and dotted blue lines indicate 5-95% uncertainty range. (D) Constrained and unconstrained ranges of TCR based on CMIP6 and CMIP5 models, compared with the IPCC AR5 likely range. Unconstrained ranges (gray box plots) are based on raw CMIP models, shown to the left of each box plot by individual dots. Constrained ranges (blue box plots) are based on the emergent constraint (as in top panels). The last (teal) box plot on each panel shows the IPCC AR5 likely (>66% probability; equivalent to 17-83% range) range. Each box plot shows 5-95% range, likely range, and median value, as illustrated in the legend.



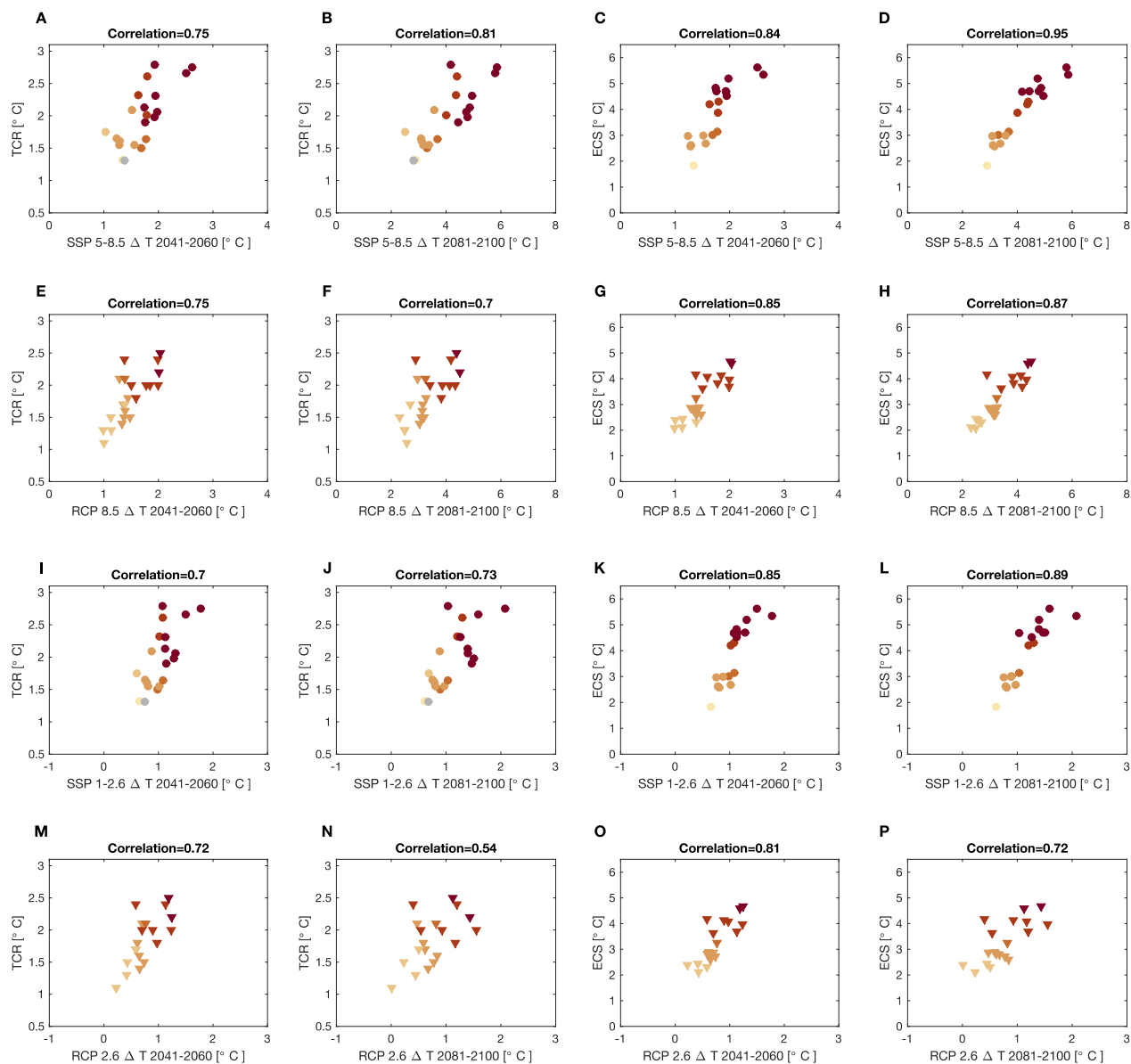
**Fig. S3. Correlation of the simulated warming trend for the period 1981–2014 with TCR, showing different types of regression and methods of estimating the uncertainty of the regression.** (A) OLS forced through the origin; (B) OLS using an alternative observational dataset (Berkeley Earth Surface Temperature<sup>31</sup>; BEST); (C) Bootstrapped estimate of the prediction error of the fit (using ensemble means where available); (D) weighted linear regression on individual ensemble members from different models; (E) like (D) but bootstrapped prediction error of the fit. The blue rectangle and blue lines indicate the constraint (likely and 5-95% range) same as in Fig. 2 A, based on the Cowtan and Way<sup>27</sup> and GISTEMP<sup>28,29</sup> datasets, while the red rectangle and red lines indicate the likely and 5-95% ranges based on the methods indicated in the title of each plot. The grey rectangles indicate the observational uncertainty ( $\pm 1\sigma$  and  $\pm 2\sigma$ , as in Fig. 2). Weights in (D) are reciprocals of the number of ensemble members per model (i.e., if a model provides a larger number of ensemble members, its members are down-weighted compared to a model with fewer members). For (E) we randomly sampled one member per model and then sampled the models randomly with replacement. Thereby, the ensemble members of models with fewer members are selected more often than members from large ensembles and the result is similar to (D). Models are colored by their respective ECS values, as in Fig. 2 and Fig. S2.



**Fig. S4. Correlations of future warming in CMIP5 and CMIP6 models (with respect to 1995–2014 baseline), with the simulated past warming trend (1981–2017).** (A–D) SSP1-2.6 scenario and RCP 2.6 scenario, (E–H) SSP5-8.5 scenario and RCP 8.5 scenario. Left columns show warming by the mid-century (2041–2060), right columns show warming by the end of the century (2081–2100). Future warming is with respect to the 1995–2014 baseline in all panels (as in Fig. S4 and Fig. 6). The grey rectangle shows observed warming trends for the period 1981–2017, based on the Cowtan and Way<sup>27</sup> and GISTEMP<sup>28,29</sup> datasets. The blue rectangle indicates the likely range (>66%) of the emergent constraints on future warming, median value is shown by dashed blue lines, and dotted blue lines indicate 5–95% uncertainty range (as in Fig. 2 and Fig. 5).



**Fig. S5. Correlations of future warming in CMIP6 models (with respect to 1995–2014 baseline), with the simulated past warming trend (1981–2017).** (A,C,E) SSP2-4.5 scenario. (B,D,F) SSP3-7.0 scenario. Top columns show warming by the mid-century (2041-2060), bottom columns show warming by the end of the century (2081-2100). Future warming is with respect to the 1995-2014 baseline in all panels (as in Fig. 5). Grey rectangle shows observed warming trends for the period 1981-2017, using the Cowtan and Way<sup>27</sup> and GISTEMP<sup>28,29</sup> datasets (as in Fig. 5). Blue rectangle indicates the likely range (>66%) of the emergent constraints on future warming. Median value is shown by dashed blue lines, and dotted blue lines indicate 5-95% uncertainty range. For model names, see Fig. 2.



**Fig. S6. Correlations of TCR and ECS with future warming in CMIP6 and CMIP5 models.** Warming for a given period (2041-2060 or 2081-2100, as indicated on the horizontal axis) is shown with respect to 1995-2014 baseline, for SSP 1-2.6, SSP 5-8.5, RCP 2.6, and RCP 8.5 scenarios, as labelled.

## Supplementary Tables

**Table S1. CMIP6 models used in this study with their TCR and ECS values.** ECS values above the IPCC AR5 likely range (of 1.5 °C to 4.5 °C) are highlighted in red, and corresponding models are referred here as high ECS models (models in the ECS column). TCR values above the likely AR5 range of (1 °C to 2.5 °C) are also highlighted in red. TCR and ECS values are calculated as in Ref.<sup>8</sup>, see Materials and Methods. For ECS and TCR values in CMIP5 models see Ref.<sup>8</sup>. (Table S1 shows available CMIP6 ensemble members as of Dec 4th 2019).

Model name	TCR [°C]	ECS [°C]	historical	Ensemble size			
				SSP 5-8.5	SSP 3-7.0	SSP 2-4.5	SSP 1-2.6
BCC-CSM2-MR	1.50	3.01	3	1	1	1	1
BCC-ESM1	1.73	3.23	3	0	0	0	0
CAMS-CSM1-0	1.75	2.29	3	2	2	2	2
CanESM5	2.66	5.62	50	50	50	50	50
CESM2	2.06	5.19	11	2	2	1	1
CESM2-WACCM	1.98	4.70	3	1	1	1	1
CNRM-CM6-1	2.13	4.83	20	6	6	6	6
CNRM-CM6-1-HR	2.47	4.28	1	0	0	0	0
CNRM-ESM2-1	1.90	4.70	5	5	5	5	5
E3SM-1-0	2.99	5.32	5	0	0	0	0
EC-Earth3	2.32	4.20	18	7	7	7	7
EC-Earth3-Veg	2.61	4.30	4	3	3	3	3
FGOALS-f3-L	2.09	2.99	3	1	1	1	1
GFDL-CM4	2.01	3.87	1	1	0	1	0
GFDL-ESM4	1.61	2.62	1	1	1	1	1
GISS-E2-1-G	1.76	2.72	22	0	0	0	0
GISS-E2-1-H	1.92	3.11	10	0	0	0	0
HadGEM3-GC31-LL	2.51	5.50	4	0	0	1	0
INM-CM4-8	1.32	1.83	1	1	1	1	1
INM-CM5-0	1.39	1.92	8	1	3	1	1
IPSL-CM6A-LR	2.31	4.52	32	1	10	5	3
MIROC-ES2L	1.55	2.68	3	1	1	1	1
MIROC6	1.55	2.57	10	3	3	3	3
MPI-ESM1-2-HR	1.65	2.97	10	1	1	1	1
MRI-ESM2-0	1.64	3.14	5	1	5	1	1
NESM3	2.79	4.68	5	2	0	2	2
NorCPM1	1.56	-	30	0	0	0	0
NorESM2-LM	1.48	2.60	3	0	0	0	0
SAM0-UNICON	2.26	3.72	1	0	0	0	0
UKESM1-0-LL	2.75	5.34	10	5	5	5	5
<b>Mean</b>	2.01	3.74	<b>30</b>	<b>21</b>	<b>19</b>	<b>22</b>	<b>20</b>
<b>Median</b>	1.95	3.72	Number of models				
<b>Max</b>	2.99	5.62					
<b>Min</b>	1.32	1.83					

*Note: ECS of INM-CM5-0 was not available at the time of the analysis, but is here included for the sake of completeness.*



**Table S2. GSAT trends for the periods 1981–2017 and 1981–2014 and estimates of the effect of internal variability of CMIP5 and CMIP6 models.** Based on the historical simulations, followed by the RCP 8.5 or SSP5-8.5 scenario (where available) using the large initial condition ensembles of 11 Earth System Models with at least 20 ensemble members (EC-EARTH was included as it is part of the Large Ensembles intercomparison). Internal variability estimates are shown in the two blue ‘standard deviation’ columns.

Model name	Ensemble size	Scenario	Mean trend 1981-2017 [°C/decade]	Mean trend 1981-2014 [°C/decade]	Standard deviation [°C/decade] 1981-2017	Standard deviation [°C/decade] 1981-2014
CanESM2	50	RCP 8.5 +historical	0.361	0.357	0.0224	0.0230
CESM1-CAM5	40	RCP 8.5 +historical	0.224	0.215	0.0282	0.0316
CSIRO-Mk3-6-0	30	RCP 8.5 +historical	0.237	0.230	0.0365	0.0395
EC-EARTH	16	RCP 8.5 +historical	0.240	0.237	0.0295	0.0297
GFDL-CM3	20	RCP 8.5 +historical	0.382	0.382	0.0474	0.0493
GFDL-ESM2M	30	RCP 8.5 +historical	0.224	0.226	0.0271	0.0316
MPI-ESM1.1	100	RCP 8.5 +historical	0.211	0.211	0.0277	0.0337
CanESM5	50	SSP5-8.5 +historical	0.404	0.396	0.0363	0.0399
CNRM-CM6-1	20	historical	-	0.206	-	0.0429
GISS-E2-1-G	22	historical	-	0.231	-	0.0291
IPSL-CM6A-LR	32	historical	-	0.256	-	0.0453
NorCPM1	30	historical - extended	0.201	0.196	0.0240	0.0267
<b>Mean</b>			<b>0.276</b>	<b>0.262</b>	<b>0.0310</b>	<b>0.0352</b>

*Note: Fig. 4 did not make use of the CNRM-CM6-1, GISS-E2-1-G, and IPSL-CM6A-LR ensembles.*

**Table S3. TCR ranges (constrained and unconstrained) in CMIP6 and CMIP5 models.** The ranges are based on an observational constraint for two different periods (1981-2014; as in Fig. 1) and (1981-2017; as in Supplementary Fig. S2). Numbers are rounded to two decimal places. Percentages were calculated on original values before rounding.

<b>Constraints on TCR in CMIP6 and CMIP5 models</b>						
(using observed warming for 1981-2014; as in main text)						
	<b>CMIP6 raw [°C]</b>	<b>CMIP6 constrained [°C]</b>	<b>CMIP5 raw [°C]</b>	<b>CMIP5 constrained [°C]</b>	<b>Both raw [°C]</b>	<b>Both constrained [°C]</b>
<b>median</b>	1.95	1.60	1.80	1.65	1.91	1.64
<b>likely range (&gt;66%)</b>	1.55 - 2.55	1.20 - 1.99	1.42 - 2.18	1.28 - 2.01	1.50 - 2.40	1.26 - 2.02
<b>5-95% range</b>	1.32 - 2.79	0.90 - 2.27	1.22 - 2.44	1.02 - 2.27	1.30 - 2.74	0.98 - 2.29
<b>difference</b>	<b>22.1%</b>	<b>-18.1%</b>	<b>9.1%</b>	<b>-8.3%</b>	<b>16.6%</b>	<b>-14.2%</b>
<b>Constraints on TCR in CMIP6 and CMIP5 models</b>						
(using observed warming for 1981-2017; sensitivity to a different period)						
	<b>CMIP6 raw [°C]</b>	<b>CMIP6 constrained [°C]</b>	<b>CMIP5 raw [°C]</b>	<b>CMIP5 constrained [°C]</b>	<b>Both raw [°C]</b>	<b>Both constrained [°C]</b>
<b>median</b>	1.98	1.71	1.80	1.68	1.90	1.70
<b>likely range (&gt;66%)</b>	1.55 - 2.59	1.38 - 2.04	1.42 - 2.18	1.33 - 2.03	1.50 - 2.34	1.36 - 2.03
<b>5-95% range</b>	1.32 - 2.77	1.13 - 2.28	1.22 - 2.44	1.08 - 2.28	1.30 - 2.69	1.11 - 2.28
<b>difference</b>	<b>15.7%</b>	<b>-13.6%</b>	<b>6.9%</b>	<b>-6.4%</b>	<b>12.0%</b>	<b>10.7%</b>

*Note: “% difference” as shown in the “raw” (i.e., unconstrained warming) columns refers to the ratio of unconstrained to constrained median warming (expressed as a percentage). The % difference in the “constrained” columns refers to the ratio of constrained to unconstrained median warming.*

**Table S4. Future warming (constrained and unconstrained) in CMIP6 models under different SSP scenarios, as labeled.** Numbers are rounded to two decimal places. Percentages were calculated on original values before rounding.

<b>Constraints on future warming in CMIP6 models</b>				
<i>(<math>\Delta T</math> with respect to 1995-2014 baseline, using observed warming for 1981-2017)</i>				
<b>mid-century (2041-2060)</b>	<b>SSP 5-8.5 raw [°C]</b>	<b>SSP 5-8.5 constrained [°C]</b>	<b>SSP 1-2.6 raw [°C]</b>	<b>SSP 1-2.6 constrained [°C]</b>
<b>median</b>	1.74	1.46	1.05	0.89
<b>likely range (&gt;66%)</b>	1.29 - 1.94	1.20 - 1.72	0.75 - 1.28	0.68 - 1.10
<b>5-95% range</b>	1.14 - 2.56	1.01 - 1.90	0.63 - 1.64	0.52 - 1.26
<b>% difference</b>	<b>19.2%</b>	<b>-16.1%</b>	<b>17.3%</b>	<b>-14.8%</b>
<b>end-of century (2081-2100)</b>	<b>SSP 5-8.5 raw [°C]</b>	<b>SSP 5-8.5 constrained [°C]</b>	<b>SSP 1-2.6 raw [°C]</b>	<b>SSP 1-2.6 constrained [°C]</b>
<b>median</b>	4.01	3.44	1.03	0.94
<b>likely range (&gt;66%)</b>	3.09 - 4.86	2.76 - 4.11	0.75 - 1.47	0.64 - 1.24
<b>5-95% range</b>	2.67 - 5.82	2.26 - 4.60	0.64 - 1.83	0.41 - 1.46
<b>% difference</b>	<b>16.4%</b>	<b>-14.1%</b>	<b>9.7%</b>	<b>-8.9%</b>

<b>Constraints on future warming in CMIP6 models</b>				
<i>(<math>\Delta T</math> with respect to 1995-2014 baseline, using observed warming for 1981-2017)</i>				
<b>mid-century (2041-2060)</b>	<b>SSP 3-7.0 raw [°C]</b>	<b>SSP 3-7.0 constrained [°C]</b>	<b>SSP 2-4.5 raw [°C]</b>	<b>SSP 2-4.5 constrained [°C]</b>
<b>median</b>	1.39	1.25	1.30	1.12
<b>likely range (&gt;66%)</b>	1.09 - 1.56	1.00 - 1.50	0.97 - 1.50	0.89 - 1.34
<b>5-95% range</b>	1.03 - 2.30	0.82 - 1.68	0.84 - 1.99	0.73 - 1.50
<b>% difference</b>	<b>11.1%</b>	<b>-10.0%</b>	<b>16.6%</b>	<b>-14.2%</b>
<b>end-of century (2081-2100)</b>	<b>SSP 3-7.0 raw [°C]</b>	<b>SSP 3-7.0 constrained [°C]</b>	<b>SSP 2-4.5 raw [°C]</b>	<b>SSP 2-4.5 constrained [°C]</b>
<b>median</b>	3.00	2.78	2.12	1.84
<b>likely range (&gt;66%)</b>	2.45 - 3.68	2.24 - 3.31	1.56 - 2.56	1.44 - 2.23
<b>5-95% range</b>	2.20 - 4.83	1.84 - 3.69	1.38 - 3.18	1.15 - 2.52
<b>% difference</b>	<b>8.1%</b>	<b>-7.5%</b>	<b>15.4%</b>	<b>-13.4%</b>

*Note: “% difference” as shown in the “raw” (i.e., unconstrained warming) columns refers to the ratio of unconstrained to constrained median warming (expressed as a percentage). The % difference in the “constrained” columns refers to the ratio of constrained to unconstrained median warming.*