Supplementary Information for

Nonlinear sensitivity of El Niño/Southern Oscillation to climate states

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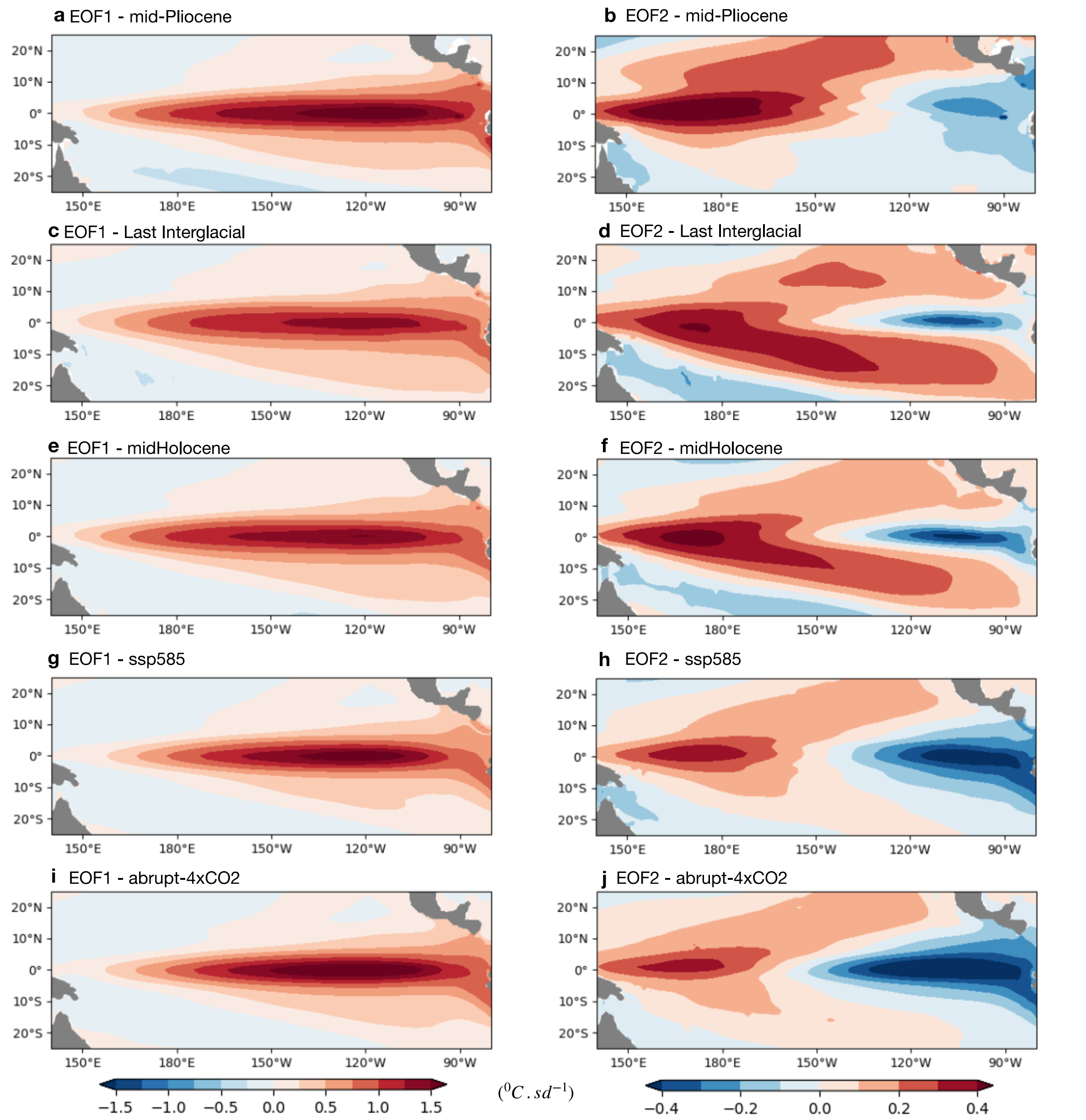
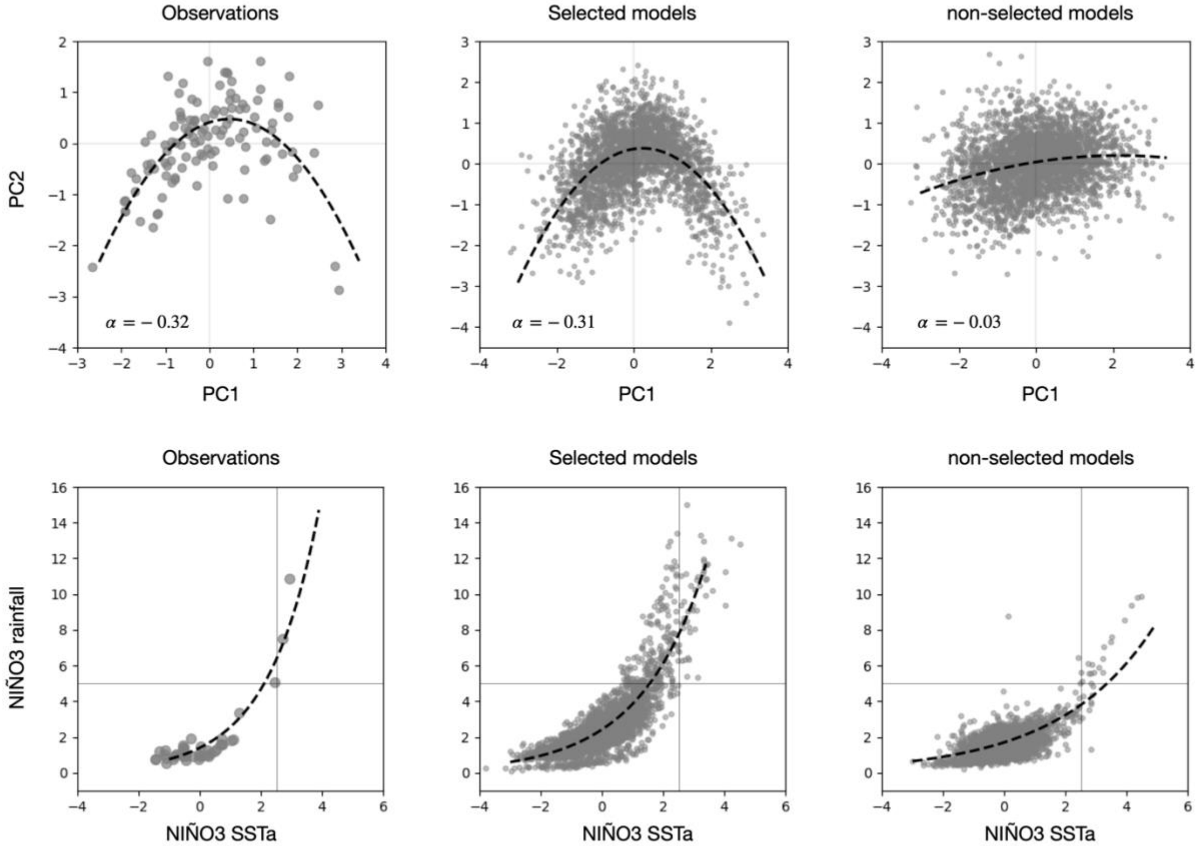
Text S1

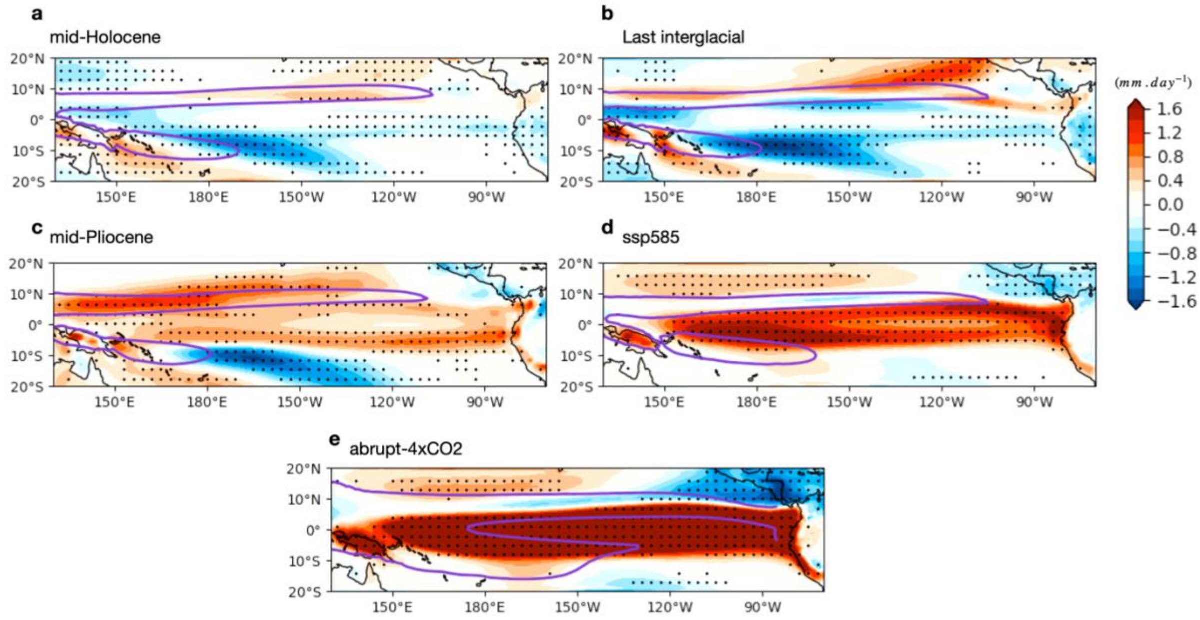
The significance of the quadratic relationship is assessed through the coefficient of determination (R^2), which is a statistical measure of how well the regression predictions approximate the real data points. To remove the possible bias of a few models that have simulated strong equatorward shifts in the position of the convection centers we have performed sensitivity analyses excluding the abrupt-4xCO2 results. Each relationship found in Figure 2 was thus statistically evaluated through a linear and a quadratic regression model obtained through the least squares method (Supporting Information Fig. S4). We find that for CP-ENSO and Niño3 indices the R^2 of the quadratic models are statistically higher than the R^2 of the linear models, indicating that the quadratic fit best represents these relationships. For EP-ENSO, although higher, the quadratic model is not statistically different from the linear model (R^2=0.66±0.03 and R^2=0.61±0.04, respectively). This indicates that when excluding extreme warming scenarios, the sensitivity of EP-ENSO to climate states can be approximated to a linear model, in agreement with Cai et al. (2018) and Pontes et al. (2022). Nonetheless, here we show that adding extreme warming scenarios (abrupt-4xCO2) yields a nonlinear relationship with significantly higher coefficient of determination (R^2=0.75±0.01) and reduced uncertainty. Sensitivities on the constraints for the future increase in EP-ENSO were also analyzed. Constraining future EP-ENSO variability with the same sensitivity of paleoclimatic simulations, by using the linear regression model, yields a 19% (4-34%) increase in EP-ENSO variability. The quadratic model that excludes abrupt-4xCO2 simulations results projects a future EP-ENSO increase of 23% (10-29%).



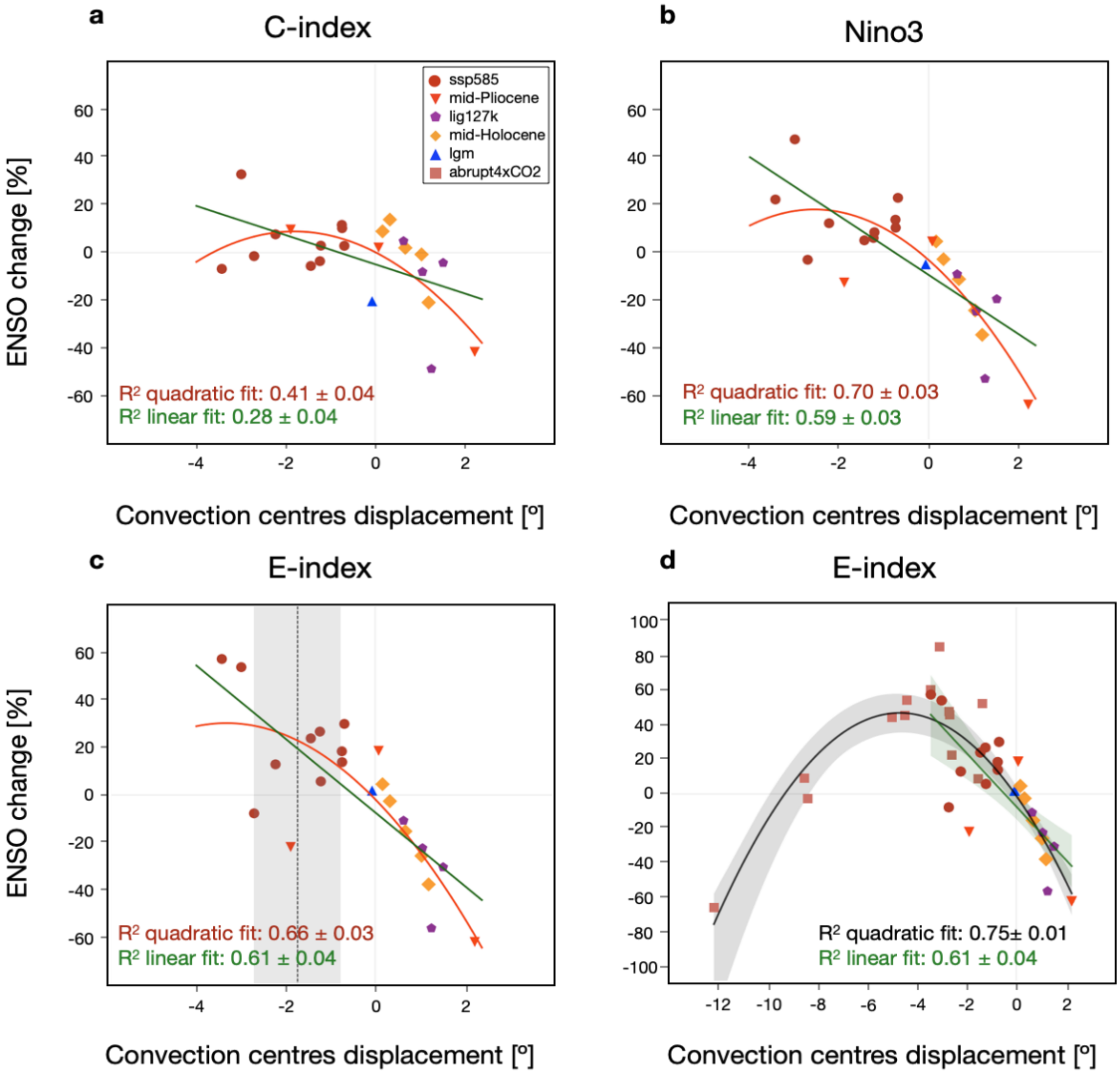
Supplementary Information Fig. S1. Multi-model mean spatial patterns of the first two SST EOFs in the tropical Pacific for each of the paleo and future scenarios evaluated in this study.



Supplementary **Information Fig. S2. Model selection criteria evaluation.** Upper row: relationship between the first and second principal components of SST anomalies in the tropical Pacific in observation, selected models and non-selected models. The nonlinear coefficient of the quadratic fitted model is indicated (a). Lower row: relationship between DJF Niño3 SST anomalies and DJF Niño3 rainfall in observations, selected models and non-selected models.



Supplementary Information Fig. S3. Multi-model mean precipitation changes. a mid-Holocene. **b** Last Interglacial. **c** Mid-Pliocene. **d** ssp585. **e** abrupt-4xCO2. Stippling indicates regions where there is at least a 75% model agreement on the sign of the change, which is statistically significant at the 95% level based on a binomial distribution. Purple lines indicate the multi-model mean 8 mm.day^{-1} rainfall contours for each experiment (mid-Holocene, Last interglacial, mid-Pliocene, ssp585, and abrup-4xCO2) as an estimative of the ITCZ and SPCZ positions.



Supplementary Information Fig. S4. Sensitivity tests for the ENSO-convection centers relationship for **a** C-index, **b** Niño3 **c** E-index. Quadratic and linear fits are indicated as well as their respective coefficients of determination (R^2). Errors were estimated through the bootstrap method. Black dashed line and grey band in **c** indicate multi-model mean and multi-model standard deviation of the displacement of the convection centers in the ssp585 simulations, respectively. **d** E-index relationship including abrupt-4xCO2 simulations. Banding indicates 95% confidence interval based on a 10,000-sample bootstrap. The black quadratic fit encompasses all data points while the green linear fit excludes abrupt-4xCO2 simulation (as in **c**). Banding indicates the 95% confidence interval based on 10,000-sample bootstrap analysis.

Supplementary Information Table S1. Values computed in pre-industrial control simulation. Models in bold have met the model selection criteria (alpha greater than 0.16 and convective feedback greater than 2). ITCZ and SPCZ columns indicate the true position in the pre-industrial control simulation. Alpha indicates the nonlinear coefficient of the relationship between the first two principal components of SSTa anomalies in the tropical Pacific. b_h indicates the value of the wind-thermocline coefficient. Asterisk indicates models that meet the nonlinear Bjerknes feedback criteria only.

	ITCZ [°]	SPCZ [°]	Alpha	Convective feedback [°C.mm^{-1}.day^{-2}]	Ocean stratification [°C]	b_h [m^3.N^{-1}]
piControl						
CAMS-CSM1-0	**9.5**	**-9.7**	**-0.26**	**2.1**	**-**	**-**
CCSM4-2deg	**10**	**-11.1**	**-0.5**	**2**	**1.4**	**2188**
CESM2-FV2	**9.2**	**-11.3**	**-0.33**	**2.8**	**1.6**	**1191**
CESM2-WACCM-FV2	**9.3**	**-10.6**	**-0.69**	**3**	**1.8**	**1048**
CESM2	**8.5**	**-10.7**	**-0.18**	**2.8**	**1.5**	**847**
CIESM	**8.1**	**11.6**	**-0.19**	**2.2**	**1.4**	**1141**
CMCC-ESM2	**8.1**	**11.6**	**-0.63**	**2.1**	**2.7**	**2139**
FGOALS-f3-L	**6.9**	**-9.8**	**-0.64**	**3.4**	**2.2**	**1847**
GISS-E2-1-G	**9.1**	**-9.9**	**-0.73**	**5**	**3.1**	**1241**
GISS-E2-2-G	**9.4**	**-10.1**	**-0.46**	**3.2**	**3.6**	**403**
HadGEM3-GC31-MM	**7.9**	**-10.2**	**-0.2**	**3.3**	**1.8**	**1782**
KIOST-ESM	**7.1**	**-10.2**	**-0.36**	**3**	**2.5**	**1523**
MIROC-ES2L	**7.4**	**-10.3**	**-0.57**	**2**	**1.5**	**1968**
MRI-ESM2-0	**8.5**	**-10.2**	**-0.42**	**3.7**	**1.4**	**942**
ACCESS-CM2	6.7	-9.2	-0.07	4.9	-	-
ACCESS-ESM1-5	7	-11.4	-0.02	3.2	-	-
BCC-CM2-MR	8.4	-9.3	-0.02	1.4	-	-
BCC-ESM1	-	-	-0.07	1.5	-	-
CCSM4-UofT	9.7	-11.8	0	1.3	-	-
CCSM4	9.1	-11	-	3.4	-	-
CESM1.2	8.9	-11.9	-	-	-	-
CESM2-WACCM	8.7	-11	-0.03	2.1	-	-
CMCC-CM2-SR5*	8.5	-11.9	-0.54	1.9	-	-
CNRM-CM6-1-HR	7.9	-8.7	-0.09	2.6	-	-
CNRM-CM6-1	8.3	-9.3	-0.05	2	-	-
CNRM-ESM2-1	8.2	-9.3	-0.09	2.3	-	-
COSMOS			-0.11	0.4	-	-
CanESM5-CanOE	8.6	-10.8	-0.12	1.9	-	-
CanESM5	8.4	-10.8	0.07	2.2	-	-
E3SM-1-0	-	-	0.07	1.5	-	-

E3SM-1-1-ECA	-	-	-0.02	-	-	-
E3SM-1-1	-	-	0.06	1.4	-	-
EC-EARTH3-AerChem	-	-	-	1.8	-	-
EC-EARTH3-CC	8	-11.7	-0.09	2.1	-	-
EC-EARTH3-LR	8	-11.8	-0.01	2.3	-	-
EC-EARTH3-Veg-LR	8	-11.5	-	0.7	-	-
EC-EARTH3-Veg	8	-11.9	-0.08	1.8	-	-
EC-EARTH3*	8.1	-11.8	-0.16	2.2	-	-
FGOALS-g3	6.3	-7.9	-0.04	2.7	-	-
FIO-ESM-2-0*	-	-	-0.33	-	-	-
GFDL-CM4	-	-	-0.02	-	-	-
GFDL-ESM4*	-	-	-0.16	-	-	-
GISS-E2-1-H*	9.3	-10.5	-0.32	1.7	-	-
GISS-E2-2-H	-	-	-0.11	1.2	-	-
HadCM3	6.4	-11.4	-0.06	-		
HadGEM3-GC31-LL	7.9	-10.8	-0.12	2.6	-	-
IITM-ESM	-	-	-0.2	3.8	-	-
INM-CM4-8	8.9	-12	0.04	3	-	-
INM-CM5-0	9.3	-11.8	0.08	2.9	-	-
IPSL-CM5A2	9.4	-9	-0.06	1.2	-	-
IPSL-CM5A	8.9	-9.1	-0.05	1.4	-	-

Supporting Information Table S1. Continued.

	ITCZ [º]	SPCZ [º]	Alpha	Convective feedback [ºC.mm^{-1}.day^{-1}]	Ocean stratification [ºC]	b_h [m^3.N^{-1}]
IPSL-CM6-LR	8.3	-10.9	0	1.2	-	-
MCM-UA-1-0*	6.6	-7.7	-0.16	0.9	-	-
MIROC4m	8.2	-8.6	0.05	0.7	-	-
MIROC6*	7.8	-12.2	-0.38	1.5	-	-
MPI-ESM1-2-HR*	9.1	-12.3	-0.45	0.5	-	-
MRI-CGCM2-3	9	-11.1	-0.15	2.1	-	-
NESM3	-	-	-0.05	-	-	-

NorESM-L	8.1	-8	-0.06	1.5	-	-
NorESM1-F	7.8	-9.9	-0.07	5.1	-	-
NorESM2-LM*	8.6	-10.7	-0.23	1.5	-	-
NorESM2-MM*	7.9	-11.1	-0.21	1.4	-	-
UKESM1-0-LL	8	-11.2	-0.04	2.1	-	-

Supplementary Information Table S2. Values computed in the paleo and future simulations. Niño3 column indicates the relative change in Niño3 standard deviation with respect to their associate pre-industrial control simulation. ITCZ and SPCZ columns indicate the true position in its respective simulation. D indicates the absolute displacement of the ITCZ and SPCZ with respect to their pre-industrial position. Ocean stratification and b_h indicates the true value for its respective simulation.

	Niño3 change (%)	ITCZ (º)	STCZ (º)	D (º)	Ocean stratification [ºC]	b_h [$m^3.N^{-1}$]
Mid-Holocene						
CESM2	**-11.6**	**8.5**	**-11.3**	**0.68**	**1.2**	**1039**
FGOALS-f3-L	**-3.2**	**6.9**	**-10.2**	**0.34**	**2.1**	**1770**
GISS-E2-1-G	**4.3**	**9.1**	**-10.1**	**0.17**	**4.1**	**1303**
MIROC-ES2L	**-35**	**7.8**	**-11.1**	**1.21**	**1.2**	**1350**
MRI-ESM2-0	**-24.8**	**8.5**	**-11.2**	**1.05**	**0.9**	**909**
ACCESS-ESM1-5	-9.6	7.4	-12.5	1.48	-	-
EC-EARTH3-LR	-3.1	7.9	-12	0.1	-	-
FGOALS-g3	-25.3	6.2	-8.5	0.52	-	-
HadGEM-GC31-LL	18.8	8.2	-11.7	1.08	-	-
INM-CM4-8	13.7	8.4	-11.3	-1.14	-	-
IPSL-CM6A-LR	-4.8	8.7	-11.3	0.78	-	-
NorESM1-F	-6.6	7.5	-9.7	-0.56	-	-
NorESM2-LM	-23.3	8.7	-11.8	1.22	-	-
Last Interglacial						
CESM2	**-20**	**9**	**-11.6**	**1.53**	**1.1**	**967**
GISS-E2-1-G	**-9.5**	**9**	**-10.7**	**0.65**	**2.7**	**1151**
FGOALS-f3-L	**-25.2**	**7.1**	**-10.6**	**1.07**	**1.5**	**1892**
MIROC-ES2L	**-53.6**	**8**	**-11**	**1.27**	**1**	**715**

ACCESS-ESM1-5	-16.5	8.1	-11.5	1.17	-	-
CNRM-CM6-1	-21	8.8	-9.6	0.89	-	-
EC-EARTH3-LR	-13.1	8.1	-12.6	0.89	-	-
FGOALS-g3	-24	6.4	-8.8	0.9	-	-
IPSL-CM6A-LR	-8.5	8.6	-11.1	0.49	-	-
NorESM1-F	-21	8.1	-10.3	0.7	-	-
NorESM2-LM	-1.1	9.3	-12.7	2.71	-	-
Mid-Pliocene						
CCSM4-2deg	**-64.5**	**10.6**	**-12.8**	**2.24**	**0.5**	**452**
CESM2	**-13.2**	**8.2**	**-9**	**-1.89**	**3.4**	**1526**
GISS-E2-1-G	**4.3**	**9.6**	**-9.5**	**0.09**	**4.1**	**1468**
CCSM4-UofT	-29	9.2	-11.6	-0.7	-	-
CCSM4	-43	8.9	-11.7	0.46	-	-
CESM1.2	-23.3	8.1	-11.7	-1.03	-	-
COSMOS	-3.2	11.9	-13.5	-0.92	-	-
EC-EARTH3-LR	-34	9.3	-12.1	1.66	-	-
HadCM3	-41.7	6.9	-12.8	1.89	-	-
HadGEM3-GC31-LL	-9.4	8.3	-10.5	0.09	-	-
IPSL-CM5A2	-18.2	9.7	-8.7	0.03	-	-
IPSL-CM5A	-15.1	9.3	-8.6	-0.04	-	-
IPSL-CM6-LR	-12.2	8.6	-11.4	0.3	-	-
MIROC4m	-16.6	8.1	-3.7	-0.1	-	-
MRI-CGCM2-3	-28.1	9.9	-9.5	0.69	-	-
NorESM1-L	-29.4	8.3	-6.1	0.24	-	-

NorESM1-F	-33.2	7.4	-10.6	0.33	-	-
Last Glacial Maximum						
MIROC-ES2L	**-5.3**	**7.3**	**-10.4**	**-0.06**	**1.8**	**1651**
INM-CM4-8	33.7	9.5	-8.5	-2.73	-	-

Supplementary Information Table S2. Continued.

	Niño3 change (%)	ITCZ (º)	SPCZ (º)	D (º)	Ocean stratification [ºC]	b_h [$m^3.N^{-1}$]
ssp585						
CAMS-CSM1-0	**18.4**	**9.5**	**-8.9**	**-0.74**	**-**	**-**
CESM2	**-3.4**	**8.3**	**-8.2**	**-2.71**	**3.6**	**1314**
CIESM	**12**	**6.8**	**-10.7**	**-2.23**	**3.1**	**1430**
CMCC-ESM2	**22.7**	**8**	**-11**	**-0.68**	**4.9**	**1876**
FGOALS-f3-L	**22**	**6.1**	**-7.2**	**-3.43**	**4.1**	**1972**
GISS-E2-1-G	**4.8**	**8.9**	**-8.8**	**-1.43**	**-**	**-**
HadGEM-GC31-MM	**10.1**	**7.6**	**-9.7**	**-0.73**	**4**	**1379**
KIOST-ESM	**8.2**	**7**	**-9.1**	**-1.21**	**3.8**	**1410**
MIROC-ES2L	**47.3**	**7.2**	**-7.6**	**-2.99**	**3.9**	**2567**
MRI-ESM2-0	**5.8**	**8.3**	**-9.1**	**-1.23**	**2.7**	**1286**
ACCESS-CM2	14.4	6.6	-8.9	-0.42	-	-
ACCESS-ESM1-5	3.6	6.8	-10.2	-1.43	-	-
BCC-CSM2-MR	-13.5	8.1	-8.9	-0.67	-	-
CAMS-CSM1-0	13.5	9.5	-8.9	-0.74	-	-
CESM2-WACCM	24.4	8.4	-9	-2.31	-	-
CMCC-CM2-SR5	12.3	8.3	-11.7	-0.35	-	-
CNRM-CM6-1-HR	19.8	7.6	-8	-0.94	-	-
CNRM-CM6-1	14.5	8.3	-8.3	-0.96	-	-
CNRM-ESM2-1	19.1	8.3	-8.3	-0.9	-	-
CanESM5-CanOE	14.8	8.6	-8.9	-1.97	-	-
CanESM5	29.1	8.5	-8.9	-1.89	-	-
E3SM-1-1-ECA	36.6	-	-	-	-	-
E3SM-1-1	30.7	-	-	-	-	-
EC-EARTH3-CC	77.7	8.1	-9.9	-1.73	-	-

EC-EARTH3-Veg-LR	71.6	8.2	-10.1	-1.18	-	-
EC-EARTH3-Veg	68.1	8.2	-10	-1.71	-	-
EC-EARTH3	86.2	8.3	-10	-1.59	-	-
FGOALS-g3	3.6	5.6	-5.9	-2.7	-	-
FIO-ESM-2-0	32.9	-	-	-	-	-
GFDL-CM4	18.2	-	-	-	-	-
GFDL-ESM4	18.6	-	-	-	-	-
GISS-E2-1-H	52.7	9.1	-9.4	-1.32	-	-
HadGEM-GC31-LL	19.9	8	-10.4	-0.36	-	-
IITM-ESM	18.1	-	-	-	-	-
INM-CM4-8	1	9	-11.5	-0.34	-	-
INM-CM5-0	-4	9.1	-11.6	-0.42	-	-
IPSL-CM6A-LR	5	8.2	-11.2	0.13	-	-
MCM-UA-1-0	21.5	5.3	-6.5	-2.49	-	-
MIROC6	30.6	7.6	-11.1	-1.43	-	-
MPI-ESM1-2-HR	7.3	8.8	-11.4	-1.13	-	-
NESM3	3.3	-	-	-	-	-
NorESM2-LM	50.2	9.2	-11.2	1.08	-	-
NorESM2-MM	43.1	8.3	-11.2	0.5	-	-
UKESM1-0-LL	1.8	8.1	-10.6	-0.57	-	-
Abrupt-4xCO2						
CESM2-FV2	**-6.5**	**6.8**	**-5.2**	**-8.51**	**5.4**	**1040**
CESM2-WACCM-FV2	**-25.6**	**6**	**-5.5**	**-8.39**	**5.1**	**846**
CIESM	**-15.9**	**6.3**	**-9**	**-4.4**	**-**	**-**
CESM2	**-67.3**	**3.4**	**-3.5**	**-12.15**	**7.9**	**133**
CMCC-ESM2	**25.7**	**7.6**	**-9.4**	**-2.7**	**6.7**	**1883**
FGOALS-f3-L	**3.1**	**5.7**	**-6**	**-5**	**5.2**	**1767**
GISS-E2-1-G	**-11.7**	**8.2**	**-8.2**	**-2.58**	**6.6**	**1468**
GISS-E2-2-G	**-16.8**	**9.3**	**-8.9**	**-1.37**	**6.4**	**751**
HadGEM3-GC31-MM	**1.8**	**7.3**	**-7.7**	**-3.07**	**6**	**1484**
MIROC-ES2L	**38.8**	**7**	**-6.3**	**-4.48**	**4.6**	**2965**

MRI-ESM2-0	**22.4**	**8**	**-7.3**	**-3.43**	**3.2**	**1327**
ACCESS-CM2	1	6.2	-6.6	-3.08	-	-
ACCESS-ESM1-5	25.5	6.7	-8.5	-3.18	-	-
CAMS-CSM1-0	1.3	9.3	-8.4	-1.51	-	-
CESM2-WACCM	1.9	6.9	-5.3	-7.49	-	-
CMCC-CM2-SR5	27.4	7.8	-9.7	-2.86	-	-
CNRM-CM6-1	12.5	7.8	-7	-2.84	-	-
CNRM-ESM2-1	12.3	7.7	-7.1	-2.66	-	-
CanESM5	26.5	8.3	-6.8	-4.09	-	-
HadGEM3-GC31-LL	23.9	8.1	-8.7	-2	-	-
INM-CM4-8	-4	8.9	-11.1	-0.82	-	-
INM-CM5-0	-5.9	8.9	-11.2	-0.93	-	-
UKESM1-0-LL	-1.4	8.1	-8.6	-2.59	-	-