

Supplementary Information for

Paleoclimate constrains future El Niño Southern Oscillation increase

Gabriel M. Pontes^{1,2,3*}, Pedro L. Silva Dias³ & Laurie Menviel^{1,2}

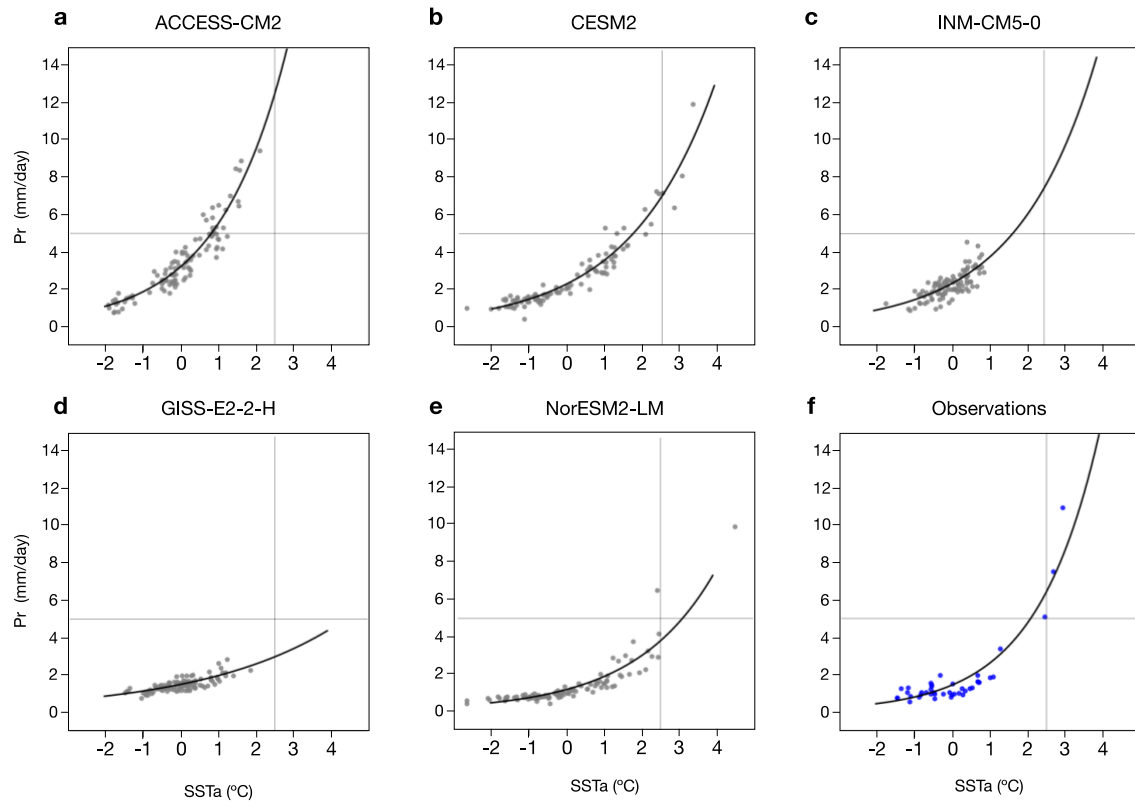
Affiliations:

¹ Climate Change Research Centre, University of New South Wales, Sydney, NSW, Australia

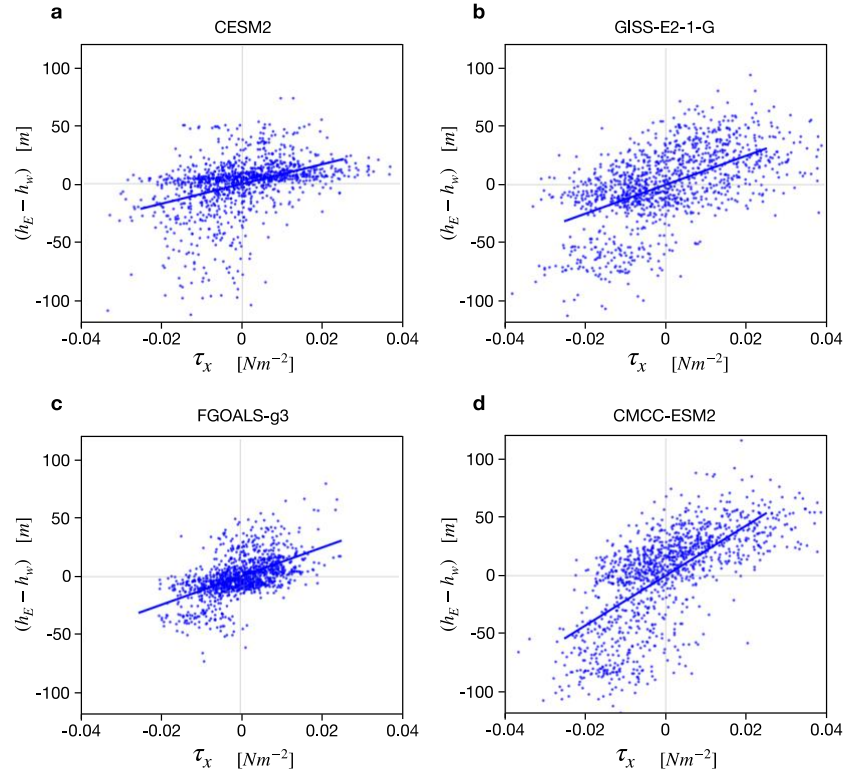
² Australian Centre for Excellence in Antarctic Sciences, University of New South Wales, Sydney, NSW, Australia

³ Institute of Astronomy, Geophysics and Atmospheric Sciences, University of São Paulo, São Paulo, SP, Brazil

*Corresponding author. Email: g.pontes@unsw.edu.au.



Supplementary Information Figure S1 | Examples of the representation of the equatorial Pacific convective feedback in climate models. Relationship between December-January-February (DJF) SST anomalies in the Niño-3 region and DJF precipitation in the Niño-3 region in 5 CMIP6 models a-e and observations f. Black line represents the exponential fit.



Supplementary Information Figure S2 | Examples of the relationship between wind stress anomalies in the western Pacific (5°S-5°N and 160°E-210°E) and thermocline slope changes between the eastern (5°S-5°N and 210°E-270°E) and western Pacific (5°S-5°N and 160°E-210°E) in the pre-industrial control simulation of four models: CEMS2 (a), GISS-E2-1-G (b), FGOALS-g3 (c), and CMCC-ESM2 (d). The wind-thermocline coupling coefficient is given by the slope of the linear fit.

Table S1. Values computed in this study.

	Niño3 s.d. change [%]	ITCZ [°]	SPCZ [°]	Overall displacement [°]	Convective feedback [°C.mm ⁻¹ .day ⁻¹]	Thermocline slope [m]	Ocean stratification [°C]	β_h [m ³ .N ⁻¹]
piControl								
ACCESS-CM2	-	6.7	-9.2	-	4.9	-62.2	1.3	929
ACCESS- ESM1-5	-	7	-11.4	-	3.2	-78.8	0.7	964
BCC-CM2-MR	-	8.4	-9.3	-	1.4	-	-	-
BCC-ESM1	-	-	-	-	1.5	-	-	-
CAMS-CSM1-0	-	9.5	-9.7	-	2.1	-	-	-
CCSM4- UTRECHT	-	10	-11.1	-	2	-72.6	1.4	2188
CCSM4-UofT	-	9.7	-11.8	-	1.3	-	-	-
CCSM4	-	9.1	-11	-	3.4	-52	1.5	2226
CESM1.2	-	8.9	-11.9	-	-	-	-	-
CESM2-FV2	-	9.2	-11.3	-	2.8	-	-	-
CESM2- WACCM-FV2	-	9.3	-10.6	-	3	-	-	-
CESM2- WACCM	-	8.7	-11	-	2.1	-40.8	1.2	968
CESM2	-	8.5	-10.7	-	2.8	-40.8	1.5	847
CIESM	-	8.1	11.6	-	-	-	-	-
CMCC-CM2- SR5	-	8.5	-11.9	-	1.9	-66.4	2.2	2128
CMCC-ESM2	-	8.1	11.6	-	2.1	-61.8	2.7	2139
CNRM-CM6-1- HR	-	7.9	-8.7	-	2.6	-81.2	?	1924
CNRM-CM6-1	-	8.3	-9.3	-	2	-77.5	2.1	1755
CNRM-ESM2-1	-	8.2	-9.3	-	2.3	-81.6	2.8	1754
COSMOS	-	-	-	-	0.4	-	-	-
CanESM5- CanOE	-	8.6	-10.8	-	1.9	-	-	-
CanESM5	-	8.4	-10.8	-	2.2	-	-	-
E3SM-1-0	-	-	-	-	1.5	-	-	-
E3SM-1-1-ECA	-	-	-	-	-	-	-	-
E3SM-1-1	-	-	-	-	1.4	-	-	-
EC-EARTH3- AerChem	-	-	-	-	1.8	-	-	-
EC-EARTH3- CC	-	8	-11.7	-	2.1	-	-	-
EC-EARTH3- LR	-	8	-11.8	-	2.3	-62.9	0.9	919
EC-EARTH3- Veg-LR	-	8	-11.5	-	0.7	-	-	-
EC-EARTH3- Veg	-	8	-11.9	-	1.8	-	-	-
EC-EARTH3	-	8.1	-11.8	-	2.2	-	-	-
FGOALS-f3-L	-	6.9	-9.8	-	3.4	-60	2.2	1847
FGOALS-g3	-	6.3	-7.9	-	2.7	-91	1.9	1230
FIO-ESM-2-0	-	-	-	-	-	-	-	-
GFDL-CM4	-	-	-	-	-	-	-	-
GFDL-ESM4	-	-	-	-	-	-	-	-
GISS-E2-1-G	-	9.1	-9.9	-	5	-34.1	3.1	1241
GISS-E2-1-H	-	9.3	-10.5	-	1.7	-	-	-
GISS-E2-2-G	-	9.4	-10.1	-	3.2	-	-	-
GISS-E2-2-H	-	-	-	-	1.2	-	-	-
HadCM3	-	6.4	-11.4	-	-	-	-	-
HadGEM3- GC31-LL	-	7.9	-10.8	-	2.6	-76	2	2011
HadGEM3- GC31-MM	-	7.9	-10.2	-	3.3	-71.1	1.8	1782
IITM-ESM	-	-	-	-	3.8	-	-	-
INM-CM4-8	-	8.9	-12	-	3	-106.8	2.5	250
INM-CM5-0	-	9.3	-11.8	-	2.9	-	-	-
IPSL-CM5A2	-	9.4	-9	-	1.2	-	-	-
IPSL-CM5A	-	8.9	-9.1	-	1.4	-	-	-
IPSL-CM6-LR	-	8.3	-10.9	-	1.2	-	-	-
KIOST-ESM	-	7.1	-10.2	-	3	-	-	-
MCM-UA-1-0	-	6.6	-7.7	-	0.9	-	-	-
MIROC-ES2L	-	7.4	-10.3	-	2	-76.6	1.5	1968

Table S1. Continued.

	Niño3 s.d. change [%]	ITCZ [°]	SPCZ [°]	Overall displacement [°]	Convective feedback [°C.mm ⁻¹ .day ⁻¹]	Thermocline slope [m]	Ocean stratification [°C]	β_h [m ³ .N ⁻¹]
MIROC4m		8.2	-8.6	-	0.7	-	-	-
MIROC6	-	7.8	-12.2	-	1.5	-	-	-
MPI-ESM1-2- HR	-	9.1	-12.3	-	0.5	-	-	-
MRI-CGCM2-3		9	-11.1	-	2.1	-	-	-
MRI-ESM2-0	-	8.5	-10.2	-	3.7	-46.9	1.4	942
NESM3	-	-	-	-	-	-	-	-
NorESM-L	-	8.1	-8	-	1.5	-	-	-
NorESM1-F	-	7.8	-9.9	-	5.1	-	-	-
NorESM2-LM	-	8.6	-10.7	-	1.5	-	-	-
NorESM2-MM	-	7.9	-11.1	-	1.4	-	-	-
UKESM1-0-LL	-	8	-11.2	-	2.1	-	-	-
Mid-Holocene								
ACCESS-ESM1- 5	-9.6	7.4	-12.5	1.48	-	-95.9	0.4	1293
CESM2	-11.6	8.5	-11.3	0.68	-	-42.4	1.2	1039
EC-EARTH3-LR	-3.1	7.9	-12	0.1	-	-	-	-
FGOALS-f3-L	-3.2	6.9	-10.2	0.34	-	-	-	-
FGOALS-g3	-25.3	6.2	-8.5	0.52	-	-93.6	1.5	62
GISS-E2-1-G	4.3	9.1	-10.1	0.17	-	-	-	-
HadGEM-GC31- LL	18.8	8.2	-11.7	1.08	-	-	-	-
INM-CM4-8	13.7	8.4	-11.3	-1.14	-	-112.4	2.2	404
IPSL-CM6A-LR	-4.8	8.7	-11.3	0.78	-	-	-	-
MIROC-ES2L	-35	7.8	-11.1	1.21	-	-88.9	1.2	1350
MRI-ESM2-0	-24.8	8.5	-11.2	1.05	-	-59.7	0.9	909
NorESM1-F	-6.6	7.5	-9.7	-0.56	-	-	-	-
NorESM2-LM	-23.3	8.7	-11.8	1.22	-	-	-	-
Last Interglacial								
ACCESS-ESM1- 5	-16.5	8.1	-11.5	1.17	-	-87	0.4	1168
CESM2	-20	9	-11.6	1.53	-	-43.5	1.1	967
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	-	-93.2	1.5	33
GISS-E2-1-G	-9.5	9	-10.7	0.65	-	-45.2	2.7	1151
IPSL-CM6A-LR	-8.5	8.6	-11.1	0.49	-	-	-	-
MIROC-ES2L	-53.6	8	-11	1.27	-	-99.5	1	715
NorESM1-F	-21	8.1	-10.3	0.7	-	-	-	-
NorESM2-LM	-1.1	9.3	-12.7	2.71	-	-	-	-
Mid-Pliocene								
CCSM4- UTRECHT	-64.5	10.6	-12.8	2.24	-	-79.9	0.5	452
CCSM4-UofT	-29	9.2	-11.6	-0.7	-	-	-	-
CCSM4	-43	8.9	-11.7	0.46	-	-55	1.2	1273
CESM1.2	-23.3	8.1	-11.7	-1.03	-	-	-	-
CESM2	-13.2	8.2	-9	-1.89	-	-	-	-
COSMOS	-3.2	11.9	-13.5	-0.92	-	-	-	-
EC-EARTH3-LR	-34	9.3	-12.1	1.66	-	-74.3	0.7	700
GISS-E2-1-G	4.3	9.6	-9.5	0.09	-	-	-	-
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								
INM-CM4-8	33.7	9.5	-8.5	-2.73	-	-	-	-
MIROC-ES2L	-5.3	7.3	-10.4	-0.06	-	-	-	-

Table S1. Continued.

	Niño3 s.d. change [%]	ITCZ [°]	SPCZ [°]	Overall displacement [°]	Convective feedback [°C.mm ⁻¹ .day ⁻¹]	Thermocline slope [m]	Ocean stratification [°C]	β_h [m ³ .N ⁻¹]
ssp585								
ACCESS-CM2	14.4	6.6	-8.9	-0.42	-	-55.1	2.7	1409
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	-	-42	3.4	743
CESM2	-3.4	8.3	-8.2	-2.71	-	-	-	-
CIESM	12	6.8	-10.7	-2.23	-	-	-	-
CMCC-CM2-SR5	12.3	8.3	-11.7	-0.35	-	-63.6	4	1721
CMCC-ESM2	22.7	8	-11	-0.68	-	-53.3	4.9	1876
CNRM-CM6-1-HR	19.8	7.6	-8	-0.94	-	-74.3	3.4	2106
CNRM-CM6-1	14.5	8.3	-8.3	-0.96	-	-70.3	4.4	1928
CNRM-ESM2-1	19.1	8.3	-8.3	-0.9	-	-70.5	5.3	1855
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	-	-57.6	3	1570
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	-	-59.8	3.1	1538
FGOALS-f3-L	22	6.1	-7.2	-3.43	-	-41.1	4.1	1972
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-G	4.8	8.9	-8.8	-1.43	-	-	-	-
GISS-E2-1-H	52.7	9.1	-9.4	-1.32	-	-	-	-
HadGEM-GC31-LL	19.9	8	-10.4	-0.36	-	-68	3.5	2045
HadGEM-GC31-MM	10.1	7.6	-9.7	-0.73	-	-63.3	4	1379
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	-	-	-	-
KIOST-ESM	8.2	7	-9.1	-1.21	-	-	-	-
MCM-UA-1-0	21.5	5.3	-6.5	-2.49	-	-	-	-
MIROC-ES2L	47.3	7.2	-7.6	-2.99	-	-64.3	3.9	2567
MIROC6	30.6	7.6	-11.1	-1.43	-	-	-	-
MPI-ESM1-2-HR	7.3	8.8	-11.4	-1.13	-	-	-	-
MRI-ESM2-0	5.8	8.3	-9.1	-1.23	-	-38	2.7	1286
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								
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-FV2	-6.5	6.8	-5.2	-8.51	-	-	-	-
CESM2-WACCM-FV2	-25.6	6	-5.5	-8.39	-	-	-	-
CESM2-WACCM	1.9	6.9	-5.3	-7.49	-	-	-	-
CESM2	-67.3	3.4	-3.5	-12.15	-	-22.3	7.9	133
CMCC-CM2-SR5	27.4	7.8	-9.7	-2.86	-	-	-	-
CMCC-ESM2	25.7	7.6	-9.4	-2.7	-	-	-	-

Table S1. Continued.

	Niño3 s.d. change [%]	ITCZ [°]	SPCZ [°]	Overall displacement [°]	Convective feedback [°C.mm ⁻¹ .day ⁻¹]	Thermocline slope [m]	Ocean stratification [°C]	β_h [m ³ .N ⁻¹]
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	-	-	-	-
FGOALS-f3-L	3.1	5.7	-6	-5	-	-	-	-
GISS-E2-1-G	-11.7	8.2	-8.2	-2.58	-	-	-	-
GISS-E2-2-G	-16.8	9.3	-8.9	-1.37	-	-	-	-
HadGEM3- GC31-LL	23.9	8.1	-8.7	-2	-	-	-	-
HadGEM3- GC31-MM	1.8	7.3	-7.7	-3.07	-	-	-	-
INM-CM4-8	-4	8.9	-11.1	-0.82	-	-	-	-
INM-CM5-0	-5.9	8.9	-11.2	-0.93	-	-	-	-
MIROC-ES2L	38.8	7	-6.3	-4.48	-	-	-	-
MRI-ESM2-0	22.4	8	-7.3	-3.43	-	-	-	-
UKESM1-0-LL	-1.4	8.1	-8.6	-2.59	-	-	-	-