

Supporting Information for

Mid-Holocene El Niño Southern Oscillation variability reduced by northern African vegetation changes in climate models

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Supplementary Note S1 : Model evaluation

The climate models used in this study suffer from certain common model biases.

Firstly, climate models commonly suffer from the double ITCZ problem i.e. the presence of a second, spurious precipitation band south of the equator in the tropical Pacific and Atlantic Oceans. The models used in this study also show the second ITCZ in both oceans, with the notable exception of EC-Earth which has no second ITCZ in the tropical Pacific (Fig. S8). The second ITCZ is most pronounced in HadCM3.

Secondly, climate models commonly suffer from various biases in the Atlantic, particularly related to the simulation of the Atlantic Niño. The models used in this study show a warm bias in the region of the Atlantic Cold Tongue, with only EC-Earth and UofT-CCSM4 showing a small and disjunct cool patch in the central equatorial Atlantic which is positioned too westwardly (Fig. S4). HadCM3 shows a considerable warm bias in the tropical Atlantic. The absence/westward displacement of the Atlantic Cold Tongue is also reflected in a significant under-estimation of west-to-east SST gradients in the equatorial Atlantic during boreal summer (Fig. S5). The under-representation of Atlantic Niño in climate models can also be gauged by the SST variability, which is expected to peak during boreal summer with the development of the Atlantic Cold Tongue. EC-Earth shows higher variability than observational datasets. The other four models show lower or temporally displaced peak variability (Fig. S7).

Thirdly, climate models commonly suffer from various biases in the Pacific, most notably the Pacific Cold Tongue bias and the Western Pacific Warm Pool bias. With the exception of GISS, the climate models used in this study show a greater westward extension of the Pacific Cold Tongue, compared to observational datasets (Fig. S9). The westward extent of the Pacific Cold Tongue is reasonable in GISS, but there is a warm bias in the southeast tropical Pacific (between 70-100 °W). EC-Earth and UofT-CCSM4 show a cool bias in the Cold Tongue region. The Western Pacific Warm Pool is generally simulated inadequately warmly, with the exception of iCESM. However, iCESM shows a greater extension of the Warm Pool in the southern tropical Pacific. With regards to SST variability, all models showed a reasonable magnitude and extent of the region with the highest SST variability in the equatorial Pacific (Fig. S10).

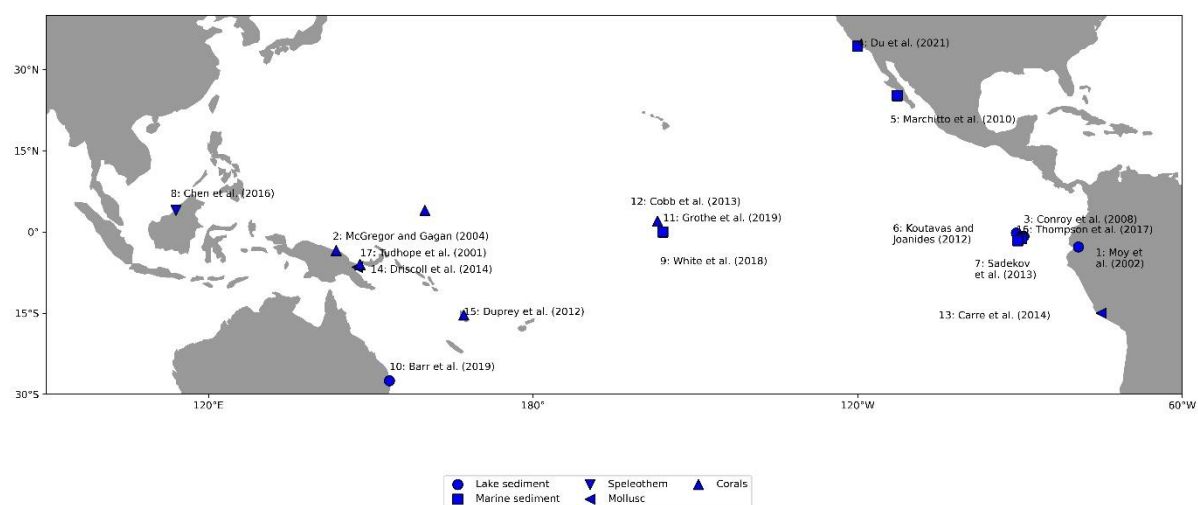


Figure S1: Sites of paleoclimatic reconstructions cited in this study and listed in Table S3.

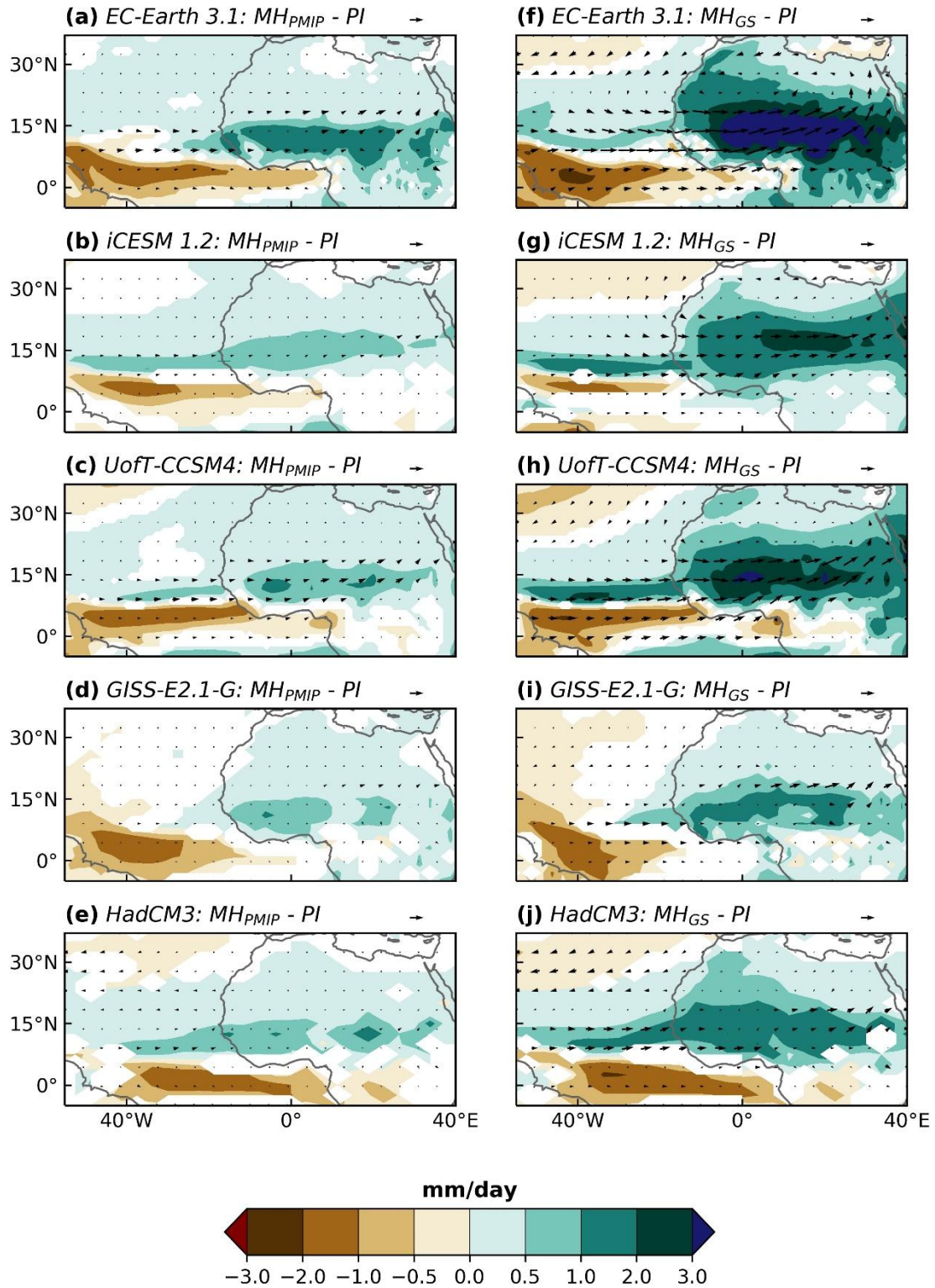


Figure S2: Annual precipitation and low-level (850 hPa) wind anomalies for (a-e) MH_{PMIP} and (f-j) MH_{GS} simulations, relative to the respective PI simulations. Arrow keys on the top-right indicate wind strength of 2.5 m/s. Only the anomalies statistically significant at the 95% confidence level are shaded.

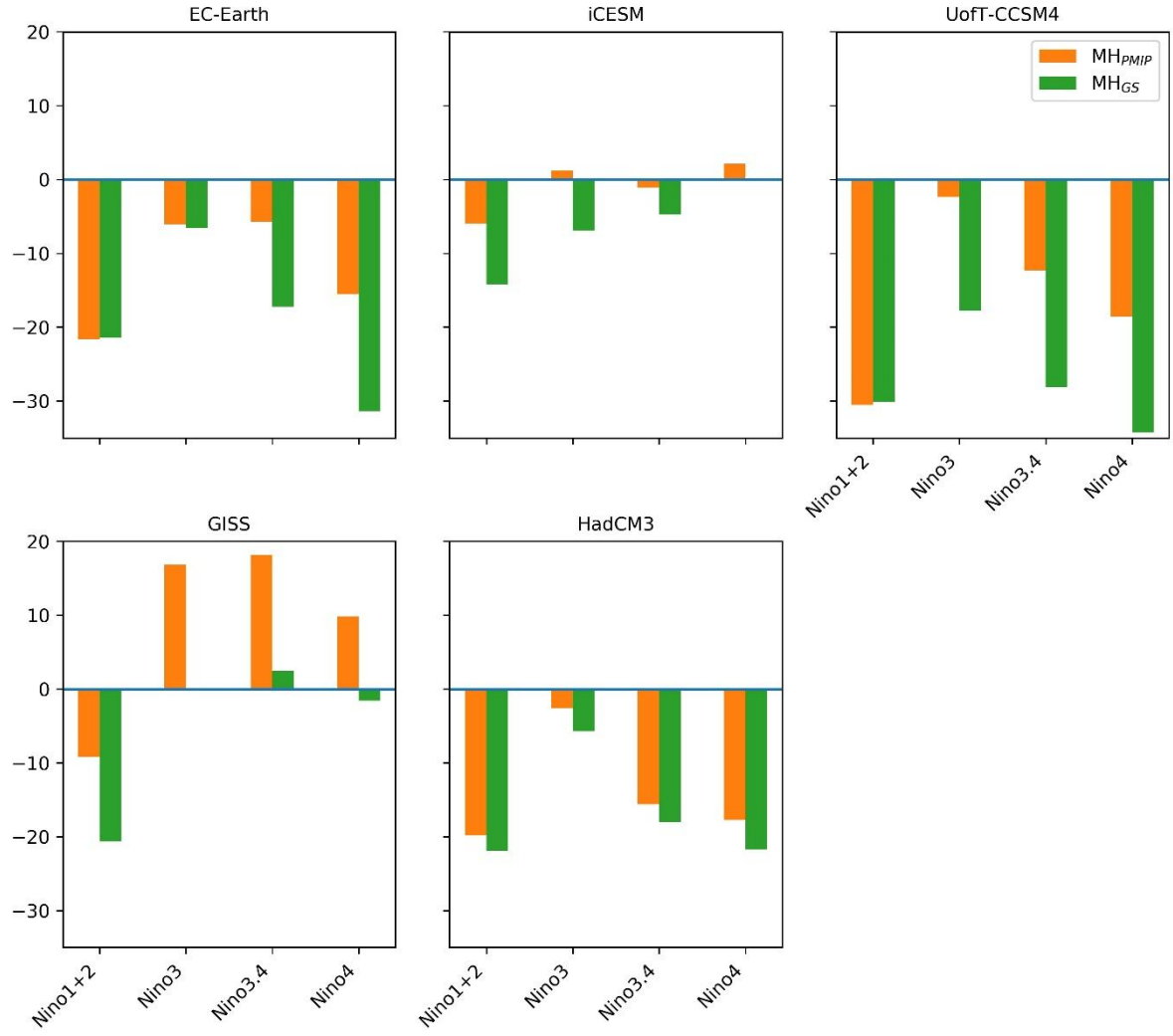


Figure S3: Percentage change in interannual SST variability averaged over the Niño index regions, for the MH_{PMIP} and MH_{GS} simulations relative to the PI.

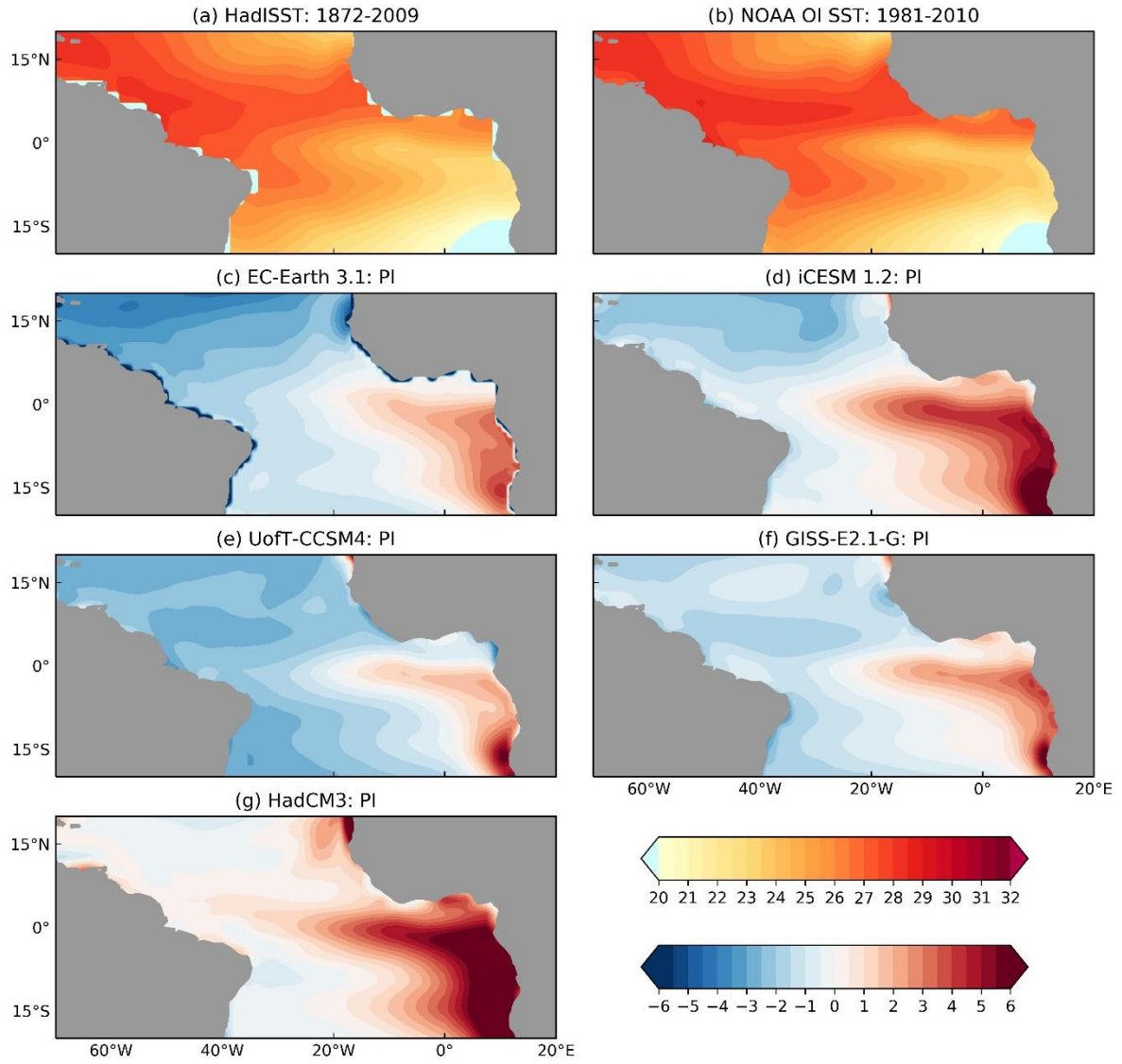


Figure S4: (a-b) Boreal summer (JJA) sea surface temperatures for the present-day observational datasets (c-g) Boreal summer SST biases in model PI simulations relative to the NOAA OI SST dataset shown in (b).

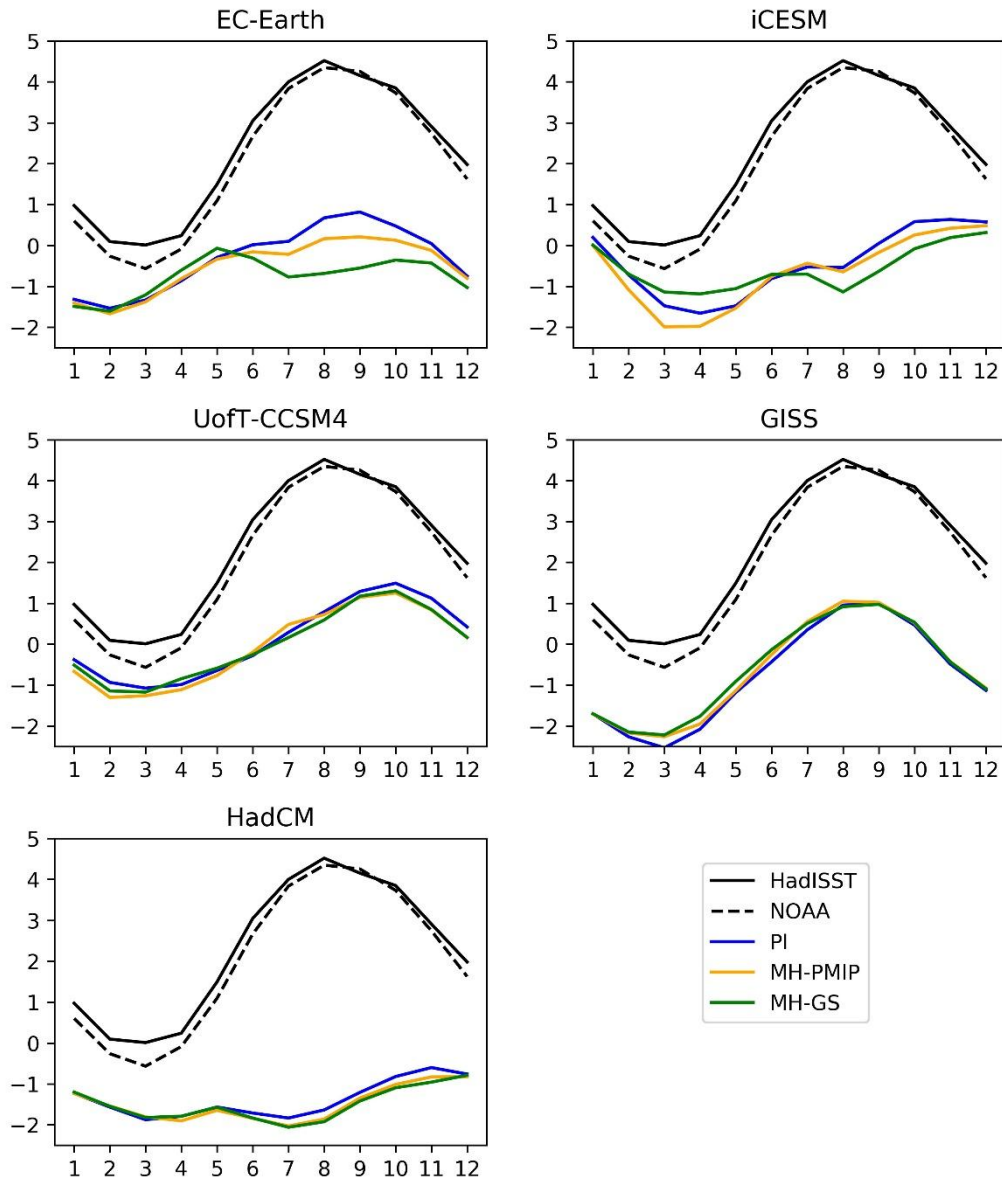


Figure S5: Comparison of west-to-east SST gradients for the equatorial Atlantic. The SST gradient is computed as the difference between the mean SST over West Equatorial Atlantic (40-30 °W, 3°S-3°N) and the East Equatorial Atlantic (0-8 °E, 10-3 °S).

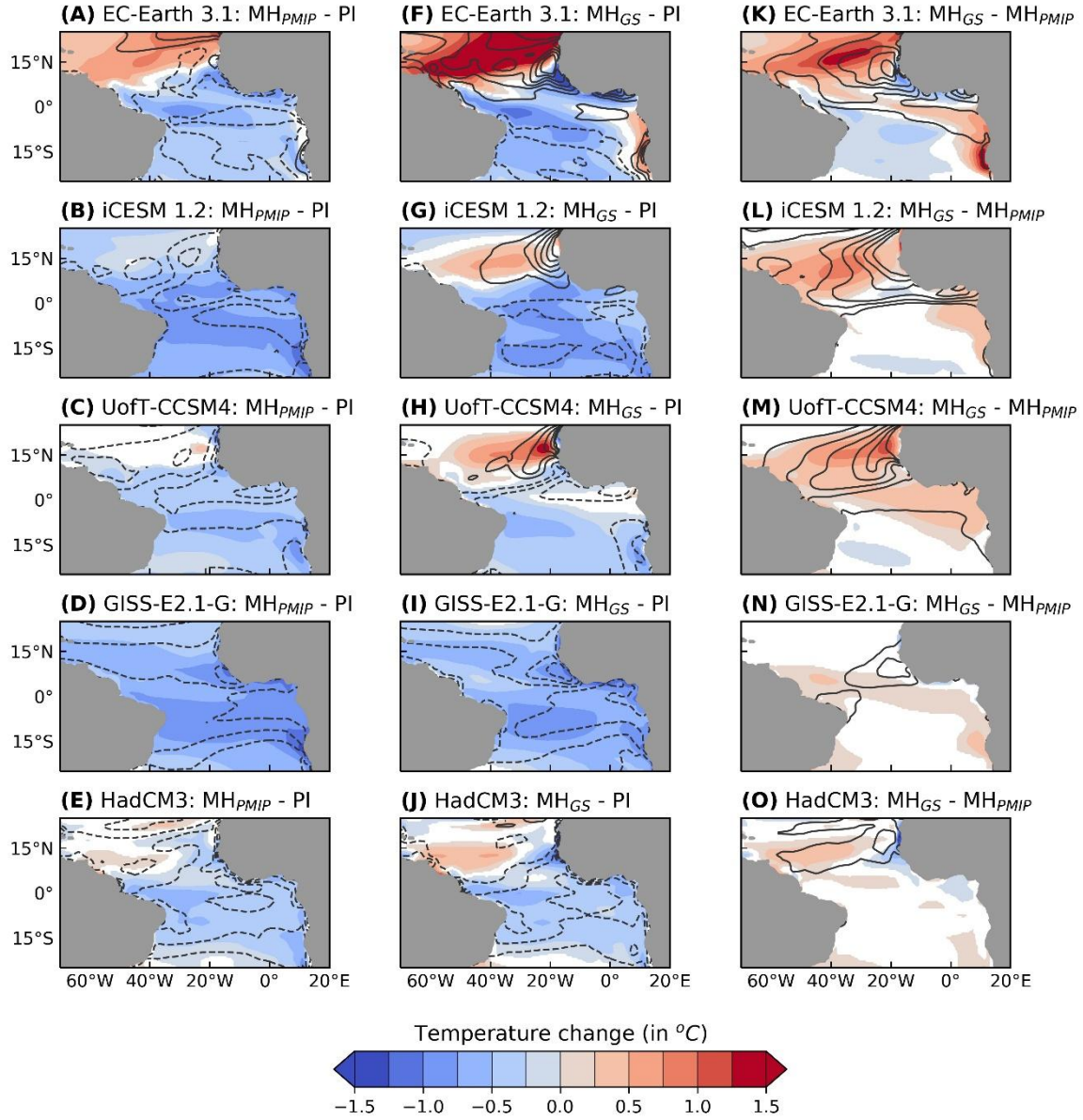


Figure S6: Changes in sea surface temperatures over the Atlantic. Colors show SST anomalies over boreal summer (JJA) and contours show SST anomalies over February-April (FMA) for the MH_{PMIP} (A-E) and the MH_{GS} (F-J) simulations relative to the reference PI simulation and for the MH_{GS} simulation relative to the MH_{PMIP} simulation (K-O). Contours are spaced at 0.25 °C. Only anomalies which are significant at the 95% confidence level are shown.

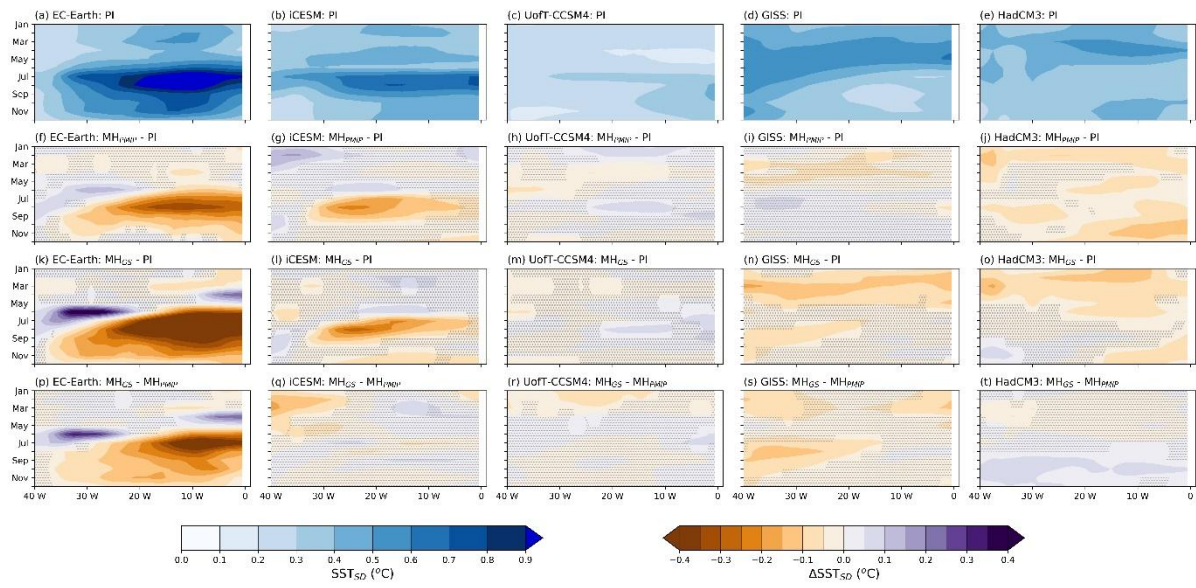


Figure S7: Changes to interannual SST variability for the equatorial Atlantic (3°S – 3°N).

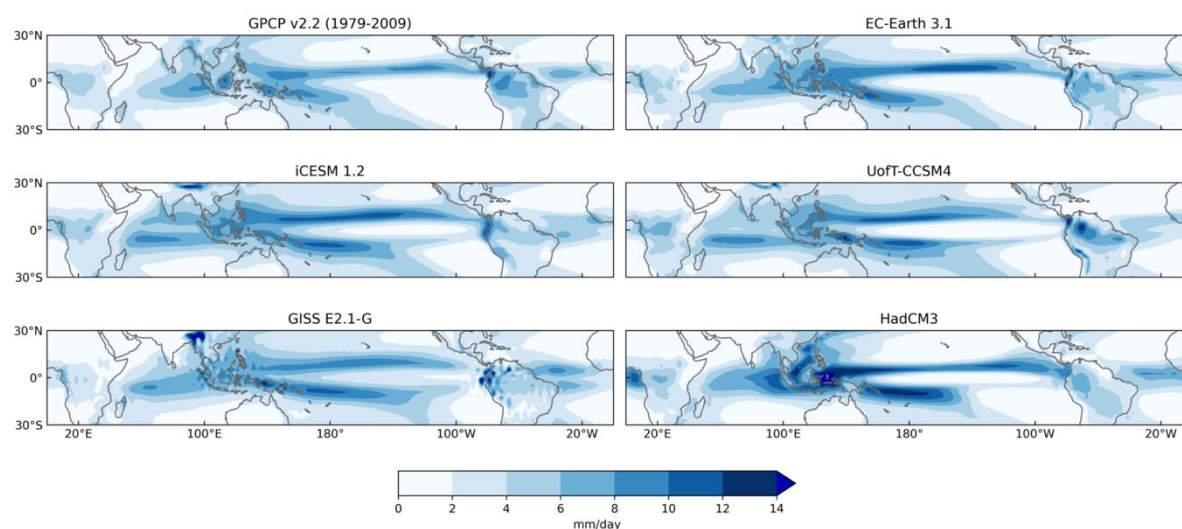


Figure S8: Comparison of mean annual precipitation shown by model PI simulations, with observational datasets.

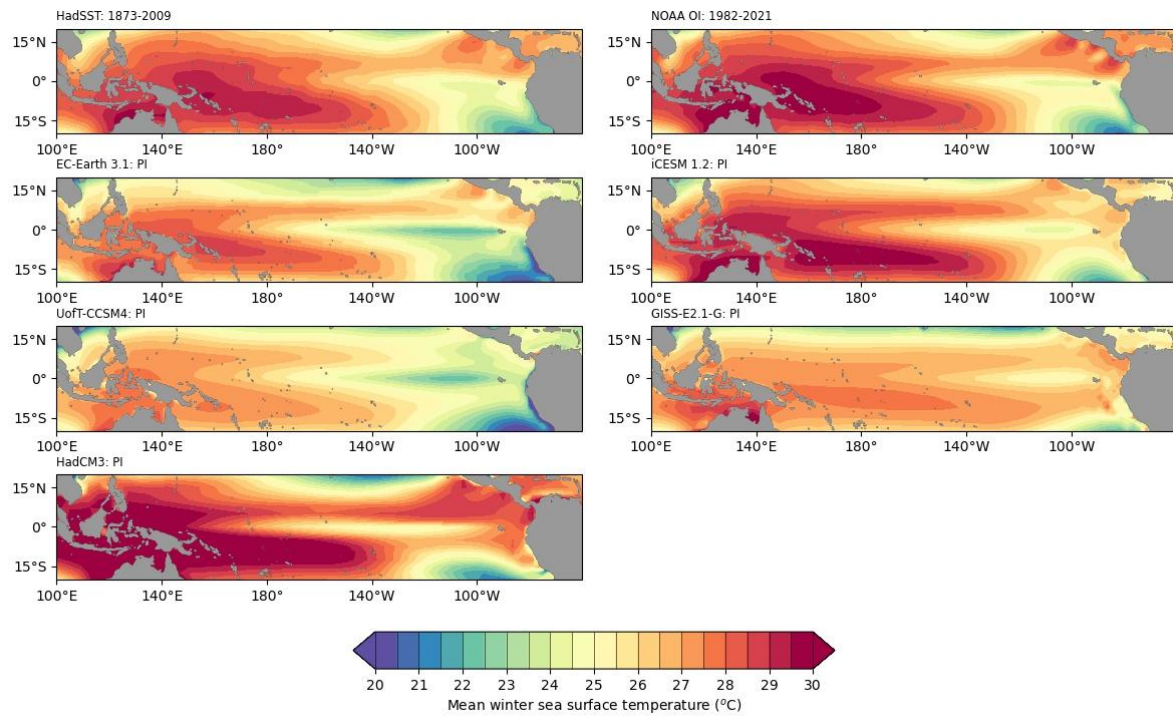


Figure S9: Comparison of boreal winter (DJF) sea surface temperatures shown by model PI simulations, with observational datasets.

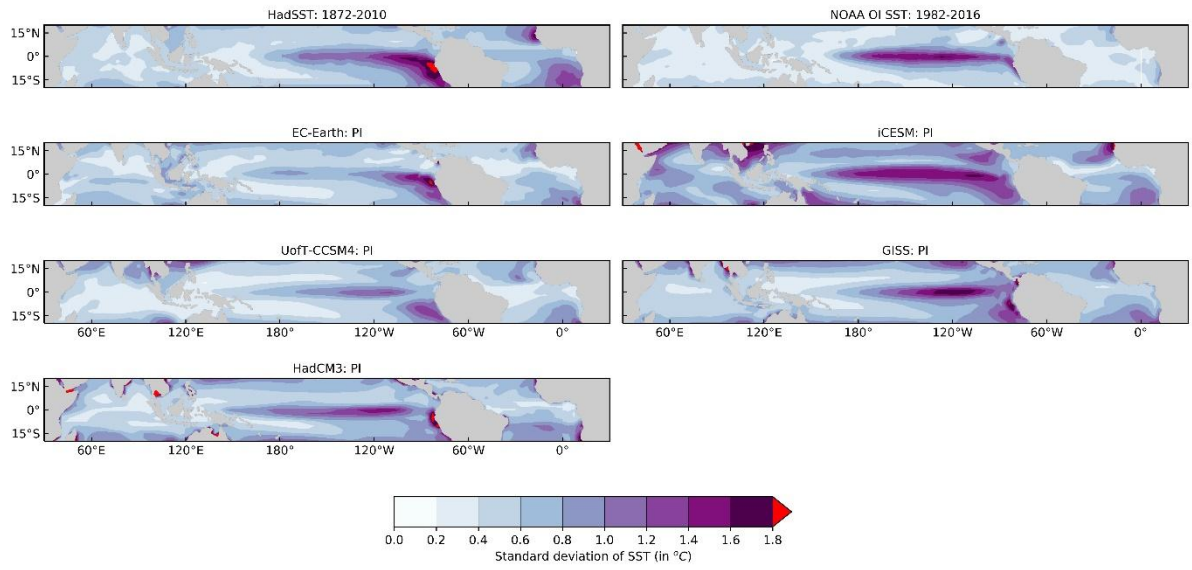


Figure S10: Comparison of boreal winter (DJF) sea surface temperature variability shown by model PI simulations, with observational datasets.

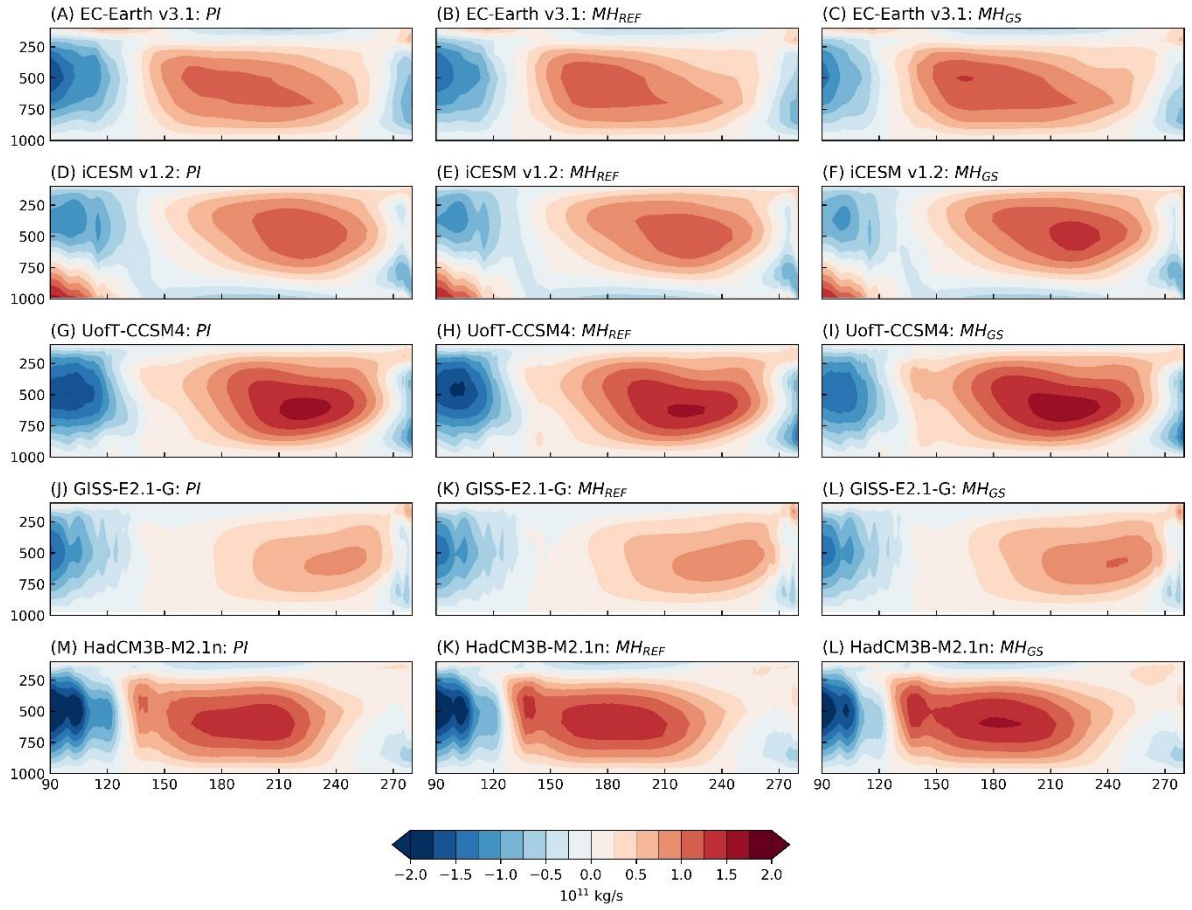


Fig. S11: Mean annual zonal mass streamfunction over the equatorial Pacific (5°S – 5°N) in 10^{11} kg/s for all simulations.

Model descriptions

	EC-Earth 3.1	iCESM 1.2	UoT-CCSM4	GISS-E2.1-G	HadCM3
Model name	EC-Earth	Community Earth System Model	Community Climate System Model	Goddard Institute for Space Studies Model	Hadley Centre coupled model version 3
Modelling center	European Consortium	National Center for Atmospheric Research (NCAR)	NCAR model (CCSM4) modified at: University of Toronto	NASA GISS	UK Met Office
Atmospheric component	Integrated Forecast System	Community Atmosphere Model v5.3 (iCAM5)	Community Atmosphere Model v4 (CAM4)	Goddard Institute for Space Studies Model E2.1	HadAM3
Atmospheric grid	1.125 x 1.125 (62)	1.9 x 2.5 (30)	1 x 1 (26)	2 x 2.5 (40)	2.5 x 3.75 (19)
Oceanic component	Nucleus for European Modelling of the Ocean v2 (NEMO2)	Parallel Ocean Program v2.0 (POP2)	Parallel Ocean Program v2.0 (POP2)	GISS Ocean Model v1	HadCM3BL
Oceanic grid	1 x 1 (46)	1 x 1 (60)	1 x 1 (60)	1 x 1.25 (40)	1.25 x 1.25 (20)
Simulation protocols for MH simulations	CMIP5 / PMIP3	CMIP6 / PMIP4	CMIP6 / PMIP4	CMIP6 / PMIP4	CMIP6 / PMIP4
Feedbacks additionally incorporated in the MH _G s simulation	Vegetation, dust	Vegetation, dust, soil	Vegetation, soil, lakes	Vegetation	Vegetation
PI-to-MH albedo change over the Sahara	0.3 to 0.15	0.3 to 0.15	0.3 to 0.16	0.3 to 0.19	
Reference for simulations	Pausata et al. (2016)	Tabor et al. (2020)	Chandan and Peltier (2020)	Tiwari et al. (2023)	This paper
Total length per simulation (years)	300	350	500-1250		700
Length used for analysis (years)	200	100	100	100	200

Table S1. Model details. Numbers in parentheses indicate number of vertical levels in the atmospheric or oceanic grid.

(a) TNI	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	4.08	2.86	2.68	1.15	0.68
MH _{PMIP}	4.17	2.46	2.74	1.29	0.22
MH _{GS}	4.2	2.41	2.74	1.47	0.11

(b) WPG	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	1.26	1.42	1.29	0.02	2.15
MH _{REF}	1.55	1.56	1.3	0.03	2.59
MH _{GS}	1.82	1.9	1.4	0	2.66

(c) EPG	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	3.63	3.6	3.2	1.52	1.59
MH _{REF}	3.55	3.33	3.46	1.88	1.44
MH _{GS}	3.48	3.34	3.39	2.05	1.4

(d) ESOI	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	1.66	2.1	3.3	-0.3	2.47
MH _{REF}	1.99	2.33	3.57	-0.06	3.07
MH _{GS}	2.4	2.69	4.07	0.12	3.41

(e) PWC Intensity	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	1.96	1.21	4.45	0.66	1.59
MH _{REF}	2.01	1.34	4.54	0.79	1.69
MH _{GS}	2.41	1.67	5.29	0.98	1.91

(f) PWC West bound	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	136	144	137.5	137	126
MH _{REF}	132	144	137.5	138	122
MH _{GS}	126	142	131	137	120

(g) PWC Center	EC-Earth	iCESM	UofT-CCSM4	GISS	HadCM3
PI	170	225	224	245	204
MH _{REF}	170	225	220	245	178
MH _{GS}	166	225	218	245	182

Table S2: Mean state indicators for the PI, MH_{PMIP} and MH_{GS} simulations: (a) Trans Niño Index (TNI), (b) West Pacific SST Gradient (WPG), (c) East Pacific SST Gradient (EPG) and (d) Equatorial Southern Oscillation Index (ESOI). All values in (a-d) were calculated over boreal winter (DJF). (e)

Pacific Walker Cell (PWC) intensity (in 10^{10} kg/s), (f) PWC West bound (in °) and (g) PWC Center (in °). All values in (e-g) are calculated over the full year.

	Reference	Location	Archive
1	Moy et al. (2002)	2.77 S, 79.23 W	Lake sediments
2	McGregor & Gagan (2004)	3.41 S, 143.61 E	Corals
3	Conroy et al. (2008)	0.8 S, 89.3 W	Lake sediments
4	Leduc et al. (2013)	8 N, 84 W	Marine sediments
5	Marchitto et al. (2010)	25.2 N, 112.7 W	Marine sediments
6	Koutavas & Joanides (2012)	1.22 S, 89.68 W	Marine sediments
7	Sadekov et al. (2013)	1.6 S, 90.42 W	Marine sediments
8	Chen et al. (2016)	4 N, 114 E	Speleothem
9	White et al. (2018)	0 N, 156 W	Marine sediments
10	Barr et al. (2019)	27.5 S, 153.46 E	Lake sediments
11	Grothe et al. (2020)	2 N, 157 W	Corals
12	Cobb et al. (2013)	2 N, 157 W 4 N, 160 W	Corals
13	Carré et al. (2014)	7 archaeological sites on the SW Peruvian coast, between 11.7 and 18.1 S	Mollusc middens
14	Driscoll et al. (2014)	6.5 S, 147.5 E	Clams
15	Duprey et al. (2012)	15.35 S, 167.18 E	Corals and clams
16	Thompson et al. (2017)	0.2 S, 90.7 W	Lake sediments
17	Tudhope et al. (2001)	6 S, 148 E	Corals

Table S3: List of proxy records cited in this study

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