Supplement of

The relative impacts of tropical Pacific teleconnections and local insolation on mid-Holocene precipitation over tropical South America

Minn Lin Wong[1,2], Xianfeng Wang[1,2,3]

[1] Asian School of the Environment, Nanyang Technological University, Singapore
[2] Earth Observatory of Singapore, Nanyang Technological University, Singapore
[3]Center for Climate Change and Environmental Health, Nanyang Technological University, Singapore

Correspondence to: Minn Lin Wong (minnlin001@e.ntu.edu.sg)

S1. Method details for La Niña-like mean state ECHAM4.6 experiment

In order to force a mid-Holocene climatological SST over the tropical Pacific in the MidH experiment, the ECHAM4.6 is forced with 41-years of modern SSTs, however, the tropical Pacific region (160–275°E; 20°N–20°S) is prescribed with the climatological SST based on the ensemble mean of mid-Holocene simulations from PMIP4 (Fig. S1). First, the year-to-year variability within the tropical pacific box is suppressed by imposing the 41-year (1979–2019) climatology in the box. This removes the modern-day ENSO variability (as was done in the NoENSO experiment). Next, to shift the climatological SSTs to the mid-Holocene state, we derive the difference in the climatological cycle between the PMIP4 'mid-Holocene' ensemble and CMIP6 'Historical' simulations. The specific models used are shown in Table S1. The difference in the mean climatological annual cycle is then added to the tropical Pacific SSTs.

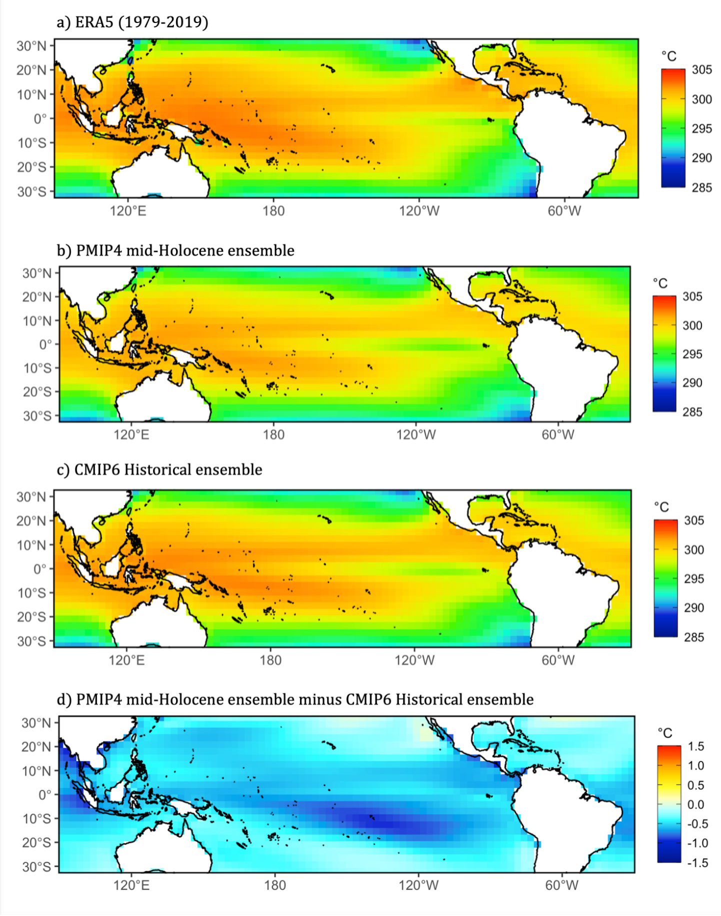


Figure S1: Annual mean climatological SST from (a) ERA5 (1979–2019), (b) PMIP4 mid-Holocene ensemble annual mean SSTs, (c) CMIP6 Historical scenario, and (d) the difference in the ensemble annual mean SSTs, mid-Holocene minus historical (panel b minus panel c).

Table S1: Models used in the calculation of the PMIP4 mid-Holocene ensemble and CMIP6 Historical ensemble (data accessed from https://aims2.llnl.gov/search).

Model
ACCESS-ESM1-5
AWI-ESM-1-1-LR
CESM2
EC-Earth3
FGOALS-f3-L
FGOALS-g3
GISS-E2-1-G
INM-CM4-8
IPSL-CM6A-LR
MPI-ESM1-2-LR
MRI-ESM2-0
NESM3
NorESM2-LM
NorESM1-F*

* Only available for the mid-Holocene scenario.

S2. $\delta^{18}O$ proxy records in tropical South America

Most speleothem $\delta^{18}O$ records in South America are catalogued in the Speleothem Isotopes Synthesis and Analysis (SISAL v2) database (Comas-Bru et al., 2020; Deininger et al., 2019. Speleothem $\delta^{18}O$ in the SISAL_V2 is presented with respect to the Vienna Pee Dee Belemnite standard (VPDB) and the values are dependent on the mineralogy of the samples, which can differ between aragonite and calcite. Therefore, we convert speleothem $\delta^{18}O$ values to their dripwater equivalents relative to the Vienna Standard Mean Ocean Water (VSMOW) using a fractionation factor for sample mineralogy (either aragonite or calcite), and the cave site temperatures that are specified by their respective authors. Samples which have unknown, or a mixed mineralogy are excluded from this analysis. The $\delta^{18}O$ proxy records that fulfil the above requirements are shown in Table S2. They are relatively evenly spread across the continent and can provide an adequate depiction of broad spatial patterns.

In Table S2, the mid-Holocene is defined as 5000–7000 BP, the pre-industrial is defined as 850–1850 CE, and the historical period is defined as 1850–2014 CE.

We do not expect $\delta^{18}O_p$ over the historical period (1850–2014 CE) to differ significantly from that in the modern period (1979–2019 CE) because there are no significant trends in the annual cycle of precipitation (WG1, IPCC AR6, 2021), and the observed pattern of warming is quite uniform. Thus, there should be no trend in teleconnections to tropical South America over the historical period. Furthermore, the amount of tropical warming from 850 CE to present is ≤ 1°C, or in term of $\delta^{18}O_p$, less than −0.24‰/°C (Kim and O'Neil, 1997). Comparing speleothem $\delta^{18}O_c$ in columns 8 and 11 of Table S2 confirms our expectation that $\delta^{18}O_c$ over the preindustrial period is indeed very similar to that over the historical period. Hence, to compare the observed and simulated changes in the $\delta^{18}O$ of precipitation since the mid-Holocene, we use the observed $\delta^{18}O_c$ over the preindustrial period (850–1850 CE) in place of the $\delta^{18}O_c$ over the historical period (1850–2014 CE) to take advantage of the much larger sample size available when using the preindustrial values and to enable us to include the ice core records in our comparison of simulated and observed $\delta^{18}O$.

Table S2: $\delta^{18}O_p$ records used in this study, and (sixth column) the inferred difference in mid-Holocene precipitation relative to modern day. The last four columns show the average $\delta^{18}O_p$ values from each proxy record for the mid-Holocene and pre-industrial timeframes, the difference between mid-Holocene and pre-industrial, and in the final column, the difference between mid-Holocene and the historical period. The number of sample points used for the historical period is shown in brackets. Locations of each site are shown in Fig. S2.

Site No.	Site name	Lon	Lat	Type of archive	Mid-Holocene condition	Samples	**MH** $\delta 18O$	**PI** $\delta 18O$	**MH-PI** $\delta^{18}O$	**MH-Hist** $\delta^{18}O$
1	Botuverá Cave[1]	-49.02	-27.13	Speleothem	Dry	1055	-2.82	-5.71	2.89	2.92 (584)
2	Jaraguá Cave[2]	-56.35	-21.00	Speleothem	Dry	205	-3.55	-4.83	1.28	1.28 (33)
3	Huagapo Cave[3]	-75.79	-11.47	Speleothem	Dry	209	-12.40	-13.37	0.97	0.81 (32)
4	Paraíso Cave[4]	-55.45	-4.07	Speleothem	Wet	119	-8.01	-5.71	-2.30	-2.24

										(26)
5	Rio Grande do Norte[5]	-37.44	-5.60	Speleothem	Wet	41	-6.21	-2.56	-3.65	-3.91 (2)
6	Paixão Cave[6]	-41.02	-12.63	Speleothem	Wet					
7	Angelica Cave[7]	-46.23	-13.40	Speleothem	Similar	46	-2.97	-2.65	-0.32	NA (0)
8	Lapa Grade Cave[8]	-44.36	-14.42	Speleothem	Similar					
9	Shatuca Cave[9]	-77.90	-5.70	Speleothem	Dry	36	-5.85	-5.89	0.40	0.32 (16)
10	Cueva del Tigre Perdido[10]	-77.30	-5.94	Speleothem	Dry	34	-7.06	-7.09	0.58	0.63 (3)
11	Santana Cave[11]	-48.72	-24.53	Speleothem	Dry					
12	El Condor Cave[12]	-77.18	-5.56	Speleothem	Dry					
13	Cueva del Diamante[12]	-77.30	-5.44	Speleothem	Dry					
14	Huascaran[13]	-77.50	-9.00	Ice core	Dry	10	-17.61	-18.52	0.91	-0.23 (1)
15	Sajama[14]	-68.53	-18.06	Ice core	Dry	10	-16.41	-16.47	0.06	1.02 (1)
16	Laguna Pumacocha[15]	-76.06	-10.70	Lake Carbonate	Dry	541	18.64	16.86	1.78	1.37 (157)
17	Lake Junin[16]	-76.11	-11.03	Lake Carbonate	Dry					

[1]Wang et al. (2017)
[2]Novello et al. (2017)
[3]Kanner et al. (2013)
[4]Wang et al. (2017)
[5]Cruz et al., (2009)
[6]Barreto and Cruz (2010)
[7]Wong et al. (2021)
[8]Strikis et al. (2011)
[9]Bustamante et al. (2016)
[10]Breukelen et al. (2008)
[11]Cruz et al. (2006)
[12]Cheng et al., (2013)
[13]Thompson et al. (1995)
[14]Reese et al. (2013)
[15]Bird et al., (2011)
[16]Seltzer et al. (2000)

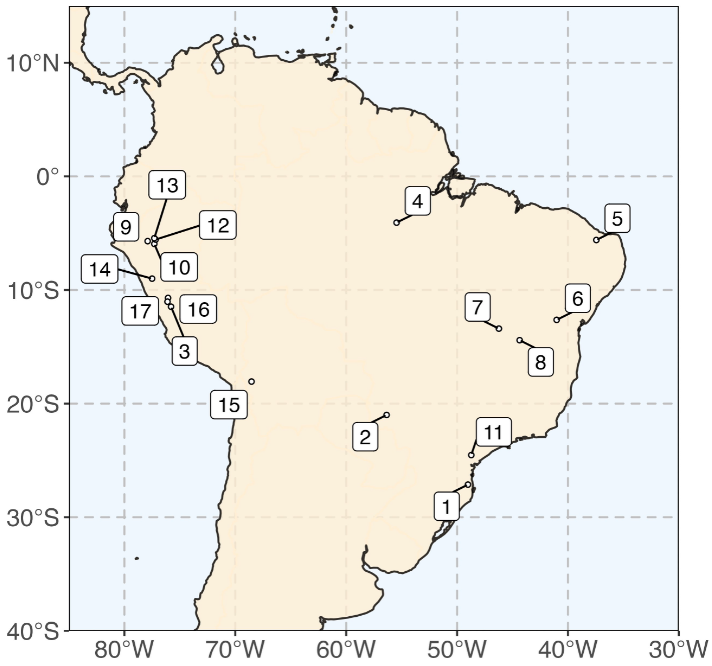


Figure S2: Location of each of the paleorecords listed in Table S2. Numbers refer to the site number in the first column in Table S2.

S3. Performance of ECHAM4.6 model

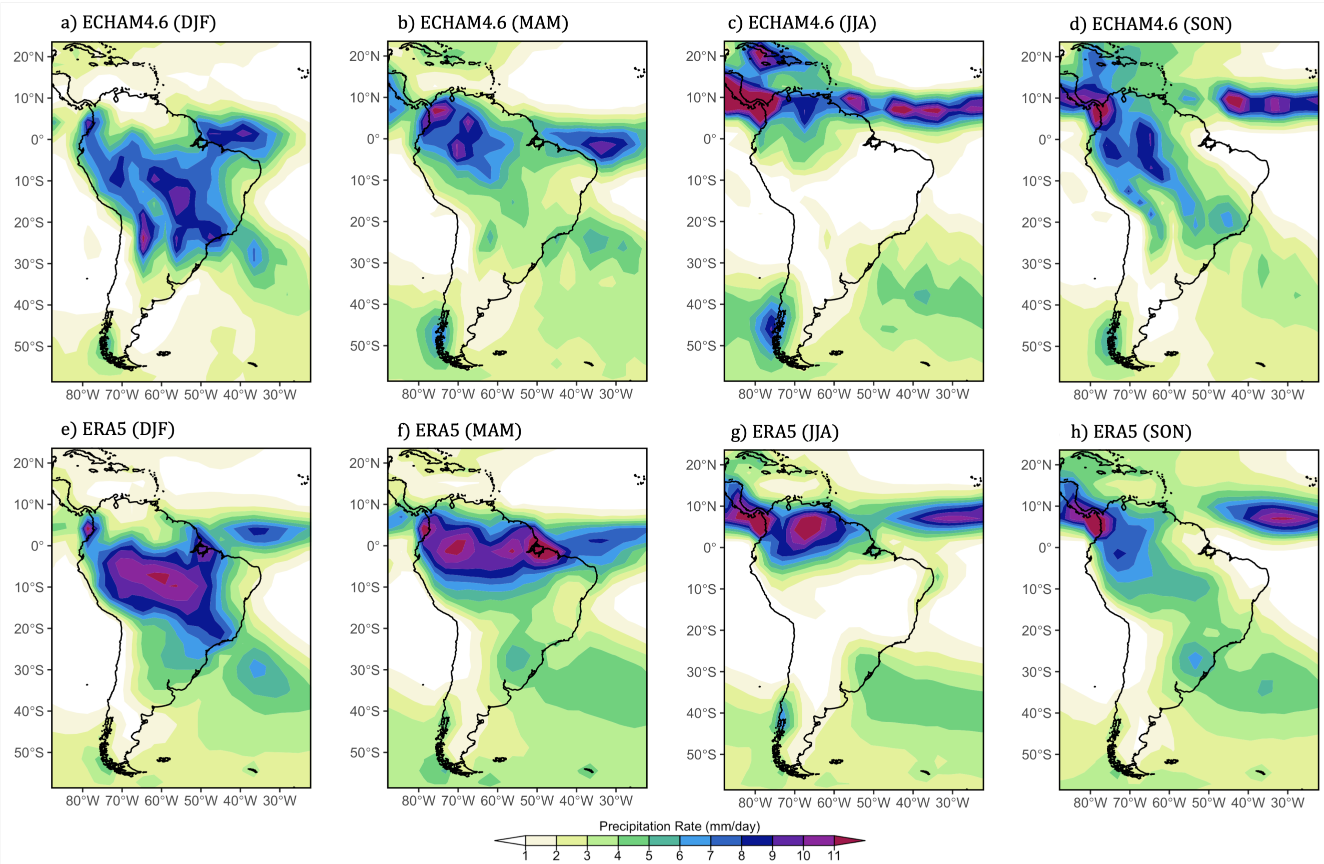
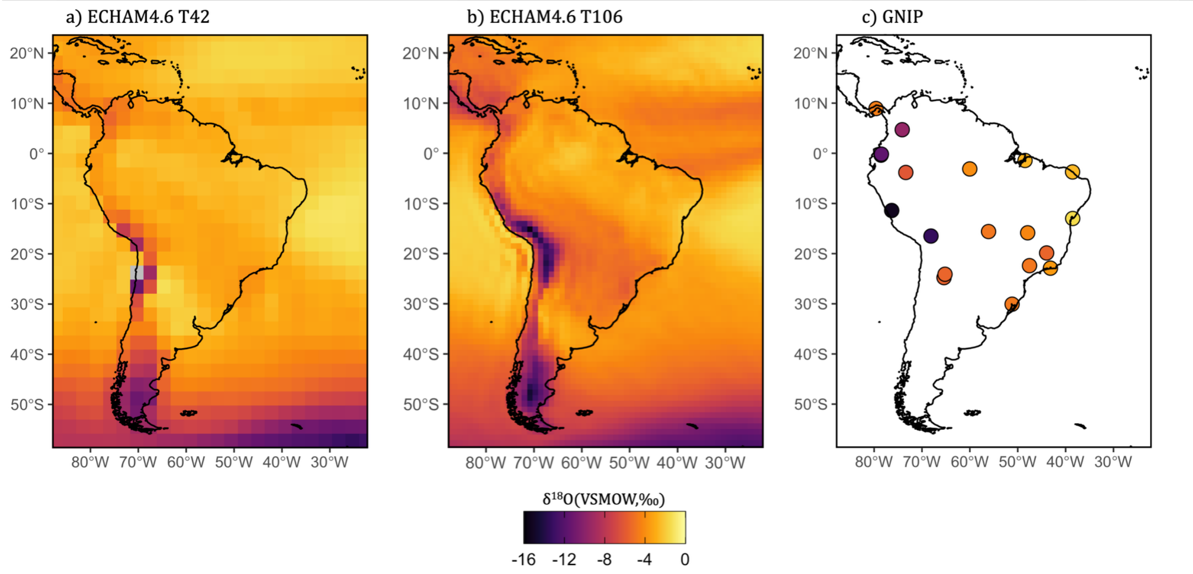


Figure S3: Seasonal precipitation rates over South America (a–d) simulated by ECHAM4.6 with prescribed SSTs over 40-years from 1980–2019 and (e–h) from ERA5 reanalysis (Hersbach et al., 2020) over the same 40-year period. Austral summer (DJF), spring (MAM), winter (JJA) and autumn (SON) climatology is shown in (a/e), (b/f), (c/g) and (d/h) respectively.

S4. ECHAM4.6 $\delta^{18}O$ comparison



90 **Figure S4: Comparisons of modern day $\delta^{18}O_p$ simulated by ECHAM4.6 at (a) T42 resolution in the current study, and (b) T106 resolution by Liu and Battisti (2015), showing a larger inland $\delta^{18}O$ gradient when the model is ran with a higher resolution. (c) Measured $\delta^{18}O_p$ from the Global Network of Isotopes in Precipitation (GNIP) stations (IAEA/WMO, 2021).**

S5. ECHAM4.6 simulation of El Niño/La Niña impact on South America

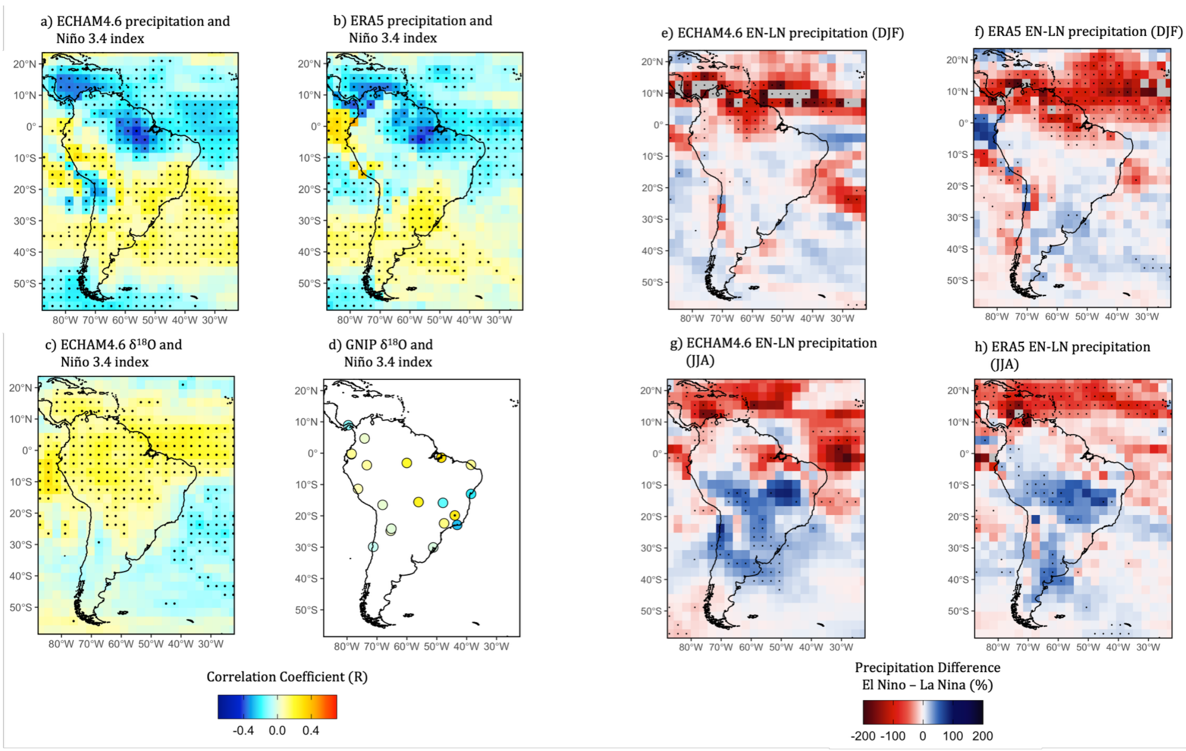


Figure S5: Modern-day ENSO-related anomalies in precipitation (a) simulated by ECHAM4.6 and (b) from ERA5 reanalyses data, found by correlating monthly values of these fields with Niño3.4. The modern-day ENSO-related anomalies are found from the Control simulation. (c) and (d) as in (a) and (b), but for the $\delta^{18}O$ of precipitation. Panel (d) shows values where proxy data extend from the mid-Holocene to modern day. The difference in precipitation (percentage), calculated as the anomaly between El Niño and La Niña years and normalized by the El Niño composite precipitation, is shown for DJF in (e) ECHAM4.6 Control simulation and (d) ERA5 Reanalysis data; and for JJA in (g) the ECHAM4.6 simulation and (h) ERA5 Reanalysis data. Stippled regions are where the correlation or precipitation difference is significant at a 95% confidence level.

S6. Differences in mid-Holocene simulation with coupled slab ocean model

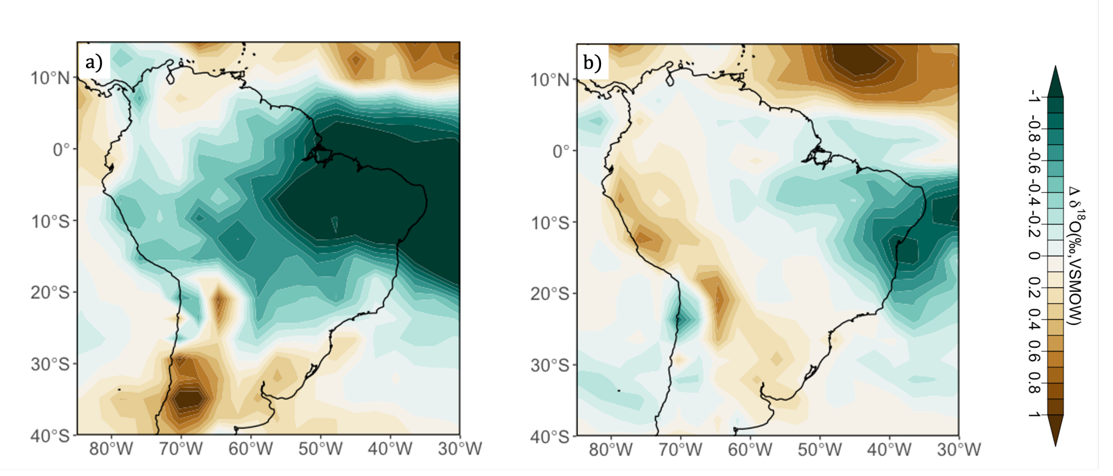


Figure S6: Mid-Holocene minus modern day $\delta^{18}O_p$ simulated by ECHAM4.6 (a) using SSTs prescribed from the PMIP4 experiments (MidH and Control), and (b) coupled to a slab ocean model (Wong et al., 2023).

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