

**On the remote impacts of mid-Holocene Saharan vegetation on South American hydroclimate: a modelling intercomparison**

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**Contents of this file**

Text S1 to S3  
Figures S1 to S6  
Table S1

## **Text S1.**

### **Model evaluation**

A comparison of the model pre-Industrial simulations with observational and reanalysis datasets (Fig. S2) elicits some shortcomings that are common to all models, albeit to different extents:

- (1) The models display a spurious second Inter Tropical Convergence Zone (ITCZ) in the southern equatorial Atlantic Ocean, which leads to an over-estimation of precipitation in the relatively dry region of northeastern Brazil.
- (2) The models do not adequately represent the South Atlantic Convergence Zone (SACZ). The northwest-southeast oriented precipitation band over South America is problematic in all models except EC-Earth. The spurious second ITCZ is a probable cause of an unrealistic Hadley Circulation which leads to increased subsidence over the south western Atlantic Ocean, and inhibiting convective precipitation over the SACZ.

There are also some model-specific regional biases. For example, there is an overestimation of precipitation in northwestern Amazon region in UofT-CCSM4 and an under-estimation of precipitation in northern South America in iCESM 1.2.

Overall, different models have different abilities to capture key elements of the climate over South America and the equatorial Atlantic Ocean. GISS-E2.1-G shows the largest (wettest) second ITCZ bias and under-estimates precipitation over the continental SACZ region. iCESM shows the widest second ITCZ, spanning nearly the entire equatorial Atlantic. EC-Earth performs relatively better than the other models, with the most muted second ITCZ and the most realistic representation of the SACZ. These observations are in line with previous studies of the ability of CMIP6 models to simulate the present-day climate over this region which indicated the superior performance of EC-Earth (Almazroui et al., 2021; Dias and Reboita, 2021). However, a relatively better performance in simulating present-day climate, where interannual variability dominates, does not necessarily indicate better ability to simulate the paleo-climate, where changes to orbital forcing, greenhouse gas concentrations or topography were more important. For instance, despite simulating present-day climate reasonably, CESM2 has been shown to have a high Equilibrium Climate Sensitivity (Zhu et al., 2022). Thus, despite inherent

biases, there are important conclusions that can be drawn by the results common to all models.

## **Text S2.**

### **Representation of the mid-Holocene Green Sahara (MH<sub>GS</sub>) in the models**

The mid-Holocene (MH) was characterized by large-scale vegetation changes from desert to shrub and savanna over northern Africa. The PMIP4 recommendations for vegetation sensitivity experiments include changing vegetation over the Sahara to evergreen shrub up to 25 °N and savanna/steppe vegetation poleward of 25 °N (Otto-Bliesner et al., 2017). The vegetation changes also led to decreases in dust mobilization and soil albedo, and changes in surface hydrology.

Different models in this study treat the presence of the Green Sahara differently. In the EC-Earth 3.1 MH<sub>GS</sub> simulation, vegetation over the Sahara was set to shrub, and dust was reduced by up to 80% relative to the PI. In the iCESM 1.2 MH<sub>GS</sub> simulation, present day Sahelian land surface and vegetation characteristics at 11 °N were imposed over the Sahara. The use of an interactive dust scheme led to a decrease in dust mobilization. In the UofT-CCSM4 MH<sub>GS</sub> simulation, tropical rainforests were extended northwards, the Sahara was completely replaced by evergreen shrubs up to 25 °N and almost completely (90%) replaced by a mix of steppe and savanna beyond 25 °N. Further, soil albedo was reduced to reflect greater moisture and organic matter, and the presence of five megalakes was incorporated through land surface changes. In the GISS-E2.1-G MH<sub>GS</sub> simulation, bare soil and grass over the Sahara were replaced by arid shrub below 25 °N and by grassland above 25 °N. The vegetation changes lead to a reduction in surface albedo from ~0.3 to 0.15-0.19 over the Sahara.

## **Text S3.**

### **Proxy-model comparisons**

To compare the effects of the Green Sahara on monsoon regimes within northern Africa and South America, we considered precipitation proxies from terrestrial and marine records within these respective domains: 0°-38°N; 20°W-45°E and 50°S-15°N; 80°W-30°W. The proxy data, derived from previously synthesized databases, includes records of pollen-based mean annual precipitation reconstructions (Bartlein *et al.*, 2011), lake level records from Africa (Tierney *et al.*, 2011), and an updated multiproxy hydroclimate reconstruction from South America (Gorenstein *et al.*, 2022). We also included hydroclimate reconstructions from Bolivia, Colombia and Peru (Harrison *et al.*, 2003) to fill in more data gaps in

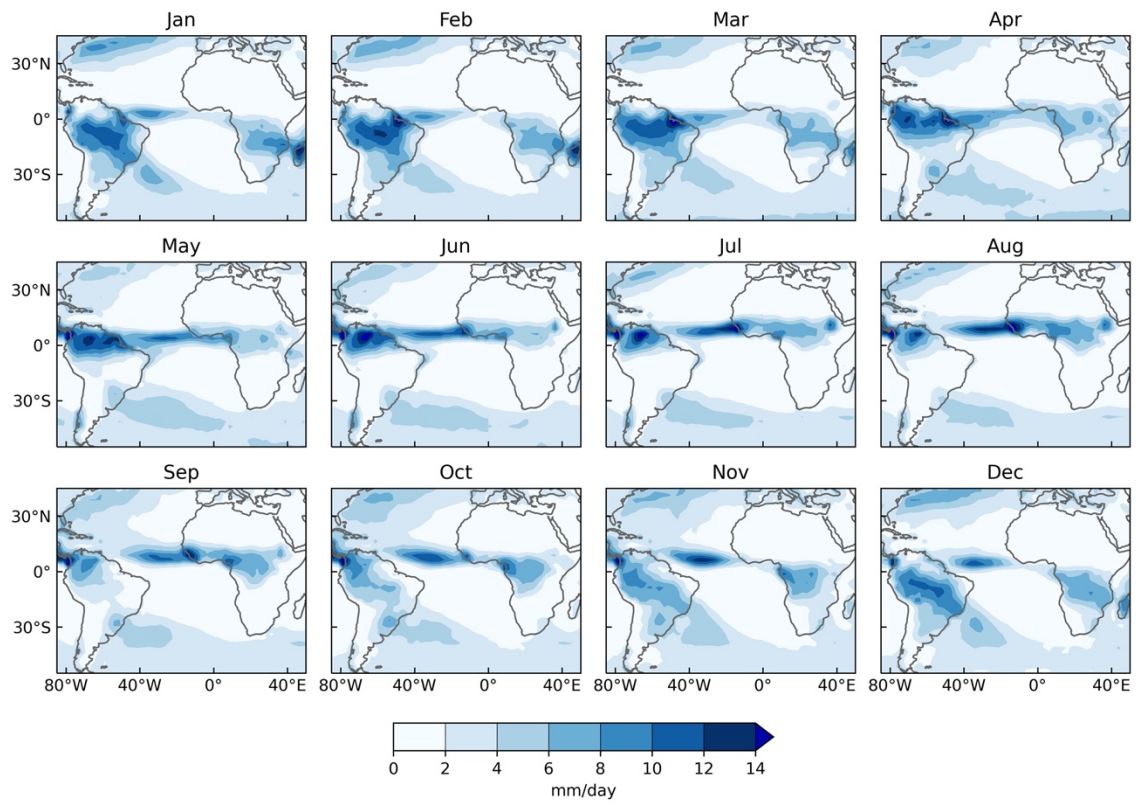
the tropical South American region. In total, we have collated 252 proxy records in which each MH hydroclimate response relative to PI is compared against model outputs.

To compare the proxies with models, MH precipitation responses relative to PI conditions were all categorically defined as either drier (rated as -1), wetter (1), or unchanged (0). Field reconstructions of mean annual precipitation from (Bartlein *et al.*, 2011) were converted to these categories based on the reported change for each grid point. Original classifications of lake level reconstructions from Africa (i.e., "low", "intermediate", and "high" (Tierney *et al.*, 2011)) for MH and PI periods were used to derive lake level status. These included higher, lower and unchanged to represent wetter, drier and unchanged, respectively. Categories for hydroclimate reconstructions from South America and additional records in this region follow the interpretation of the original publications (i.e., Harrison *et al.*, 2003; Gorenstein *et al.*, 2022). Simulated changes in precipitation from the nearest grid points to the proxy sites were extracted and similarly placed into three categories based on the direction of change and statistical significance.

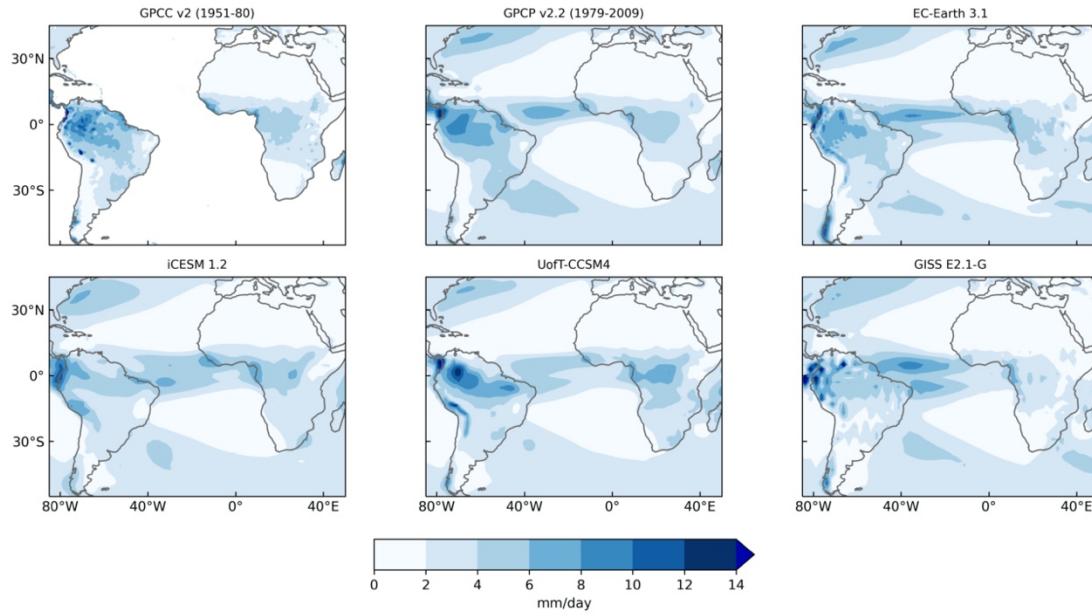
To quantify the agreement between models and proxies, we used Cohen's  $\kappa$  statistic defined as the observed fractional agreement ( $p_o$ ) between raters (i.e., proxies and models) relative to the probability of random agreement ( $p_e$ ):

$$\kappa = \frac{p_o - p_e}{1 - p_e};$$

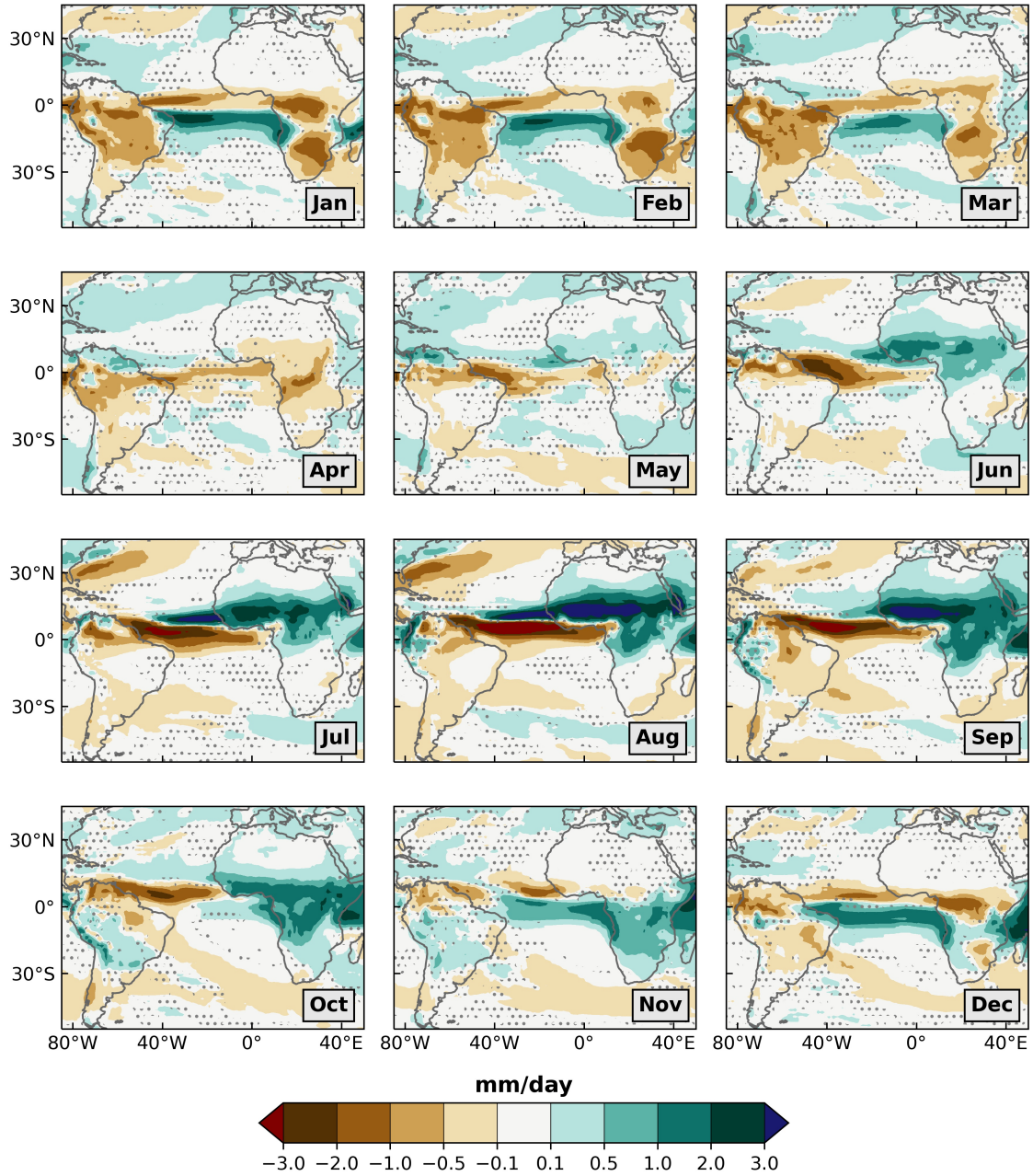
where  $p_o$  is the sum of the diagonal elements in the proxy-model matrix divided by the total number of samples,  $N$ ; and  $p_e$  is the product of the sum of each matrix row and column (given by the frequency of occurrence of each category) normalized by  $N$ . We implemented weights in the  $\kappa$  calculation by multiplying the data by a weight matrix that penalizes models for a total disagreement (i.e., drier when it should be wetter and vice versa) to a value of 0 and near miss (i.e., drier or wetter when it should be unchanged) to a value of 0.5.



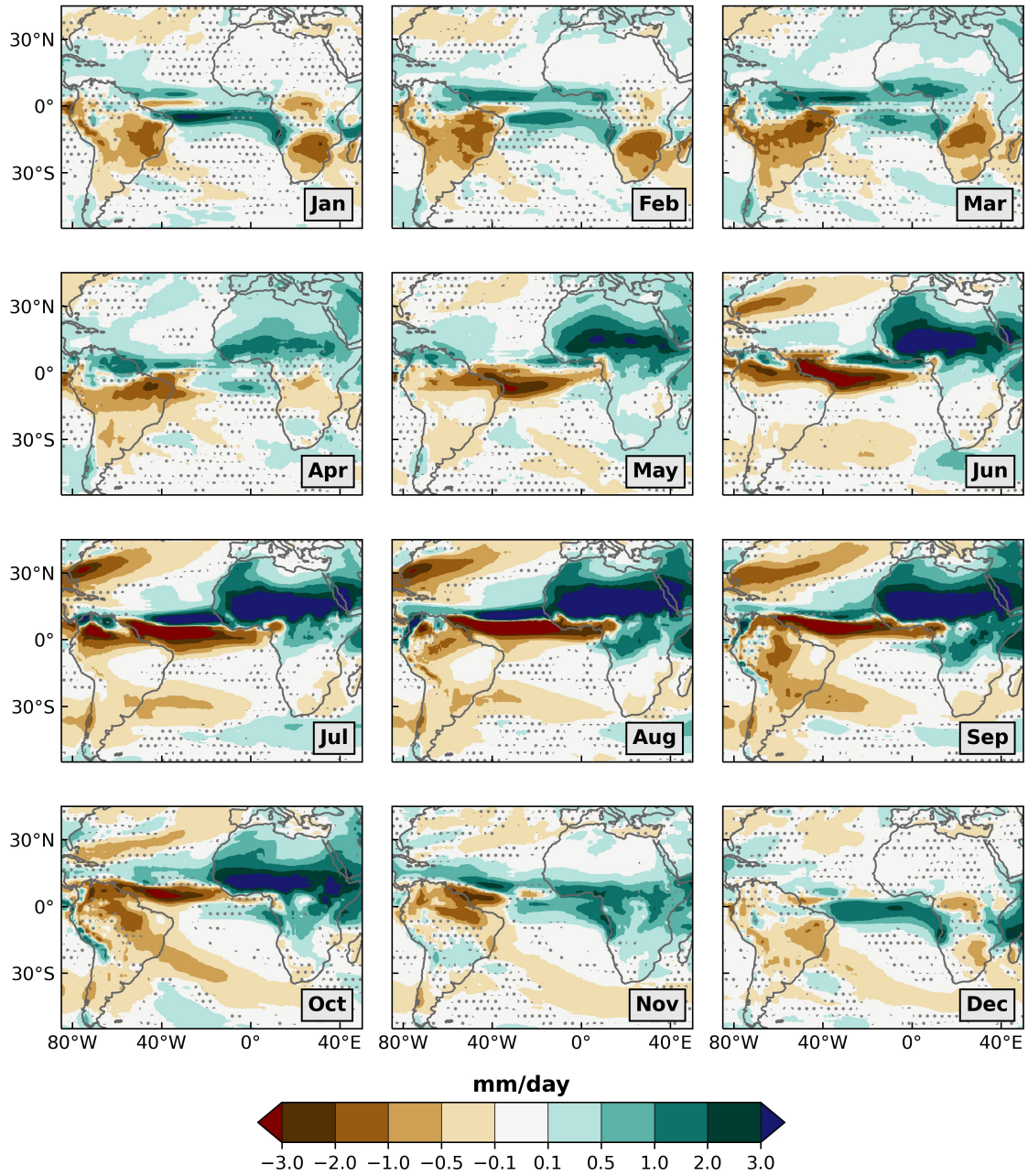
**Figure S1.** Present-day monthly precipitation patterns from the Global Precipitation Climatology Project (GPCP) version 2.2 from 1979-2009 (Huffman et al., 2015).



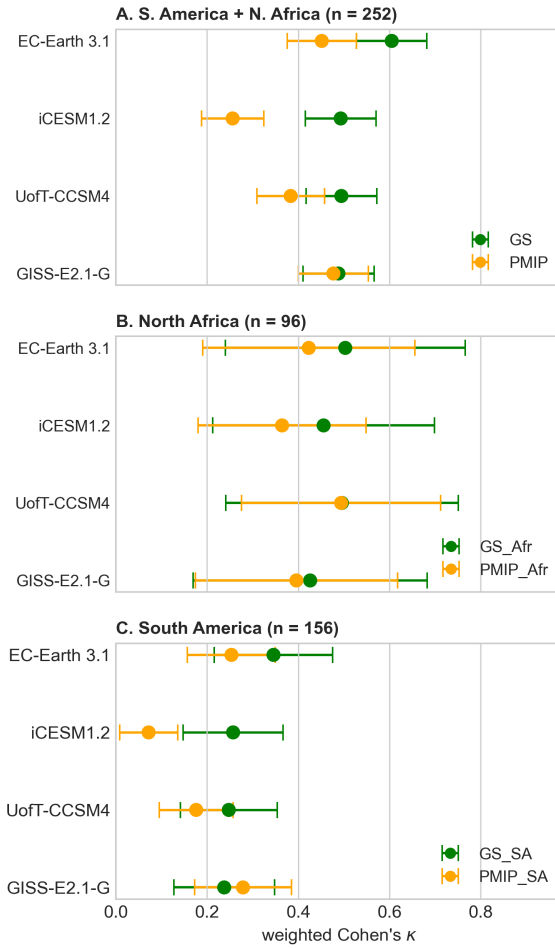
**Figure S2.** Comparison of annual precipitation patterns over South America between the Global Precipitation Climatology Centre (GPCC) Reanalysis Dataset, Global Precipitation Climatology Project (GPCP) Dataset and the PI simulations from EC-Earth 3.1, iCESM 1.2, UofT-CCSM4 and GISS-E2.1-G.



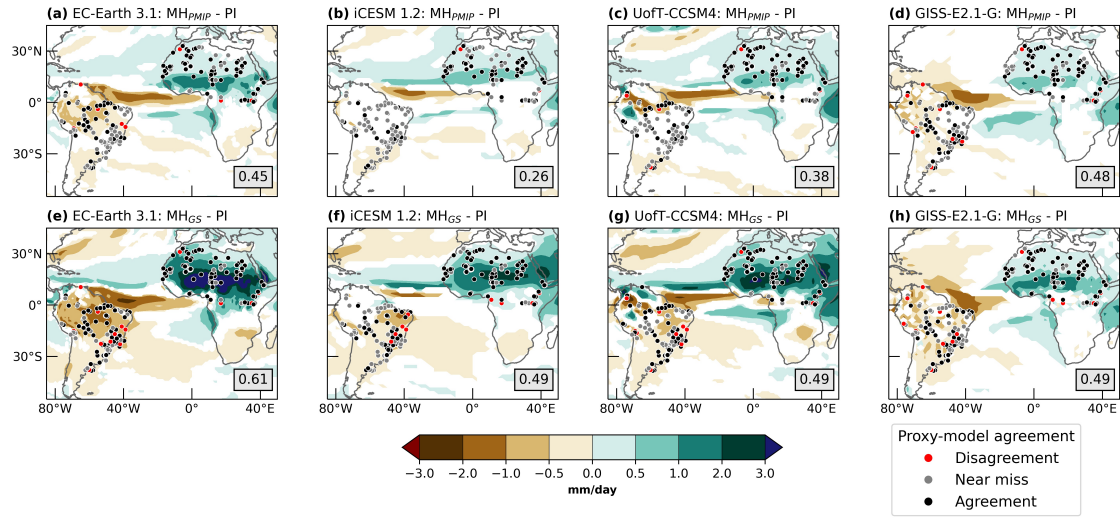
**Figure S3.** Precipitation changes between MH<sub>PMIP</sub> and PI experiments, shown as multi-model averages for each month. Stippling indicates areas in which less than three models agree on the sign change.



**Figure S4.** Precipitation changes between MH<sub>GS</sub> and PI scenarios, shown as multi-model averages for each month. Stippling indicates areas in which less than three models agree on the sign change.



**Figure S5.** Weighted Cohen's  $\kappa$  score between  $MH_{GS}$  (blue dots) and  $MH_{PMIP}$  (orange dots) scenarios over (a) South America and northern Africa, (b) northern Africa ( $0^{\circ}$  to  $38^{\circ}N$  and  $20^{\circ}W$  to  $45^{\circ}E$ ) and (c) South America ( $50^{\circ}S$  to  $15^{\circ}N$  and  $80^{\circ}W$  to  $30^{\circ}W$ ) regions. All datapoints are statistically significant ( $p < 0.05$ ). Error bars indicate 95% confidence intervals.



**Figure S6.** Proxy-model agreement over the region of study. Colors show MH-PI annual precipitation changes in mm/day. Only changes significant at the 95% confidence level are shown. Proxy sites are shown by circles, with the color indicating disagreement (“total miss”; red), near-miss (grey) and agreement (black).

|                                                           | <b>EC-Earth 3.1</b>                                    | <b>iCESM 1.2</b>                        | <b>UoFT-CCSM4</b>                    | <b>GISS-E2.1-G</b>                             |
|-----------------------------------------------------------|--------------------------------------------------------|-----------------------------------------|--------------------------------------|------------------------------------------------|
| Model name                                                | EC-Earth                                               | Community Earth System Model            | Community Climate System Model       | Goddard Institute for Space Studies Model      |
| Atmospheric component                                     | Integrated Forecast System                             | Community Atmosphere Model v5.3 (iCAM5) | Community Atmosphere Model v4 (CAM4) | Goddard Institute for Space Studies Model E2.1 |
| Atmospheric grid                                          | 1.125 x 1.125 (62)                                     | 1.9 x 2.5 (30)                          | 1 x 1 (26)                           | 2 x 2.5 (40)                                   |
| 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                            |
| Oceanic grid                                              | 1 x 1 (46)                                             | 1 x 1 (60)                              | 1 x 1 (60)                           | 1 x 1.25 (40)                                  |
| Simulation protocols                                      | CMIP5 / PMIP3                                          | CMIP6 / PMIP4                           | CMIP6 / PMIP4                        | CMIP6 / PMIP4                                  |
| Feedbacks incorporated in the MH <sub>GS</sub> simulation | Vegetation, dust                                       | Vegetation, dust, soil                  | Vegetation, soil, lakes              | Vegetation                                     |
| PI-to-MH albedo change over northern Africa               | 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)           | This paper                                     |

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