Palaeo-conditioning a coupled climate model to reproduce the Holocene greening of the Sahara and the warm poles of the Eocene

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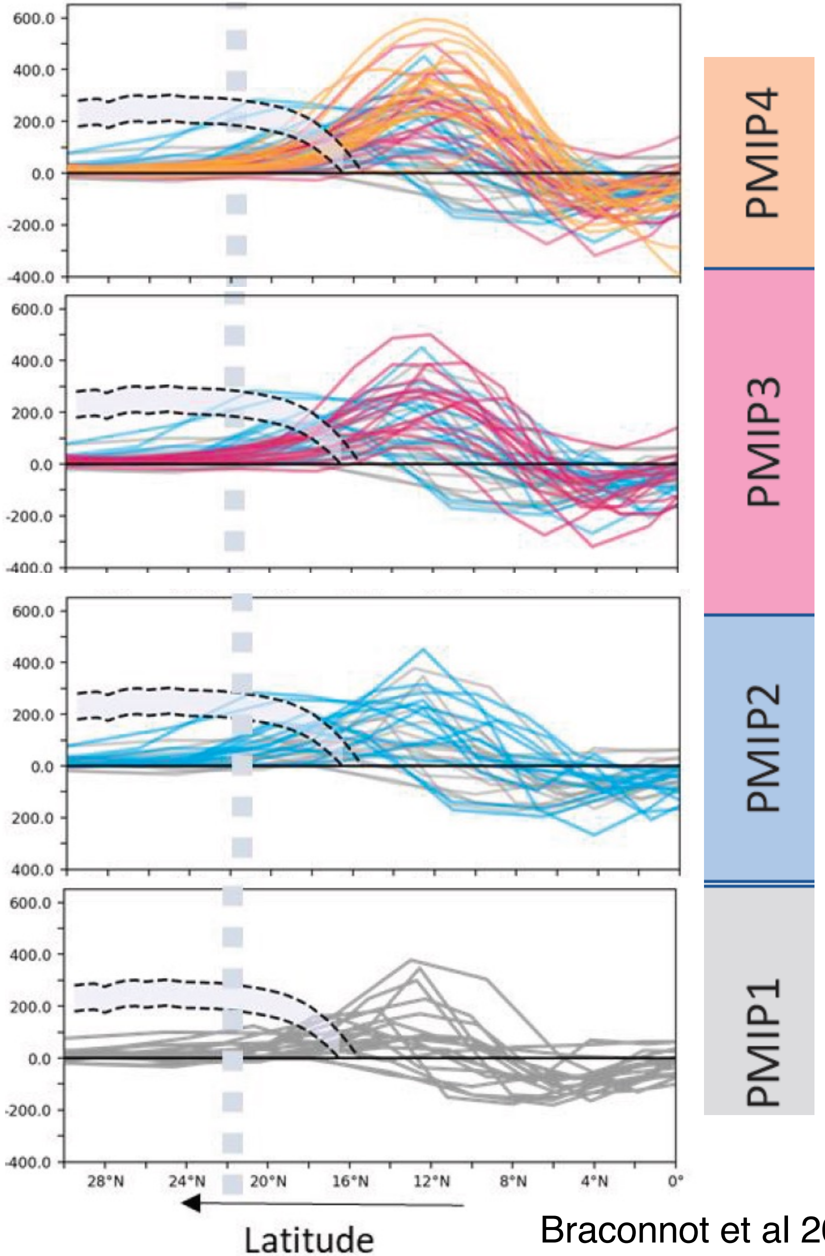
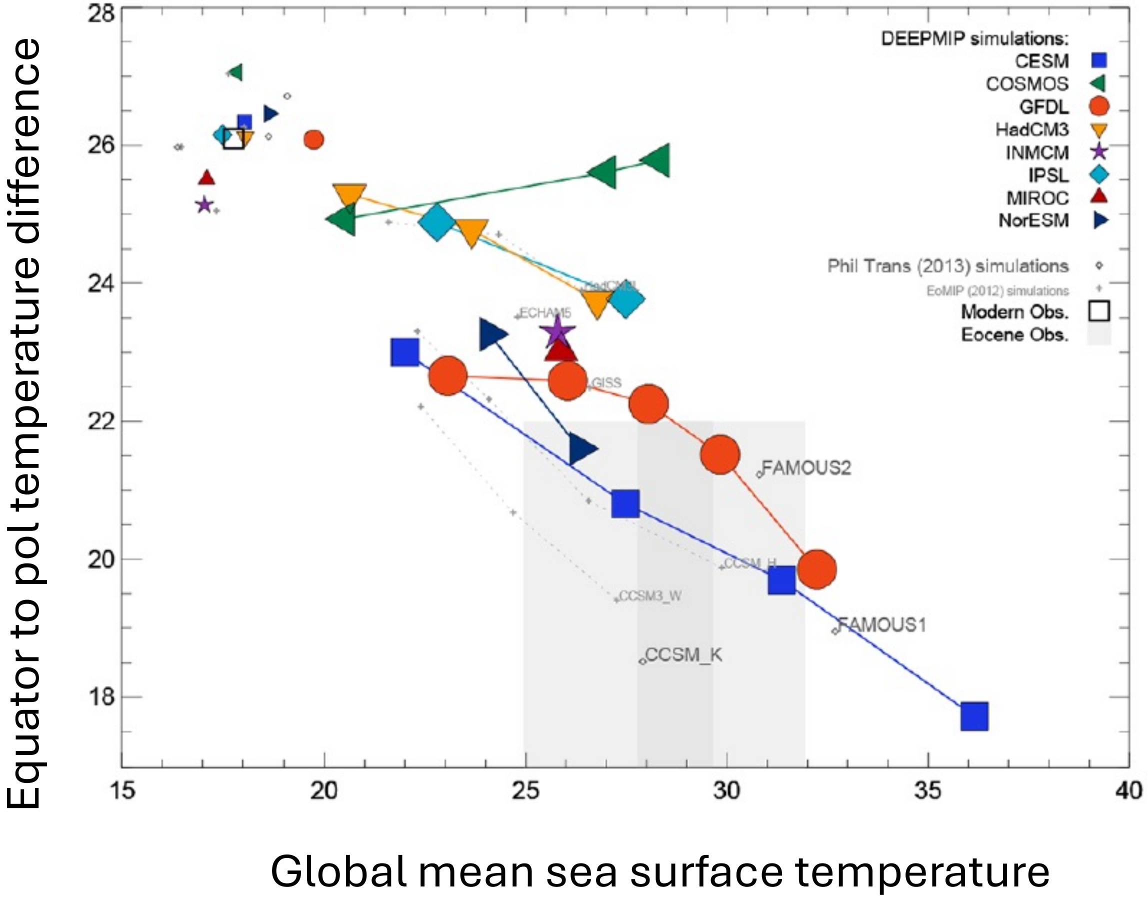
Systematic errors in paleoclimate simulations

Mid-Holocene – wet Sahara



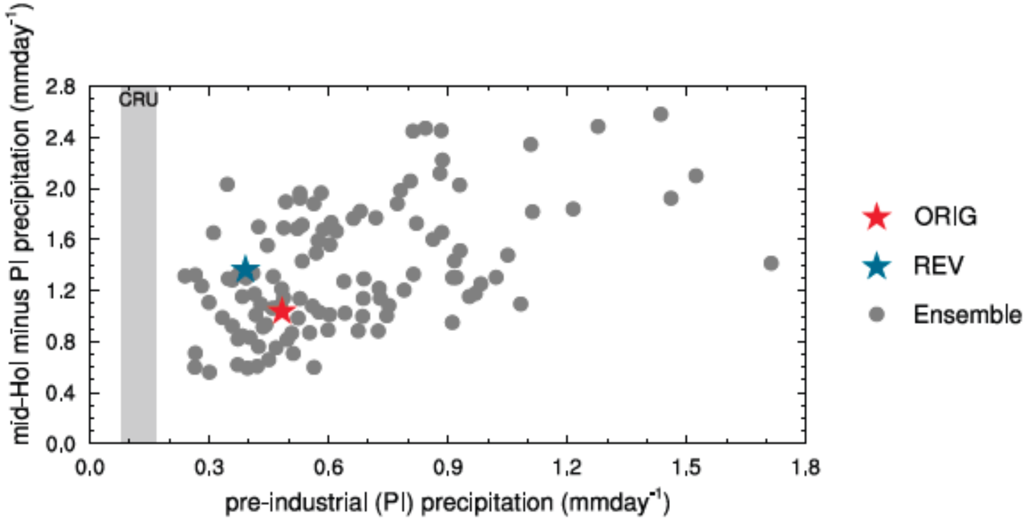
Braconnot et al 2021, PAGES Magazine

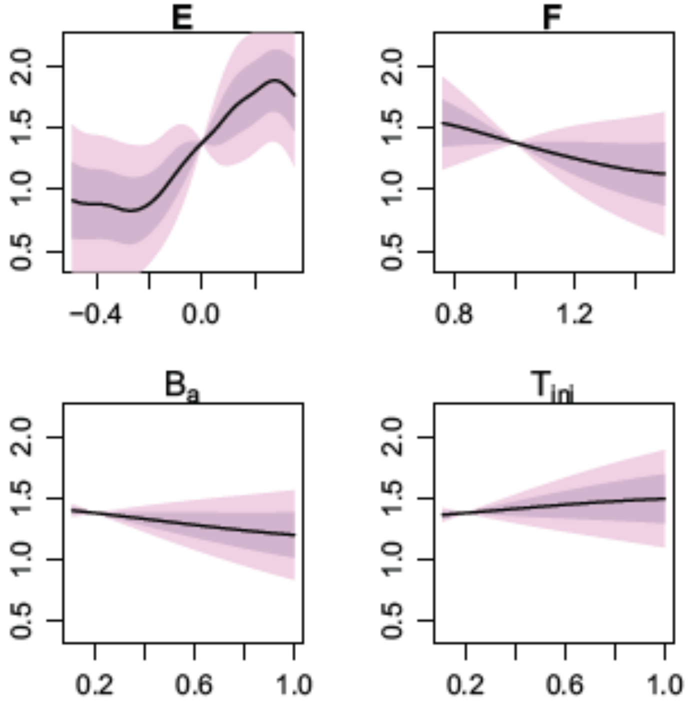
Early Eocene –warm poles

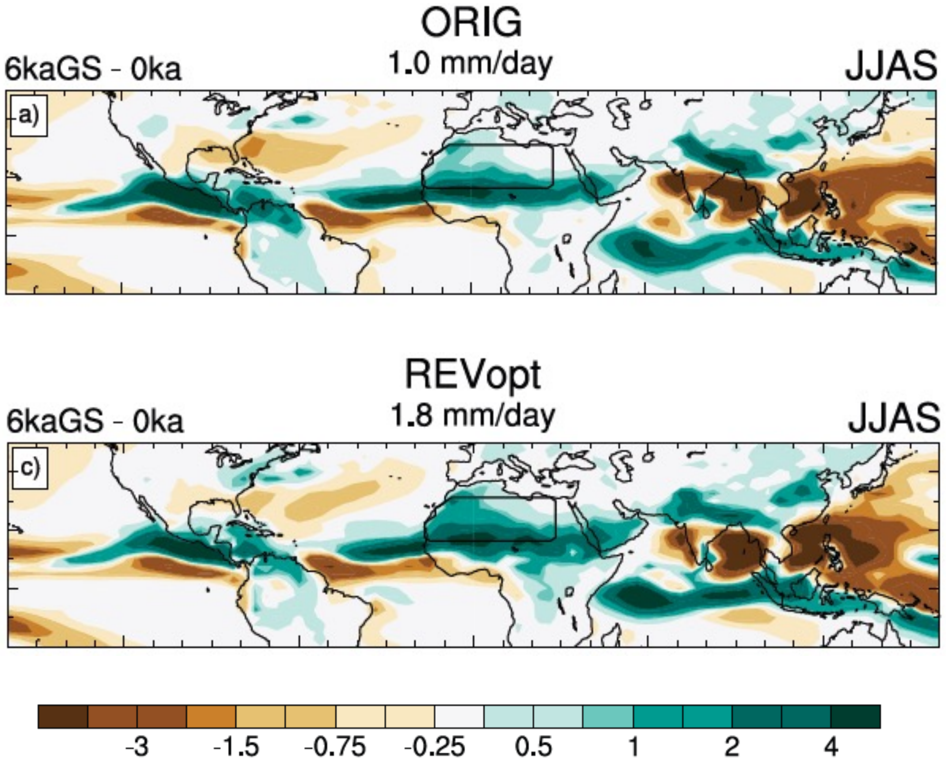


Lunt et al 2021, Clim Past

Single model ensemble for the Green Sahara







Our perturbed parameter approach with HadCM3 has already shown great potential in improving the palaeo-simulations fo the Green Sahara.

Hopcroft et al 2021; Hopcroft & Valdes, 2021, 2022

Progress in simulating Eocene warmth

Two approaches have shown improvements in simulating the polar warmth for the Eocene.

1. Changing cloud condensation number and effective radius to be more representative of pristine atmospheric conditions (Kiehl & Shields, 2013)

2. Tuning model parameters, particularly for clouds (e.g. Sagoo et al 2013).

We adopted both avenues in this study:

1. We changed the CCN density from 600/150 cm^{-3} over land/ocean respectively to **125/70 cm^{-3}** (versus 50 cm^{-3} everywhere in Kiehl & Shields, 2013) and the effective liquid cloud drop radius is changed from 9.5/13.5 μm over land/ocean respectively to **13.5** μm everywhere, versus 17 μm everywhere in Kiehl & Sheilds, (2013).

2. We sample a range of parameters in HadCM3 to tackle the second pathway including the level-dependent critical relative humidity for cloud formation, and several parameters that control convection.

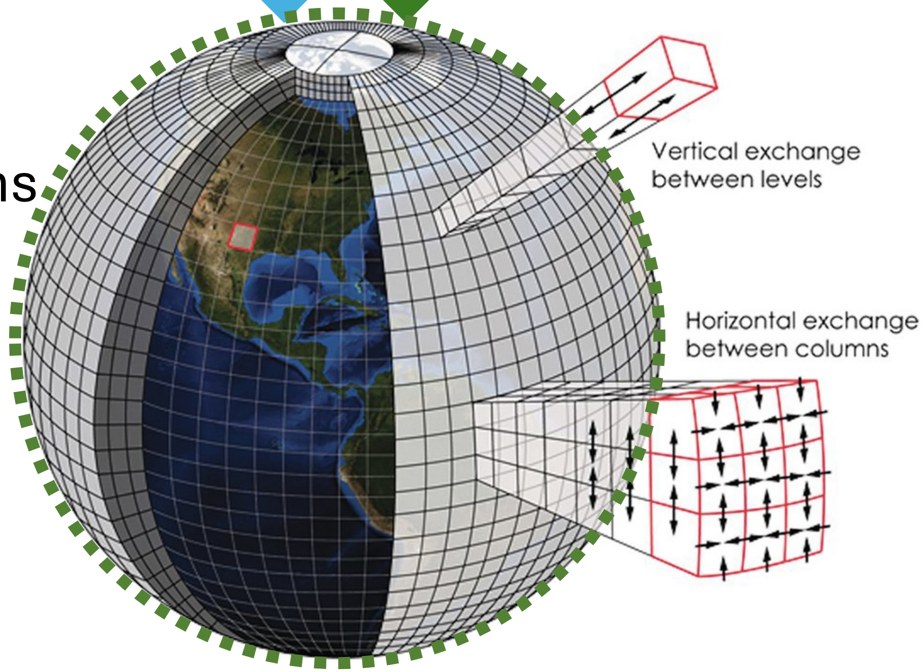
Aim of this work

Evaluation c.f. present-day

Evaluation cf. palaeo

- Newton's Laws of Motion
- 1st Law of Thermodynamics
- Conservation of Mass & Moisture
- Hydrostatic Balance
- Ideal Gas Law
- **Parametrisations**

- Physics
- Observations
- Numerical methods



Kotomarthi et al (2021)

Cambridge Univ. Press

- Projections
- Understanding past
- Attribution of recent/current climate

HadCM3 model history

HadCM3B (Gordon et al 2000; Valdes et al. 2017)

+ convection and vegetation updates (Hopcroft & Valdes, 2021): changes to the vertical entrainment/detrainment and vegetation moisture stress.

= HadCM3B**B-v1.0**

+ bug fixes to Rayleigh scattering (for clouds and aerosols): refractive index coefficients being too small by approximately 20%.

+ changes to cloud condensation number and effective radius: changed the CCN density from 600/150 cm^{-3} over land/ocean respectively to 125/70 cm^{-3}. Similarly, the effective liquid cloud drop radius is changed from 9.5/13.5 μm over land/ocean respectively to 13.5 μm everywhere.

+ atmosphere gravity wave limit

+ atmosphere surface pressure calculation diffusion

+ ocean streamfunction diffusion term

+ ocean bottom friction

+ ocean salinity conservation

= HadCM3BB-**v1.1**

+ palaeo-conditioning (this work)

= HadCM3BB-v2

A new ensemble using a slightly modified configuration of HadCM3

HadCM3BB-M2.1d-**v1.1**
Gordon *et al*. 2000; Valdes *et al*. 2017;
Hopcroft & Valdes, 2021; Valdes *et al.* in prep.

⟶ 1118 x **pre-industrial**, **mid-Holocene** and **Early Eocene** simulations

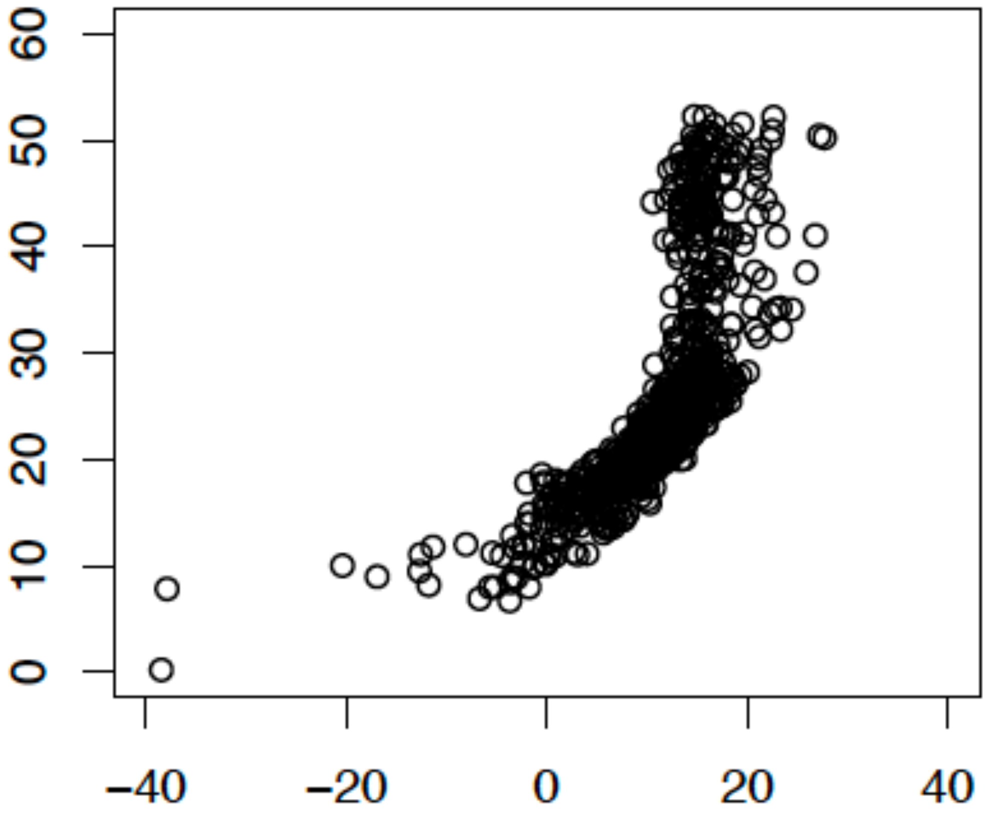
Sampling 19 model parameters that control:

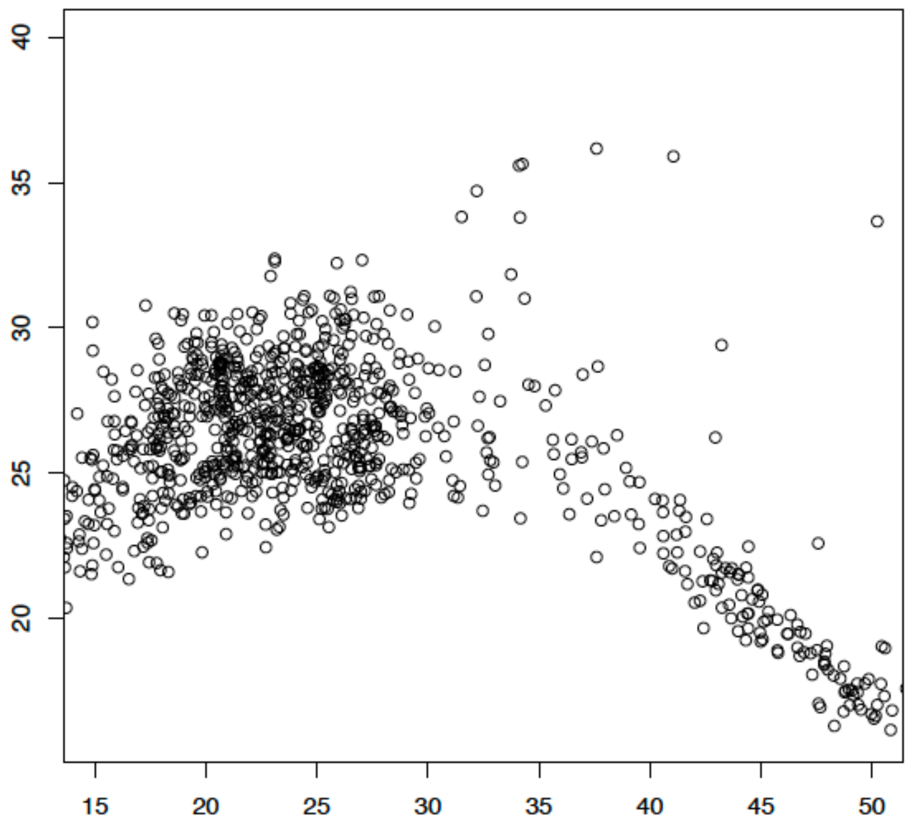
- clouds
- convection
- boundary layer
- vegetation
- atmosphere-ocean coupling
- ocean mixing

Hadley Centre **C**oupled **M**odel version **3**
Bristol/**B**irmingham configuration with
Met **O**ffice **S**urface **E**xchange **S**cheme
2.1 with **d**ynamic vegetation
-**v**ersion **2.0**

PARAMETER	Component/ scheme	Description	In Sagoo et al 2013?	In Hopcroft et al 2021?
XSBMIN	convection	Minimum convective temperature increment (K)		✓
AE	convection	Vertical dependence of entrainment		✓
Amdet	convection	Sensitivity of detrainment to relative humidity		✓
Fconv	convection	Overal entrainment/detrainment		✓
VF1	Large scale cloud	Ice fall speed (ms^{-1})	✓	✓
AFAC_CHN	Air-sea coupling	Surface heat flux multiplier from bulk aerodynamics		
AFAC_CDN	Air-sea coupling	Surface momentum flux multiplier from bulk aerodynamics		
ALPHAM	Sea-ice	Albedo of sea-ice as a function of temperature	✓	
PSI_CLOSE	Vegetation	Water stress of vegetation		(✓)
CW sea	Large scale precipitation	Cloud liquid water for precipitation over sea	✓	
CW land	Large scale precipitation	Cloud liquid water for precipitation over land	✓	
CT	Large scale precipitation	Conversion rate of cloud liquid water droplets to precipitation (s^{-1})	✓	✓
RH_{crit} 1,2,3	Clouds	Critical relative humidity for cloud formation at 4 levels	✓	
KAPPA0_SI	Ocean	Vert. diffusivity at surface	✓	
DKAPPADZ_SI	Ocean	Vert. diffusivity rate of increase	✓	
AHI3_SI	Ocean	isopycnal diffusion coefficient 3	✓	

The perturbed parameter ensemble shows spread in some diagnostics –e.g. equator-pole temperature gradient.





Climatic targets across three time-periods

variable	units	season	region	mean	uncertainty	Reference	Model
Present-day							
surface air temperature	C	ann	global-mean	14.05	0.15	Jones et al. (2013)	10.2
precipitation	mm/day	ann	Northern Africa (15-30N)	0.12	12%	Harris et al. (2014)	1.0
precipitation	mm/day	ann	Equatorial Africa (0-15N)	2.9	12%	Harris et al. (2014)	4.6
Mid-Holocene							
precipitation	mm/day	ann	Northern Africa (15-30N)	1.21	0.10	Bartlein et al. (2011)	1.1
precipitation	mm/day	JJA	Northern Africa (15-30N)	1.8	0.15	Assuming 2/3 during JJA	2.6
precipitation	mm/day	DJF	North Coast Africa (Libya)	0.55	0.1	Blanchet et al. (2021)	0.5
Early-Eocene							
surface air temperature	C	ann	global-mean	27	3.25	Inglis et al. (2020)	20.6
equator-pol SST gradient	C	ann	global-mean	19.5	2.5	Inglis et al. (2020); Lunt et al. (2021)	28.8

Tuning against all palaeo-constraints together ‘palaeo-conditioning’

Bayes’ theorem applied to this problem:

Prior specification on the model parameters

Likelihood of the data given the model

$$p\,(m \mid d) = \frac{p\,(m) \times p\,(d \mid m)}{p\,(d)}$$

Posterior distribution on the model given the data

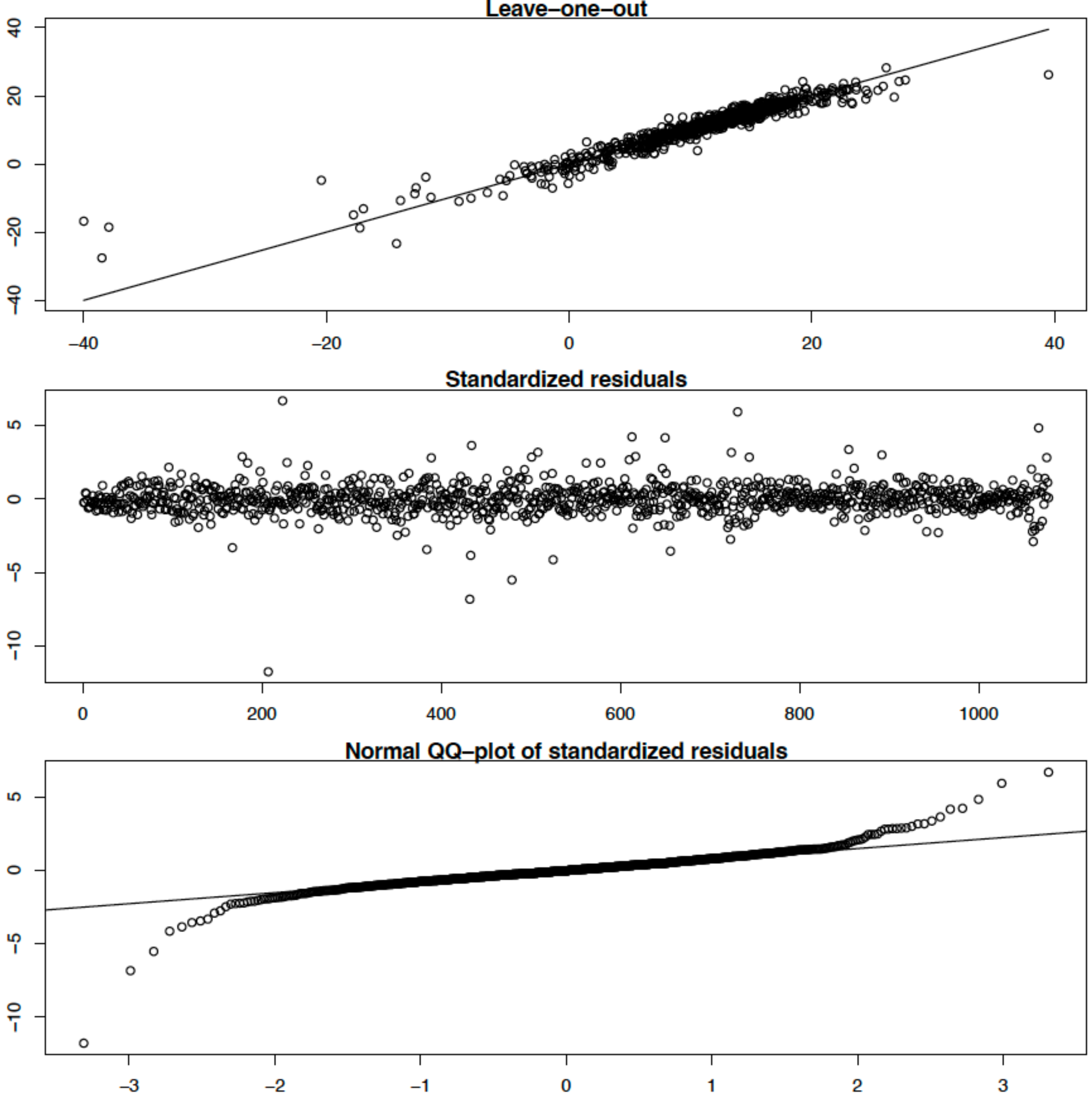
Evidence

We can closely approximate the left-hand side using a Markov chain Monte Carlo **(MCMC)** sampling algorithm but this requires x 1000s samples

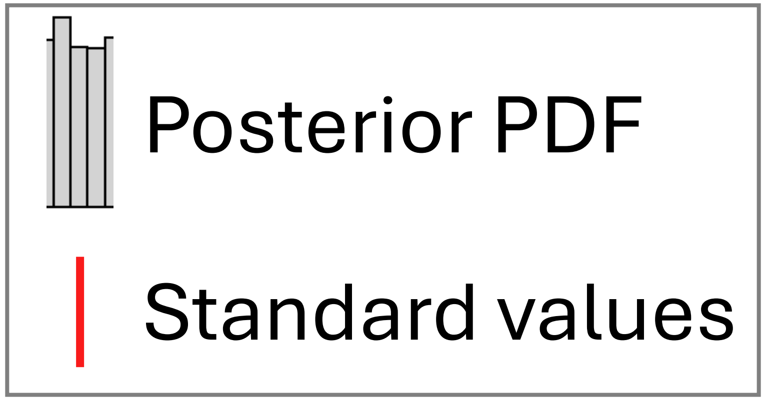
⟶ **use the emulator** instead of the climate model.

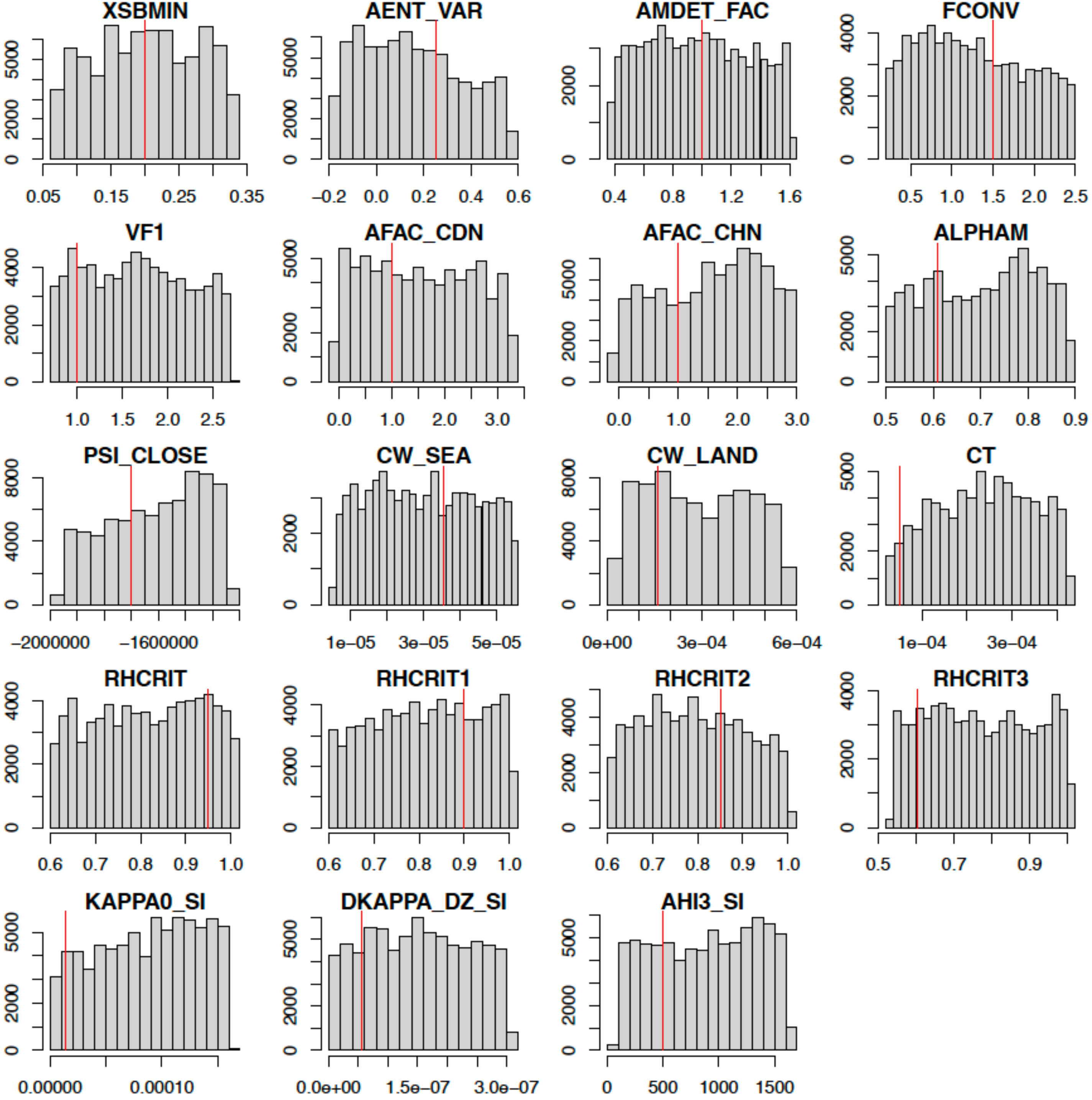
See e.g. Rougier, 2007

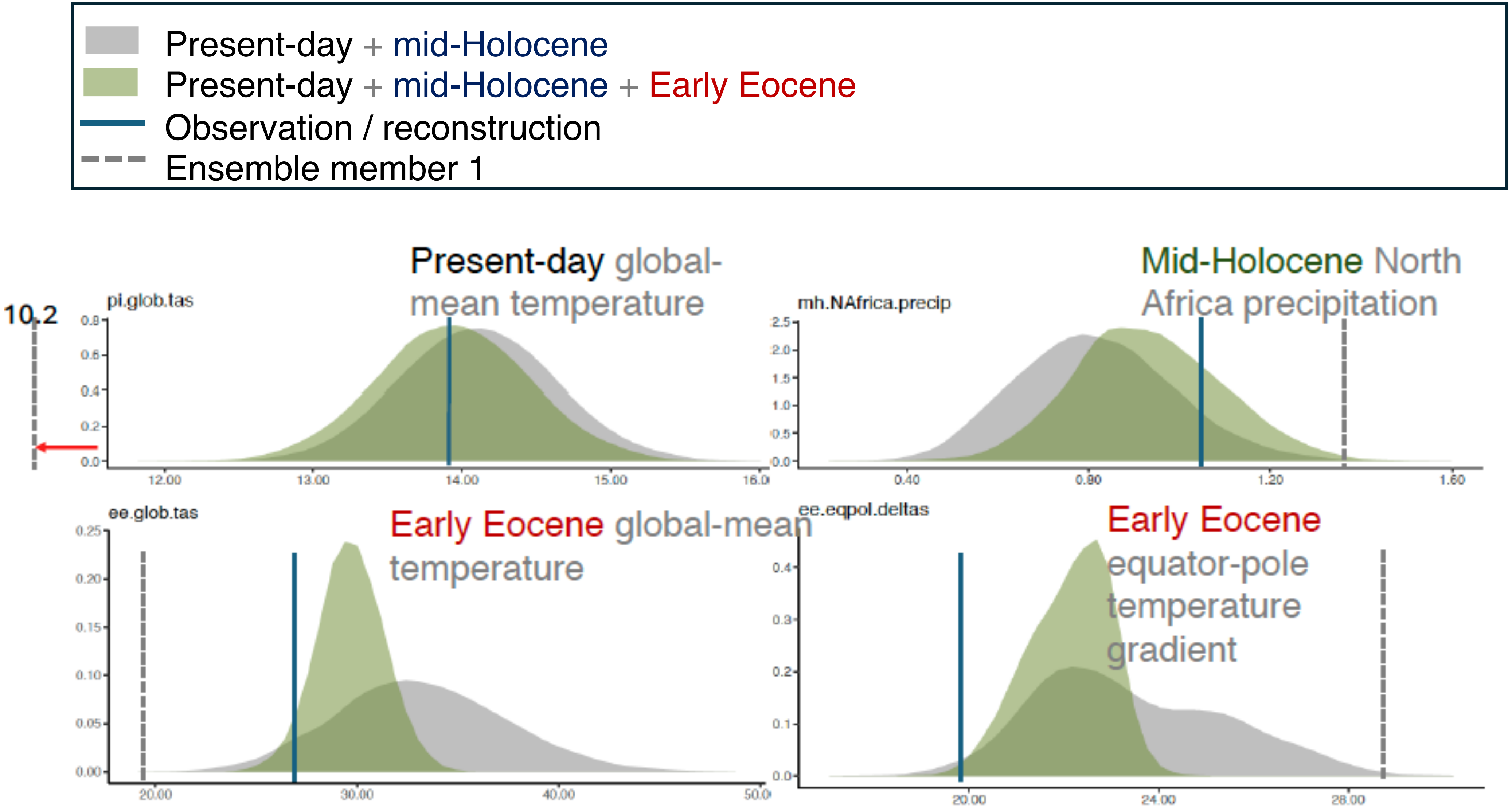
Leave-one-out emulator validation of **pre-industrial** global-mean surface air temperature (°C)



Example of Prior sampling of model parameters



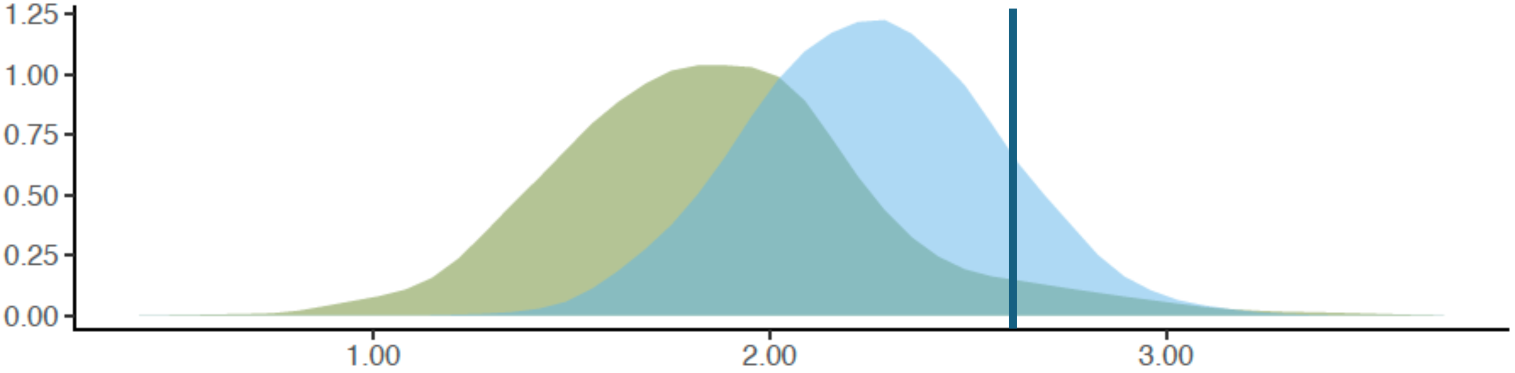




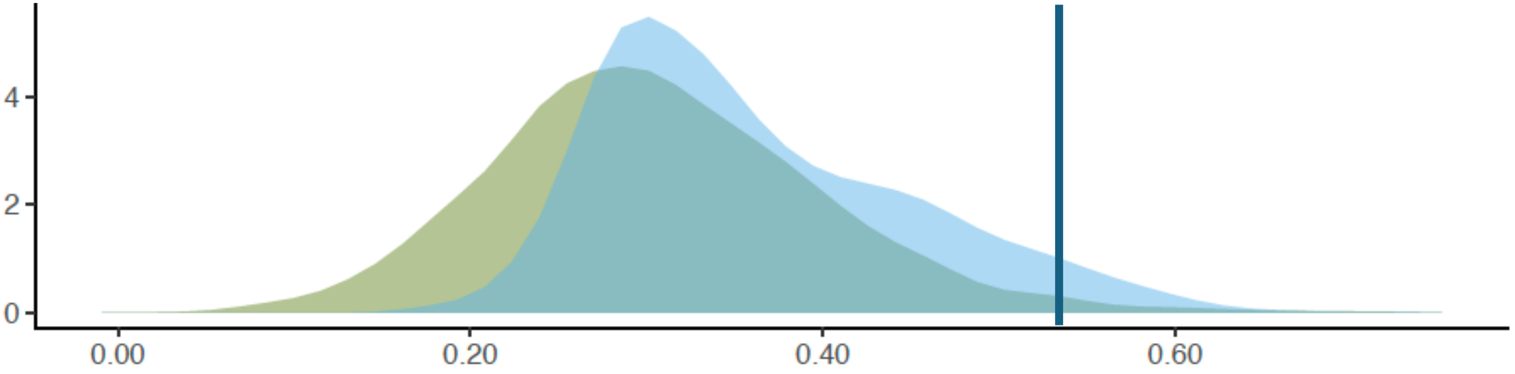
The model is able to improve both the overly-cold pre-industrial global mean temperature and the Eocene polar-equator gradient and global mean temperature. This occurs without too much of a degradation of the North Africa precipitation for the mid-Holocene.

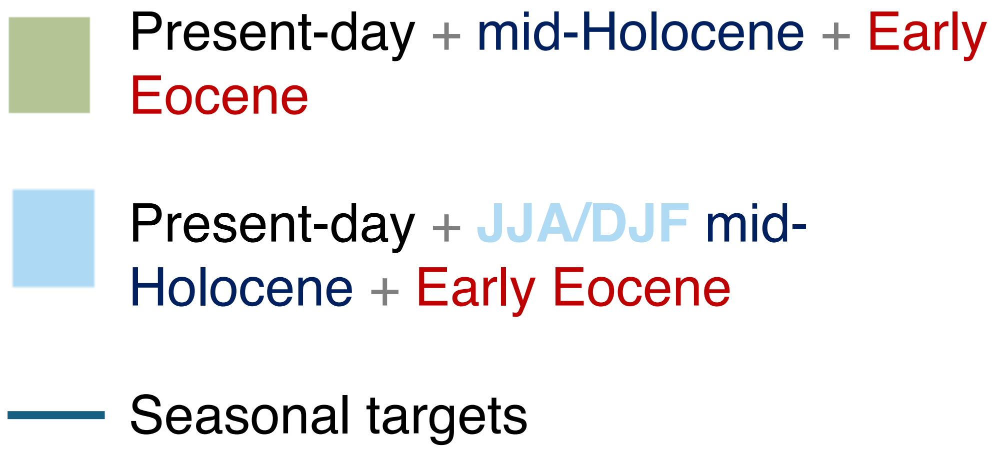
We attempted to condition the model to satisfy the winter storms hypothesis for the Green Sahara (e.g. Kutzbach et al 2020, Blanchet et al 2021). The emulator struggles to produce much additional precipitation over the North Eastern sector of the Sahara.

West Sahara JJA precipitation

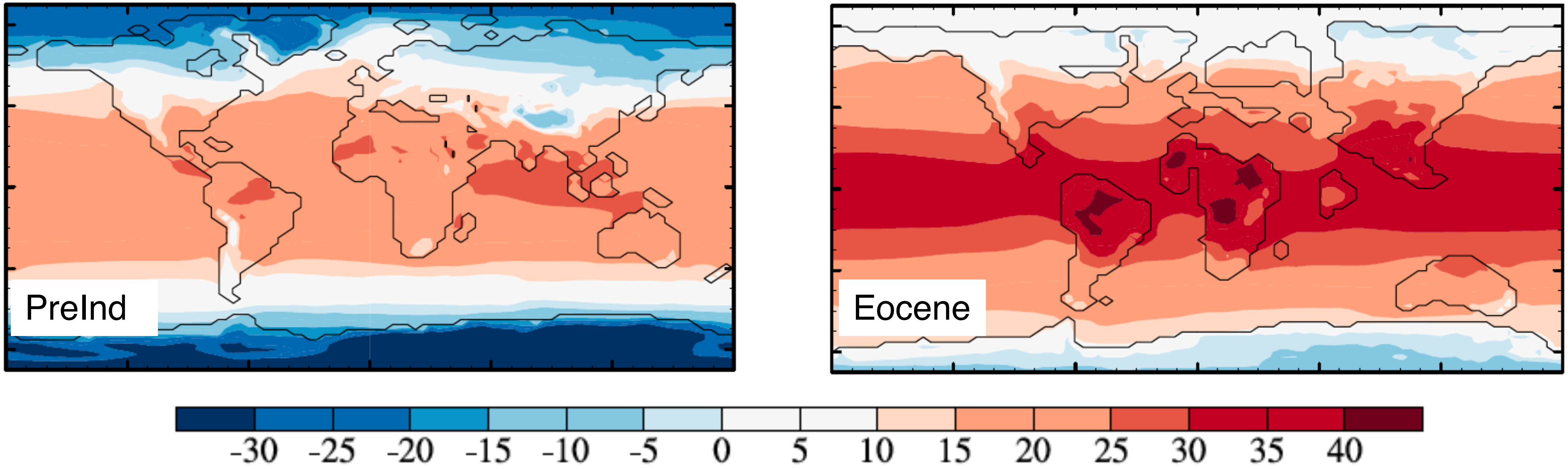


North East Sahara DJF precipitation





The tuned parameters (Present-day + mid-Holocene + Early Eocene) were used in HadCM3BB simulations for the pre-Industrial and Early Eocene. The global mean Eocene warming increases from 7.5°C in ensemble member 1 to 12°C in the tuned mode. The Eocene polar gradient reduces from 26 °C in ensemble member 1 to 20°C in this tuned version.



HadCM3BB simulations with the conditioned parameter values: pre-Industrial and Early Eocene annual mean temperature.

The tuned parameters also produce significant changes ot the global mean-temperature field for the Holocene so that the global-mean temperature anomaly is warmer rather than cooler than the pre-industrial.

However, the preliminary tuned version does not satisfy records of vegetation expansion over North Africa during the mid-Holocene as well as the earlier work which did not include the Eocene targes. We are thus continuing to work on this.

Conclusions

⚠ Emergent behaviour of climate model simulations depends heavily on parameterisations (clouds, mixing, eddies, aerosols etc). These are more important than gridcell size (above about ~10 km c.f. ~ 250 km in HadCM3).

😐 Present-day observations are an incomplete test.

☺ A simple paleoclimate tuning can markedly improve the simulation of more than one contrasting climatic state (i.e. mid-Holocene *and* Early Eocene).

Paleo-conditioned models need further testing but should provide different answers about future climate and provide much better estimates for other paleo states (e.g. PETM).