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Simulation of the mid-Pliocene Warm Period using HadGEM3: experimental design and results from model–model and model–data comparison

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TEXT

1. Model description

1.1. HadGEM2-AO

The immediate predecessor to HadGEM3 is the family of HadGEM2 models, all of which vary in terms of level of complexity but all of which have a common computational framework (Tindall and Haywood 2020, Martin *et al*. 2011), which HadGEM3 also shares. The most complex full Earth system version of the family, HadGEM2-ES, was included in the previous IPCC Assessment Report, AR5. Tindall and Haywood (2020) conducted a Pliocene simulation for PlioMIP1 using the fully coupled version of this model, HadGEM2-AO (hereafter referred to as HadGEM2). This model has the same atmospheric spatial resolution as HadGEM3, but only 38 atmospheric vertical levels; for full details on HadGEM2, see Collins *et al*. (2011), Martin *et al*. (2011) and Tindall and Haywood (2020). In contrast to the HadGEM3 *mPWP* simulation, the HadGEM2 Pliocene simulation uses dynamic vegetation from TRIFFID (Top-down Representation of Interactive Foliage and Flora Including Dynamics, see Cox 2001), and a previous iteration of the PRISM boundary conditions, PRISM3 (see Dowsett *et al*. 2007 and Dowsett *et al*. 2010). It should be noted that, whilst PRISM3 was mostly implemented in this model, this does not include the orography, which was the same as pre-industrial away from ice sheet regions. It should also be noted that the LSM used in this model differs slightly from both PRISM3 and HadGEM3 simulations, in that the Bering Sea, Canadian Archipelago and Hudson Bay gateways are all open (Tindall and Haywood 2020).

1.2. HadCM3

The original fully-coupled atmosphere-ocean version of the UK's physical climate model is HadCM3 (Gordon *et al*. 2000), and over the years this has been used extensively for paleoclimate simulations and has been updated/optimised according to the simulation in question. Although no longer considered a state-of-the-art model, its fast speed and relatively cheap computational cost still makes it appropriate for paleoclimate simulations (Hunter *et al*. 2019) and, thanks to this, it has been included in every phase of CMIP to date. Both of the older HadCM3 simulations used here (HadCM3-PRISM2 and HadCM3-PlioMIP1) have an atmospheric resolution of 3.75° longitude by 2.5° latitude with 19 vertical levels, and an ocean resolution of 1.25 ° longitude/latitude with 20 vertical levels; for full details, see Gordon *et al*. (2000). For a land surface scheme, both of these simulations use the 1st generation Met Office Surface Exchange Scheme (MOSES1, see Cox *et al*. 1999), and both use dynamic vegetation. Concerning boundary conditions, HadCM3-PRISM2 predates PlioMIP1 and thus uses PRISM2, whereas HadCM3-PlioMIP1 was included in PlioMIP1 and, similar to HadGEM2, uses PRISM3 boundary conditions.

1.3. PlioMIP2 models

The same 16 models as those in H16 are included here as a comparison to HadGEM3. These models, along with their spatial resolutions, are listed in Table 4; see Table 1 in H16 for full information (including boundary conditions, equilibrium climate sensitivity values and references) on each model. It should be noted that one of these models is HadCM3 but is slightly different to the earlier versions discussed here; the model, HadCM3-PlioMIP2, was run by Hunter *et al*. (2019) and is equivalent (concerning updates) to the version developed by Valdes *et al*. (2017), HadCM3B-M2.1 (which includes an updated land surface scheme, MOSES2, see Essery *et al*. 2001). In short, whereas MOSES1 treats each model grid point as a homogeneous surface and calculates energy and moisture fluxes using effective parameters, MOSES2 has subgrid heterogeneity and an improved representation of surface and plant processes (Hunter *et al*. 2019); see Valdes *et al*. (2017) for a complete comparison of MOSES1 and MOSES2. All of the models included in PlioMIP2 use PRISM4 boundary conditions.

2. Atmospheric equilibrium of Hadley Centre models

As discussed in the main manuscript (Section 3.1.2), the fact that the 1.5 m air temperature, TOA radiation balance and ocean temperature/salinity are all still trending suggests that the HadGEM3 *mPWP* simulation is not yet in full atmospheric or oceanic equilibrium. These values are repeated in Table S2, shown alongside the centennial temperature trends and mean TOA radiation balance from the other Hadley Centre models used here. All the other models appear to be closer to equilibrium, with all temperature trends below 0.2°C century^{-1} and all TOA radiation balances less than 0.5 W m^{-2}. The caveat that the HadGEM3 *mPWP* simulation is not in equilibrium (and therefore has further warming still to go, as discussed in the manuscript) whereas the other versions of the same UK model are closer to equilibrium should therefore be considered when making these comparisons.

TABLES

Value	Mega biome	BLT	NLT	C3 Grass	C4 Grass	Shrubs	Urban	Lakes	Bare soil	Land ice
1	Tropical forest	0.92	0	0	0.02	0.01	0	0	0.05	0
2	Warm-temperate forest	0.75	0	0.07	0.03	0.1	0	0	0.05	0
3	Savanna and dry woodland	0.18	0	0	0.67	0.05	0	0	0.1	0
4	Grassland and dry shrubland	0.05	0	0	0.55	0.3	0	0	0.1	0
5	Desert	0	0	0	0.02	0.13	0	0	0.85	0
6	Temperate forest	0	0.75	0.1	0	0.1	0	0	0.05	0
7	Boreal forest	0	0.7	0.2	0	0.025	0	0	0.075	0
8	Tundra	0	0	0	0	0.4	0	0	0.6	0
9	Dry tundra	0	0	0	0	0.4	0	0	0.6	0
28	Land ice	0	0	0	0	0	0	0	0	1

Table S1 - Lookup table to translate mega biomes from PRISM3 into HadGEM3 PFTs. Values in first column correspond to those in Figure 2

Model and simulation		1.5m air temperature trends (°C)	Mean TOA radiation ($W m^{2}$)
HadCM3-PRISM2	**PI**	0.13	-0.14
	Pliocene	0.19	0.26
HadCM3-PlioMIP1	**PI**	0.06	-0.09
	Pliocene	0.01	0.37
HadCM3-PlioMIP2	**PI**	0.06	-0.11
	Pliocene	0.01	0.04
HadGEM2	**PI**	0.05	0.4
	Pliocene	0.14	0.48
HadGEM3	***piControl***	0.51	0.18
	piControl_mod	-0.47	0.21
	mPWP	0.34	0.88

Table S2 - Centennial trends (calculated via a linear regression) and mean TOA radiation over the last 50 years of the simulations from all the Hadley Centre models used here. Negative TOA radiation = net radiation flux is downward

FIGURES

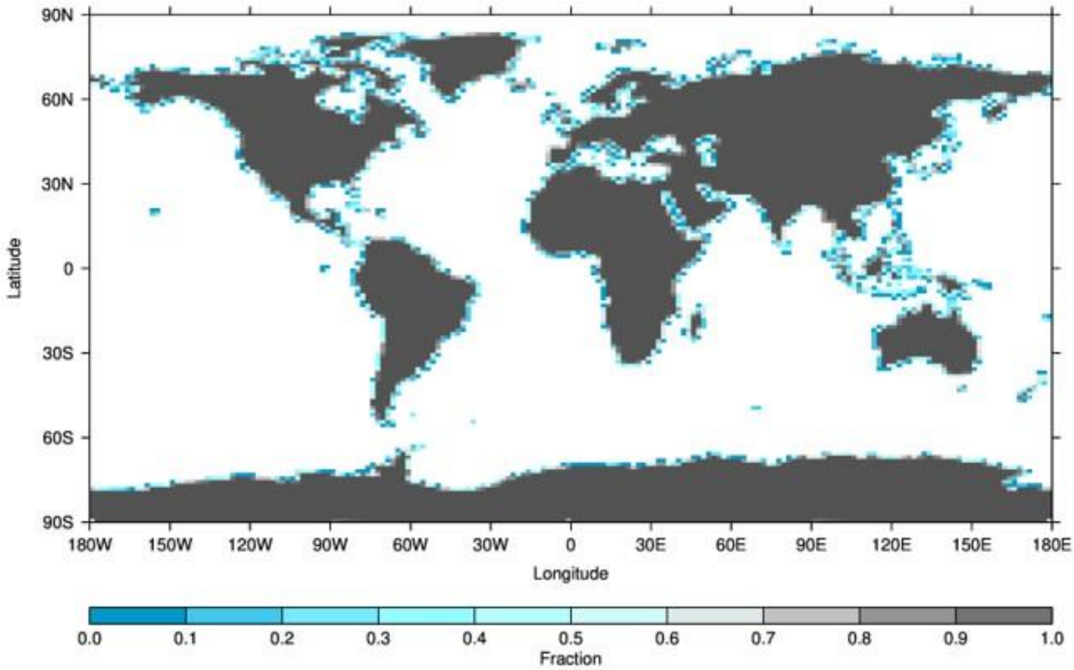

Figure S1 - Land sea mask used in HadGEM3 *mPWP* and *piControl* simulations, with colours showing fractional coverage of coastal grid points

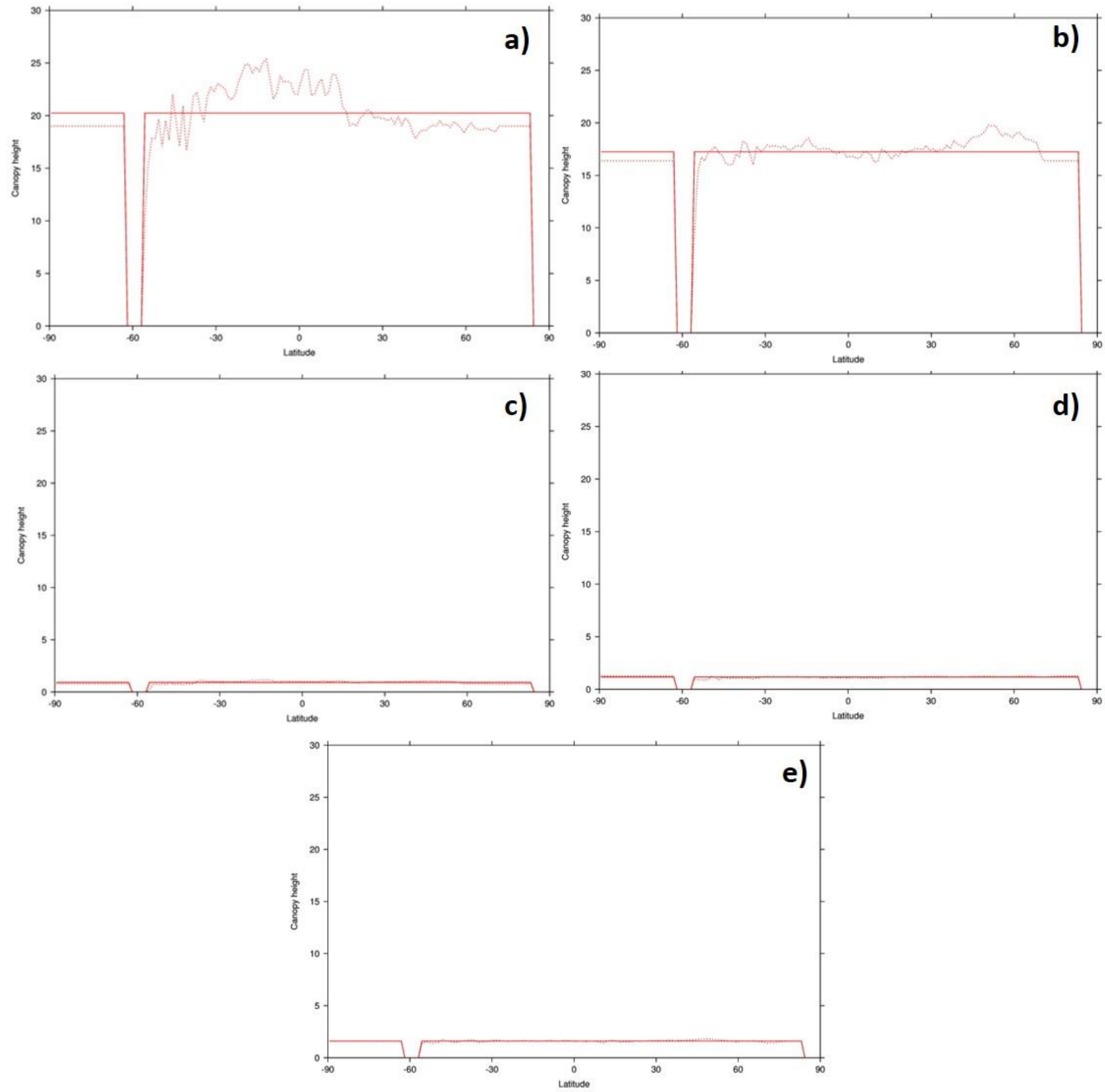

Figure S2 – Canopy height used in HadGEM3, for each PFT. Dashed lines show global mean from *piControl* simulation, solid lines show latitudinally varying function of this global mean, used in *mPWP* simulation. a) broadleaf trees; b) needle-leaved trees; c) temperate C3 grass; d) tropical C4 grass; e) shrubs

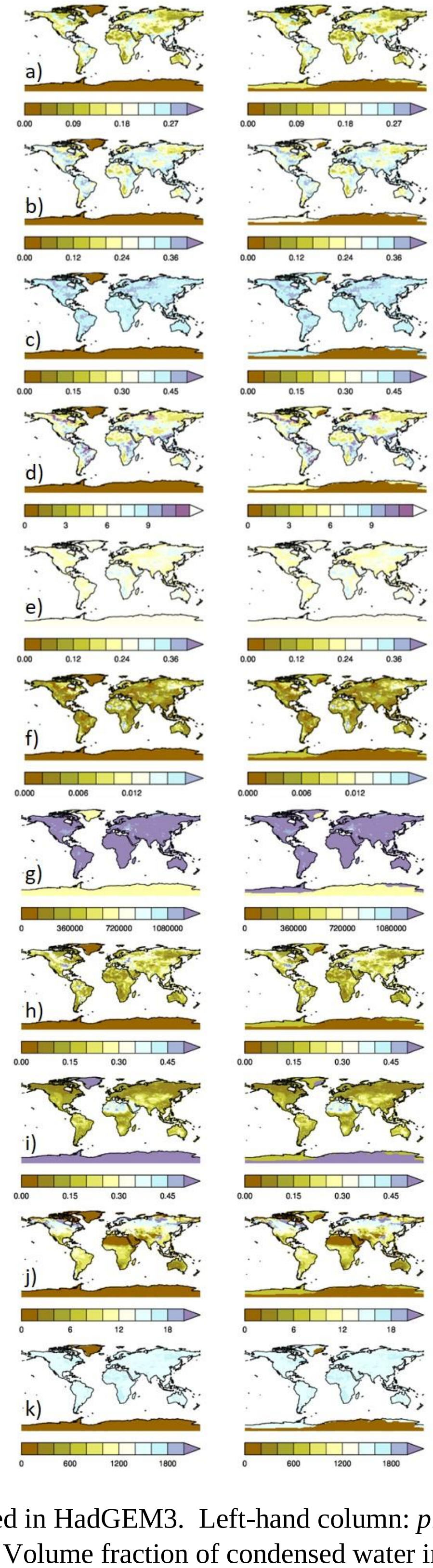

Figure S3 - Soil parameters used in HadGEM3. Left-hand column: *piControl* simulation, right-hand column: *mPWP* simulation. a) Volume fraction of condensed water in soil at wilting point, b) Volume fraction of condensed water in soil at critical point, c) Volume fraction of condensed water in soil at saturation point, d) Clapp-Hornberger "B" coefficient, e) Thermal conductivity, f) Hydraulic conductivity at saturation, g) Thermal capacity, h) Saturated soil water suction, i) Snow-free albedo of soil, j) Soil carbon content, k) Soil bulk density

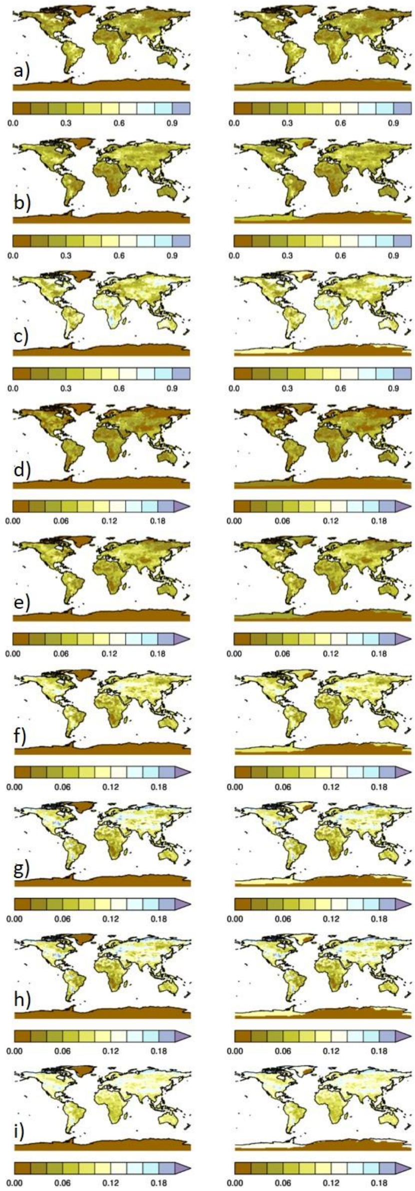

Figure S4 - Soil dust properties used in HadGEM3. Left-hand column: *piControl* simulation, right-hand column: *mPWP* simulation. a) Dust parent soil clay fraction, b) Dust parent silt clay fraction, c) Dust parent soil sand fraction, d) Dust soil mass fraction (Division 1), e) Dust soil mass fraction (Division 2), f) Dust soil mass fraction (Division 3), g) Dust soil mass fraction (Division 4), h) Dust soil mass fraction (Division 5), i) Dust soil mass fraction (Division 6)

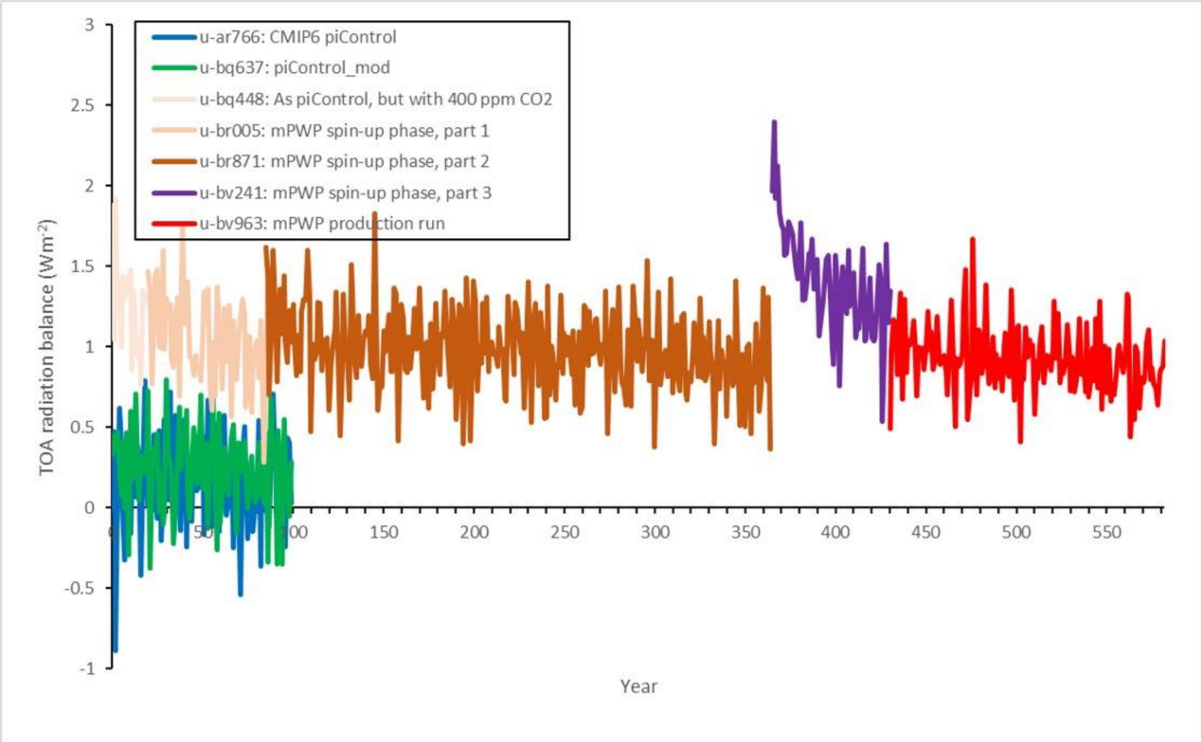

Figure S5 – Annual global mean net top of atmosphere (TOA) radiation from the HadGEM3 *mPWP* spin-up phase and production run, as well as the last 100 years from the CMIP6 *piControl* and the *piControl_mod*. See Williams *et al*. (2020) for the *piControl* spin-up phase that preceded this simulation

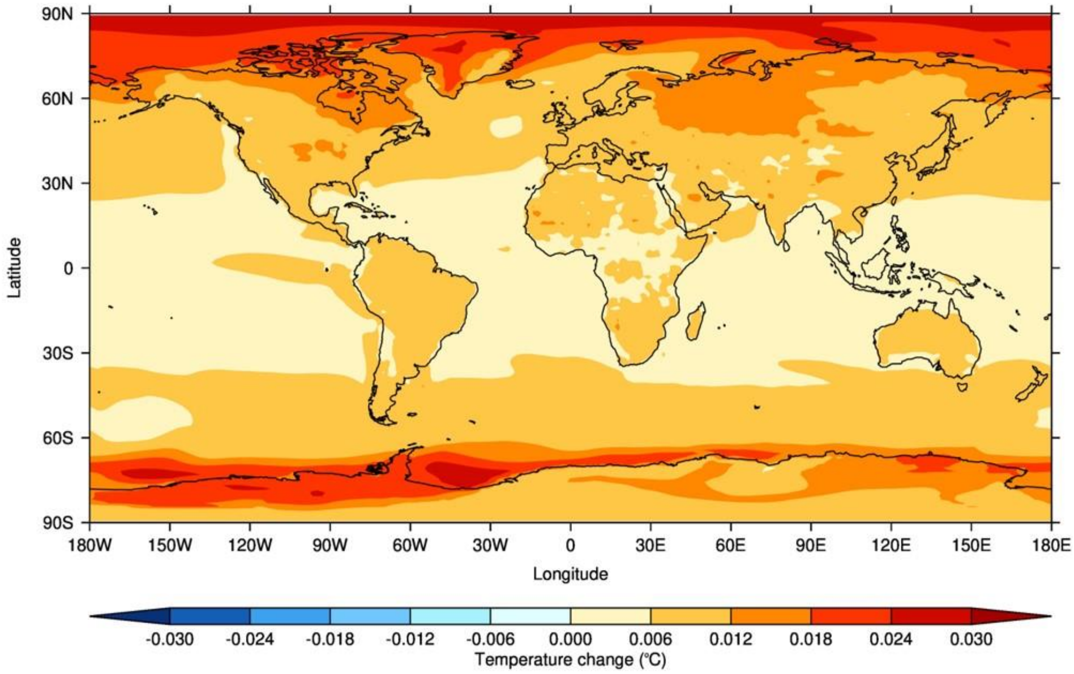

Figure S6 - Statistically significant (as calculated by a Mann-Kendall test, using the 99% level) centennial trends in 1.5m temperature from the HadGEM3 Pliocene *mPWP* simulation

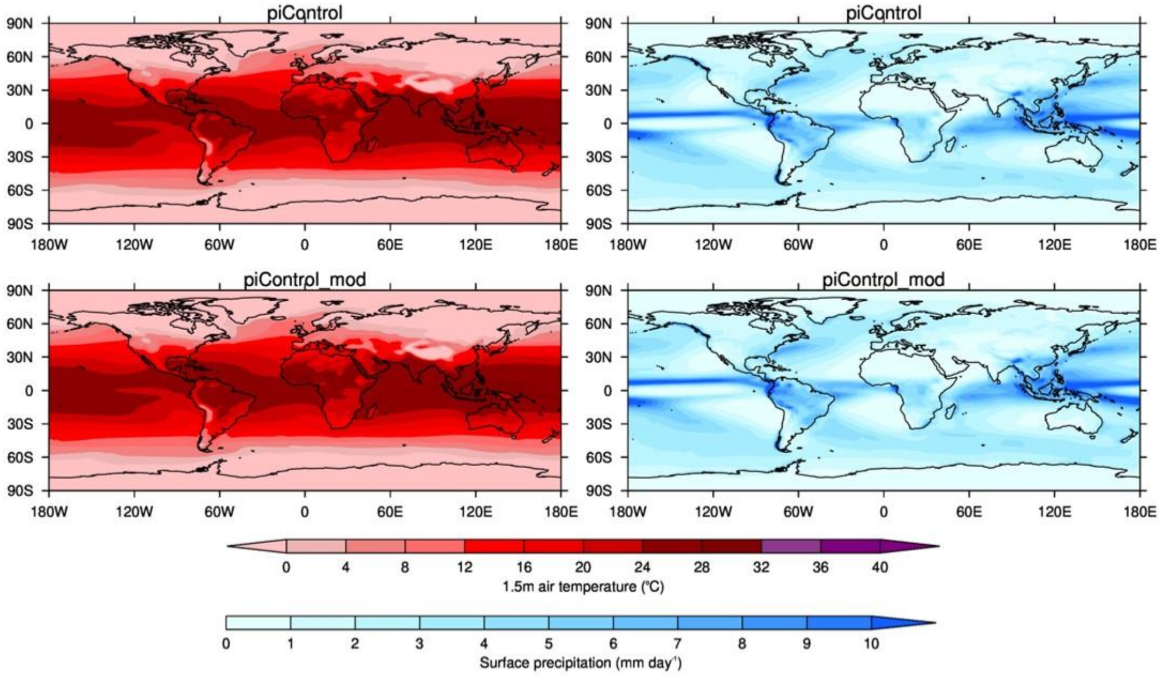

Figure S7 – PI climatologies from HadGEM3, calculated over the last 50 years of the simulations. Left-hand column: Annual mean 1.5 m air temperature, right-hand column: Annual mean surface precipitation

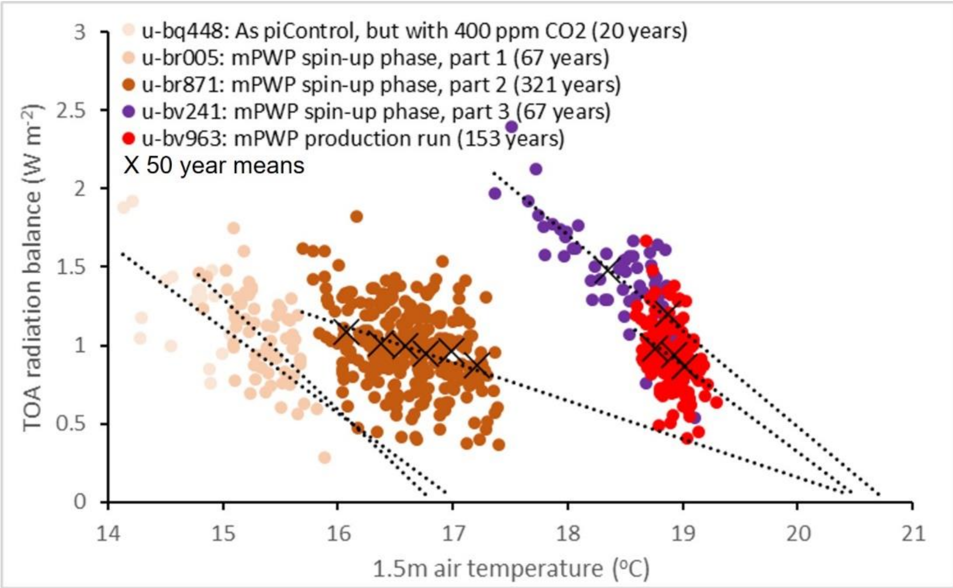

Figure S8 – Gregory plot of global mean net top of atmosphere (TOA) radiation versus 1.5 m air temperature from the HadGEM3 *mPWP* spin-up phase and production run. Coloured dots show annual means for each stage, crosses show 50 year means and dotted lines show 'line of best fit', projected forward until an equilibrium state (i.e. TOA radiation balance of 0 W m^{-2})

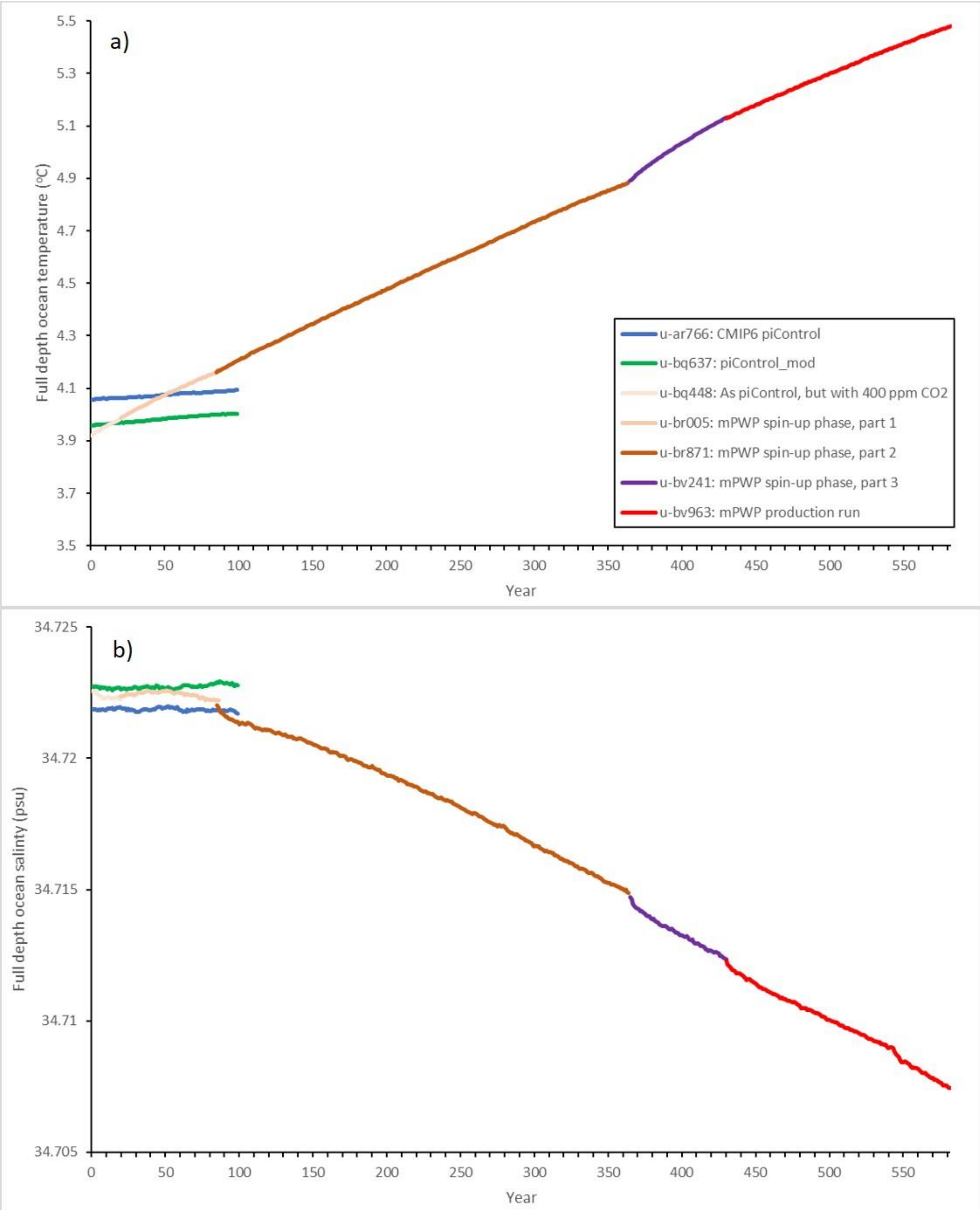

Figure 9 – Annual global mean measures of climate equilibrium from the HadGEM3 *mPWP* spin-up phase and production run, as well as the last 100 years from the CMIP6 *piControl* and the *piControl_mod*. See Williams *et al*. (2020) for the *piControl* spin-up phase that preceded this simulation: a) Full depth ocean temperature, b) Full depth ocean salinity

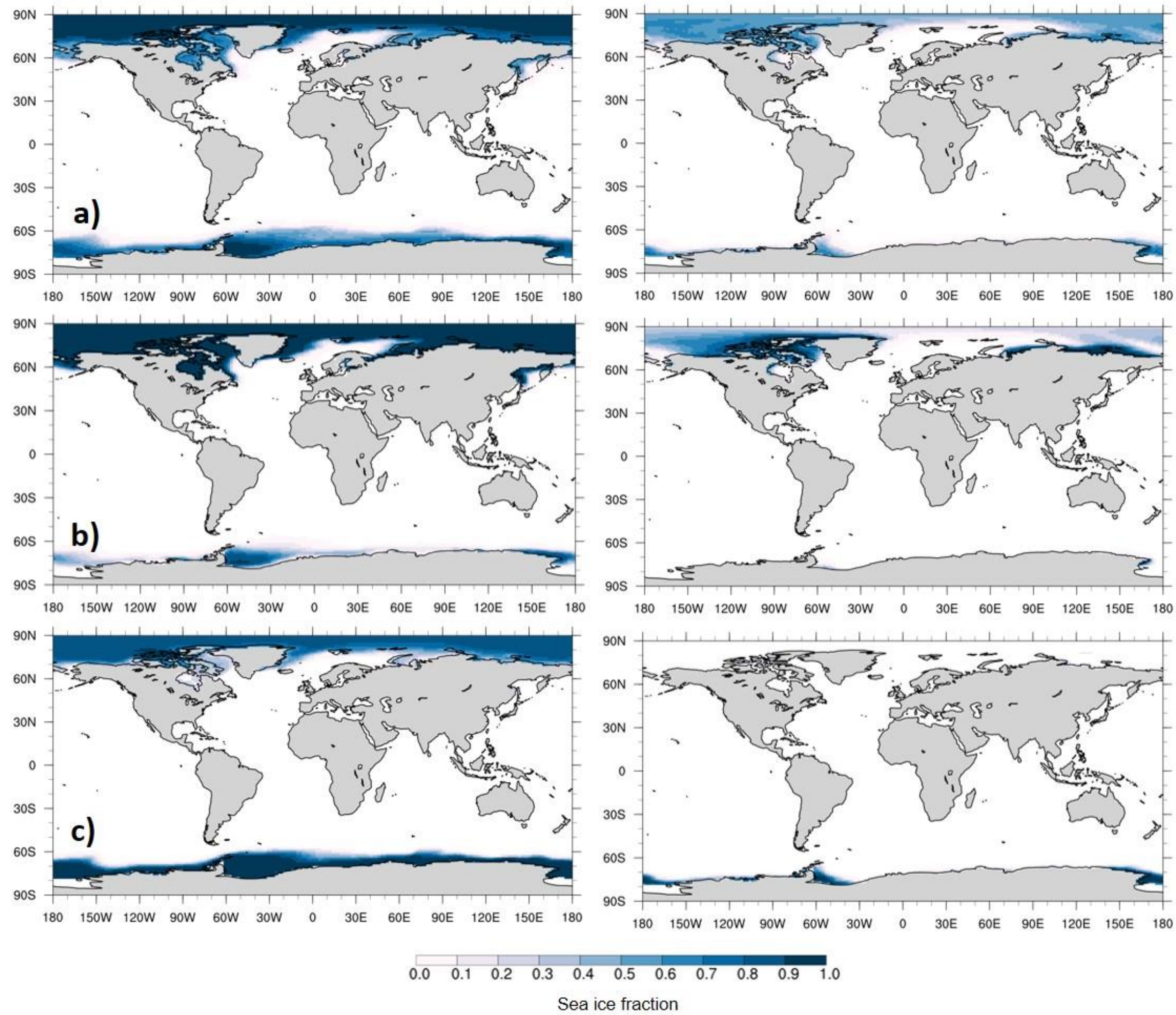

Figure S10 – Sea ice fraction climatology from HadGEM3. Left-hand column: *piControl_mod* simulation, right-hand column: *mPWP* simulation. a) Annual, b) DJF, c) JJA

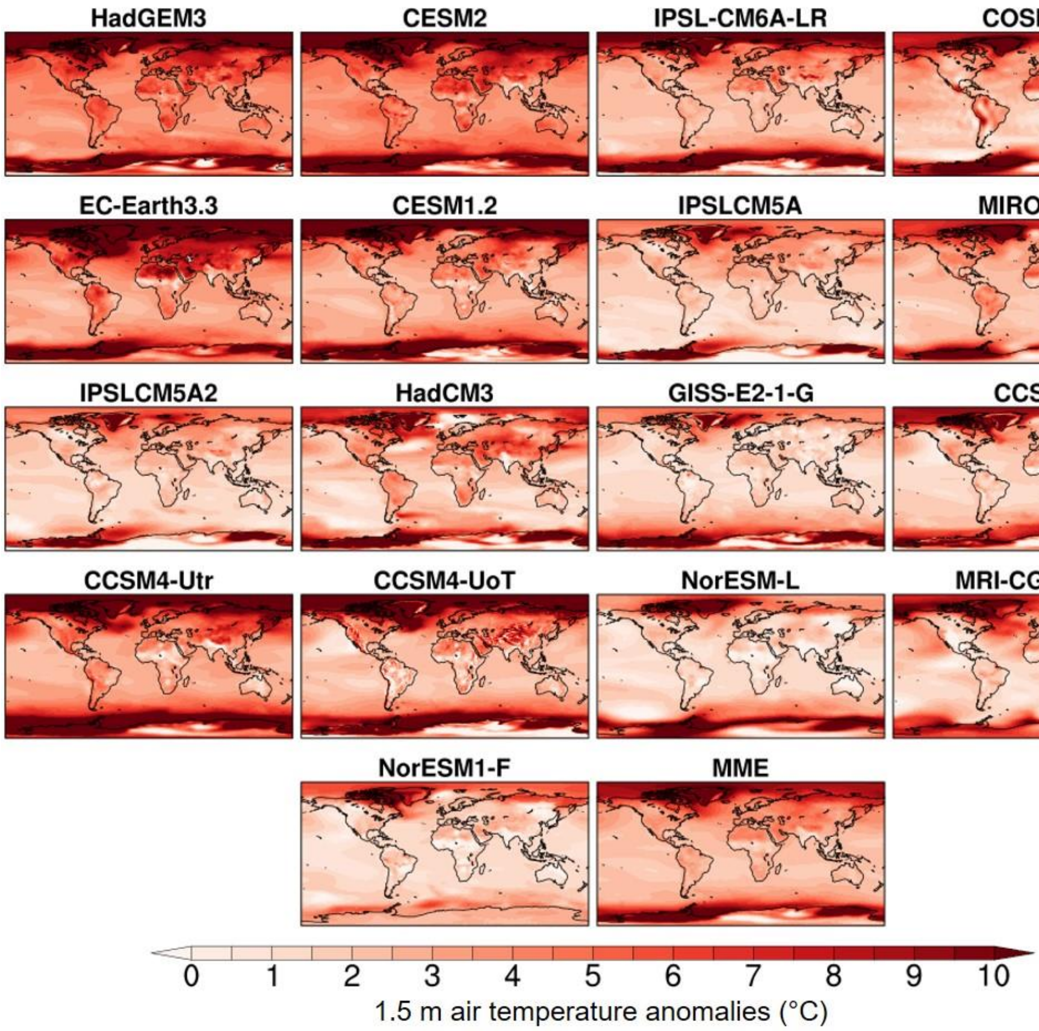

Figure S11 – 1.5 m air temperature climatology differences (Pliocene - PI) from HadGEM3 *mPWP* simulation and all other models in PlioMIP2, as well as multi-model ensemble mean (MME)