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Wednesday 10 June 2020

Dear Dr Loutre,

Re: Submission of manuscript "*CMIP6/PMIP4 simulations of the mid-Holocene and Last Interglacial using HadGEM3: comparison to the pre-industrial era, previous model versions, and proxy data*" by CJR Williams *et al*. to Climate of the Past (PMIP4 Special Edition).

Thank you very much for your most recent comments. I have now made all the corrections that you requested, so please see below for my responses:

1. Minor comment

I invite you to double check the writing of the supplementary material and make it 'easier' to read. In particular the first sentence (l21-22) looks very strange to me. I think it would be worth to remind the readers what are GA, GC, GO, GIS (only the 'full words' for the acronyms, such as 'Global Atmosphere', 'Global Ocean', … nothing more. And would it be possible to explain in a few words what you mean with 'bottom-up and top-down developments' (l24-35)?

This has now been corrected, with the first sentence being changed so that it makes more logical sense (and is more independent from the main manuscript), the acronyms being listed, and that last sentence being removed (as we considered it ambiguous)

2. Major comment

Your data availability section does not comply with the requirements from COPERNICUS. I asked the Climate-of-Past co-editors-in-chief and I copy here the answer…

As requested, I have now added in the website to the ESGF portal, and have made it clearer that although my simulations have not yet been uploaded to this, they are nevertheless publicly available, by contacting myself. As I say in my manuscript, we plan to upload our simulations to the ESGF portal, and will do so in the near future. However, CMIP6 protocol states that the data must all be in a correct and consistent format - a process called CMORising - and this is a lengthy and nontrivial process. It would seriously delay publication of this manuscript if the data have to be uploaded to the ESGF before publication. I hope the clarification that I have added will satisfy your regulations? If not, would an acceptable alternative be that I provide climatologies of the relevant fields (temperature, precipitation etc) from the model simulations as a supplementary netcdf file? Please let me know the best option.

Lastly, I have also corrected the reference list, as per your comment in the email dated 2 June 2020:

Please note that your reference list has not been compiled according to our standards. Please consider adjusting your reference list with the next revision of your manuscript. The manuscript preparation guidelines can be seen at: https://www.climate-of-the-past.net/for_authors/manuscript_preparation.html.

This has now been corrected.

I very much hope that my manuscript now meets your technical specifications, and is deemed acceptable and ready for publication.

Yours sincerely,

Dr Charles JR Williams, and co-authors

CMIP6/PMIP4 simulations of the mid-Holocene and Last Interglacial using HadGEM3: comparison to the pre-industrial era, previous model versions, and proxy data

~~The UK contribution to CMIP6/PMIP4: mid-Holocene and Last Interglacial experiments with HadGEM3, and comparison to the pre-industrial era and proxy data~~

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Short title: mid-Holocene and Last Interglacial experiments with HadGEM3
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ABSTRACT

Palaeoclimate model simulations are an important tool to improve our understanding of the mechanisms of climate change. These simulations also provide tests of the ability of models to simulate climates very different to today. Here we present the results from two brand-new simulations using the latest version of the UK's physical climate model, HadGEM3-GC3.1; the mid-Holocene (~6 ka) and Last Interglacial (~127 ka) simulations, both conducted under the auspices of CMIP6/PMIP4. This is the first time this version of the UK model has been used to conduct paleoclimate simulations. These periods are of particular interest to PMIP4 because they represent the two most recent warm periods in Earth history, where atmospheric concentration of greenhouse gases and continental configuration ~~is~~ are similar to the pre-industrial period, but where there were significant changes to the Earth's orbital configuration, resulting in a very different seasonal cycle of radiative forcing.

Results for these simulations are assessed firstly against the same model's preindustrial control simulation (a simulation comparison, to describe and understand the differences between the preindustrial and the two paleoclimate simulations), and secondly against previous versions of the same model relative to newly-available proxy data (a model-data comparison, to compare all available simulations from the same model with proxy data to assess any improvements due to model advances)~~, previous versions of the UK model, and models from the previous CMIP5 exercise~~. The introduction of this newly available proxy data adds further novelty to this study. Globally, for metrics such as 1.5m temperature and surface rainfall, whilst both the recent paleoclimate simulations are mostly capturing the expected sign and, in some places, magnitude of change relative to the preindustrial, this is geographically and seasonally dependent. Compared to newly-available proxy data (including SST and rainfall), and also incorporating data from previous versions of the model, shows that the relative accuracy of the simulations appears to vary according to metric, proxy reconstruction used for comparison and geographical location. In some instances, such as mean rainfall in the mid-Holocene, there is a clear and linear improvement, relative to proxy data, from the oldest to the newest generation of the model. When zooming into northern Africa, a region known to be problematic for models in terms of rainfall enhancement, the behaviour of the West African monsoon in both recent paleoclimate simulations is consistent with current understanding, suggesting a wetter monsoon during the mid-Holocene and (more so) the Last Interglacial, relative to the preindustrial era. However, regarding the well-documented 'Saharan greening' during the mid-Holocene, results here suggest that the most recent version of the UK's physical model is still unable to reproduce the increases suggested by proxy data, consistent with all other previous models to date. ~~When the current version is compared to the previous generation of the UK model, the most recent version suggests limited improvement. In common with these previous model versions, the simulations reproduce global land and ocean temperatures (both surface and at 1.5 m) and a West~~

African monsoon that is consistent with the latitudinal and seasonal distribution of insolation. The Last Interglacial simulation appears to accurately capture Northern Hemisphere temperature changes, but without the addition of Last Interglacial meltwater forcing cannot capture the magnitude of Southern Hemisphere changes. Model-data comparisons indicate that some geographical regions, and some seasons, produce better matches to the palaeodata (relative to pre-industrial) than others. Model-model comparisons, relative to previous generations same model and other models, indicate similarity between generations in terms of both the intensity and northward enhancement of the mid-Holocene West African monsoon, both of which are underestimated. On the 'Saharan greening' which occurred the mid-Holocene African Humid Period, simulation results are likewise consistent with other models. The most recent version of the UK model appears to still be unable to reproduce the amount of rainfall necessary to support grassland across the Sahara.

1. INTRODUCTION

Simulating past climates has been instrumental in improving our understanding of the mechanisms of climate change (e.g. Gates 1976, Haywood *et al*. 2016, Jungclaus *et al*. 2017, Kageyama *et al*. 2017, Kageyama *et al*. 2018, Kohfeld *et al*. 2013, Lunt *et al*. 2008, Otto-Bliesner *et al*. 2017, Ramstein *et al*. 1997), as well as in identifying and assessing discrepancies in palaeoclimate reconstructions (e.g. Rind & Peteet 1985). Palaeoclimate scenarios can also provide tests of the ability of models to simulate climates that are very different to today, often termed 'out-of-sample' tests. This notion underpins the idea that robust simulations of past climates improve our confidence in future climate change projections (Braconnot *et al*. 2011, Harrison *et al*. 2014, Taylor *et al*. 2011). Palaeoclimate scenarios have also been used to provide additional tuning targets for models (e.g. Gregoire *et al*. 2011), in combination with historical or pre-industrial conditions.

The international Climate Model Intercomparison Project (CMIP) and the Palaeoclimate Model Intercomparison Project (PMIP) have spearheaded the coordination of the international palaeoclimate modelling community to run key scenarios with multiple models, perform data syntheses, and undertake model-data comparisons since their initiation twenty-five years ago (Joussaume & Taylor 1995). Now in its fourth incarnation, PMIP4 (part of the sixth phase of CMIP, CMIP6), it includes a larger set of models than previously, and more palaeoclimate scenarios and experiments covering the Quaternary (documented in Jungclaus *et al*. 2017, Kageyama *et al*. 2017, Kageyama *et al*. 2018 and Otto-Bliesner *et al*. 2017) and Pliocene (documented in Haywood *et al*. 2016).

PMIP4 specifies experiment set-ups for two ~~warm~~ interglacial simulations: the mid-Holocene (MH) at ~6 ka and the Last Interglacial (LIG) at ~127 ka (although spanning ~~covering~~ ~129-116 ka in its entirety). These are the two most recent warm periods (particularly in the Northern Hemisphere) in Earth history, and are of particular interest to PMIP4; indeed, the MH experiment is one of the two entry cards into PMIP (Otto-Bliesner *et al*. 2017). This is because whilst the atmospheric concentration of greenhouse gases, the extent of land ice, and the continental configuration is similar in these PMIP4 set-ups compared to the pre-industrial (PI) period, significant changes to the seasonal cycle of radiative forcing, relative to today, do occur during these periods due to long-term variations in the Earth's orbital configuration. The MH and LIG both have higher boreal summer insolation and lower boreal winter insolation compared to the PI, as shown by Figure 1, leading to an enhanced seasonal cycle in insolation as well as a change in its latitudinal distribution. The change is more significant in the LIG than the MH, due to the larger eccentricity of the Earth's orbit at that time. Note that, in this figure and indeed all subsequent figures using monthly or seasonal data, the data have been calendar adjusted (Joussaume & Braconnot 1997) according to the method of Pollard & Reusch (2002) and Marzocchi *et al.* (2015); see the Supplementary Material (SM1) for the same figure but using the modern calendar.

Palaeodata syntheses indicate globally warmer surface conditions of potentially ~0.7°C than PI in the MH (Marcott *et al*. 2013) and up to ~1.3°C in the LIG (Fischer *et al*. 2018). During both warm periods there is abundant palaeodata evidence indicating enhancement of Northern Hemisphere summer monsoons (e.g. Wang *et al*. 2008) and in the case of the Sahara, replacement of desert by shrubs and steppe vegetation (e.g. Drake *et al*. 2011, Hoelzmann *et al*. 1998), grassland and xerophytic woodland/scrubland (e.g. Jolly *et al*. 1998a, Jolly *et al*. 1998b, Joussaume *et al*. 1999) and inland water bodies (e.g. Drake *et al*. 2011, Lezine *et al*. 2011). Recent palaeodata compilations involving either air temperatures or SST (Capron *et al*. 2014, Hoffman *et al*. 2017) reveal that the maximum temperatures were reached asynchronously in the LIG between the Northern and Southern Hemispheres. Concerning precipitation, historically this has been lacking relative to temperature or SST reconstructions. One often-cited study for the MH is that of Bartlein *et al*. (2011), comprising a combination of existing quantitative reconstructions based on pollen and plant macrofossils; this provides evidence of the interaction between orbital variations and greenhouse gas forcing, and the atmospheric circulation response. More recently, one newly-published dataset of LIG precipitation proxy data (which the current study benefits from as part of the model-data comparison, see below) is that of Scussolini *et al*. (2019). Here, a number of climate models are assessed against this brand-new dataset, finding an agreement with proxy data over Northern Hemisphere landmasses, but less so in the Southern Hemisphere (Scussolini *et al*. 2019).

Many modelling studies have been undertaken in an attempt to reproduce the changes suggested by proxy data throughout the Quaternary, and especially during the interglacial periods discussed here, and there is not scope in this current study to give a full review here. An overview of multi-model assessments during the LIG can be found in Lunt *et al*. (2013). However, one example is the aforementioned monsoon enhancement (and expansion/contraction) during the Quaternary, and previous studies have focused on various aspects of this, such as whether any expansion was hemispherically consistent or asynchronous between hemispheres (e.g. Kutzbach *et al*. 2008, McGee *et al*. 2014, Singarayer & Burrough 2015, Singarayer *et al*. 2017, Wang *et al*. 2006, Wang *et al*. 2014). During the LIG, the aforementioned asynchronous temperature distribution between the hemispheres ~~Furthermore,~~ has been investigated by a number of model simulations~~, suggest~~ suggesting that this may have been caused by meltwater induced shutdown of the Atlantic Meridional Overturning Circulation (AMOC) in the early part of the LIG, due to the melting of the Northern Hemisphere ice sheets during the preceding deglaciation (e.g. Carlson 2008, Smith & Gregory 2009, Stone *et al*. 2016). ~~During both warm periods there is abundant palaeodata evidence indicating enhancement of Northern Hemisphere summer monsoons (e.g. Wang *et al*. 2008) and in the case of~~

~~the Sahara, replacement of desert by shrubs and steppe vegetation (e.g. Drake *et al*. 2011, Hoelzmann *et al*. 1998) and inland water bodies (e.g. Drake *et al*. 2011, Lezine *et al*. 2011).~~

The driving mechanism producing the climate and environmental changes indicated by the palaeodata for the MH and LIG ~~and MH~~ is different to current and future anthropogenic warming, as the former results from orbital forcing changes whilst the latter results from increases in greenhouse gases. Moreover, the orbital forcing primarily acts on shortwave radiation whereas greenhouse gas changes primarily act upon the longwave radiation flux, and the orbital forcing can lead to uneven horizontal and seasonal changes whereas greenhouse gas forcing can cause more uniform anomalies (it should be noted that whilst a precise calculation of the radiative forcing due to changes in MH and LIG greenhouse gases is beyond the scope of this study, such a calculation could follow the methodology of Gunnar *et al*. [1998]). Nevertheless, despite these differences in driving mechanism, ~~However,~~ these past high latitude (and mainly Northern Hemisphere) warm intervals are a unique opportunity to understand the magnitudes of forcings and feedbacks in the climate system that produce warm interglacial conditions, which can help us understand and constrain future climate projections (e.g. Holloway *et al*. 2016, Rachmayani *et al*. 2017, Schmidt *et al*. 2014). Running the same model scenarios with ever newer models enables the testing of whether model developments are producing improvements in palaeo model-data comparisons, assuming appropriate boundary conditions are used. Previous iterations of PMIP, with older versions of the PMIP4 models, have uncovered persistent shortcomings (Harrison *et al*. 2015) that have not been eliminated despite developments in resolution, model physics, and addition of further Earth system components. One key example of this is the continued underestimation of the increase in rainfall over the Sahara in the MH PMIP simulations (e.g. Braconnot *et al*. 2012).

In this study we run and assess the latest version of the UK's physical climate model, HadGEM3-GC3.1.~~–~~ Whilst older versions of the UK model have been included in previous iterations of CMIP, and whilst present-day and future simulations from this model are included in CMIP6, the novelty of this study is that this is the first time this version has been used to conduct any paleoclimate simulations. In Global Coupled (GC) version 3 (and therefore in the following GC3.1), there have been many updates and improvements, relative to its predecessors, which are discussed extensively in Williams *et al*. (2017) and a number of companion scientific model development papers (see Section 2.1). As a brief introduction, however, GC3 includes a new aerosol scheme, multilayer snow scheme, multilayer sea ice and several other parametrization changes, including a set relating to cloud and radiation, as well as a revision to the numerics of atmospheric convection (Williams *et al*. 2017). In addition, the ocean component of GC3 has other changes including ~~a new~~ an updated ocean and sea ice model, a new cloud scheme, and further revisions to all parametrization schemes (Williams *et al*. 2017). See Section 2.1 for further details.

Following the CMIP6/PMIP4 protocol, here the PMIP4 MH and LIG simulations have been conducted and assessed, with the assessment adopting a two-pronged approach. -Firstly a simulation comparison is made between these simulations and the same model's PI simulation (to describe and understand the differences between them). Secondly a model-data comparison is made between the current and previous versions of the same model relative to newly-available proxy data, thereby assessing any improvements due to model advances~~comparing the results with available proxy data, previous versions of the UK's same physical climate model, and other models from CMIP5~~. In addition to a global assessment, a secondary ~~The~~ focus of this paper is on the fidelity of the temperature anomalies ~~globally~~ and the degree of precipitation enhancement in the Sahara, the latter of which has proved problematic for several generations of models. ~~The results discussed here are split into two sections: after an assessment of the level of equilibrium gained during the spin-up phase, the main focus is on the model-data and model-model comparisons using the production runs.~~ Following this introduction, Section 2 describes the model, the experimental design, ~~and~~ the proxy data used for the model-data comparisons, and a brief discussion of the simulation spin-up phases. Section 3 then presents the results, beginning with the model-model comparison and following with the model-data comparison, and -f~~divided into two subsections: i) equilibrium during the spin-up phase; and ii) model-data and model-model comparisons from the production runs. Finally~~finally~~,~~ section 4 summarises and concludes.

2. MODEL, EXPERIMENT DESIGN, ~~AND~~ DATA AND SPIN-UP SIMULATIONS

2.1. Model

2.1.1. Model terminology

In this paper, and consistent with CMIP nomenclature, the 'spin-up phase' of the simulations refers to when they are spinning up to atmospheric and oceanic equilibrium, whereas the 'production run' refers to the end parts (usually the last 50 or 100 years) of the simulation used to calculate the climatologies, presented as the results. When discussed as geological intervals, the preindustrial, mid-Holocene and Last Interglacial are referred to as the PI, MH and LIG respectively. In contrast, when discussed as the three most recent simulations using HadGEM3 (see below), consistent with CMIP they are referred to as the *piControl*, *midHolocene* and *lig127k* simulations, respectively. When the *midHolocene* and *lig127k* are discussed collectively, they are referred to as the 'warm climate simulations'; whilst it is acknowledged that other factors differentiate these simulations such as orbital configuration or CO_2, 'warm climate simulations' was deemed an appropriate collective noun.

2.1.2. Model details

The ~~MH and LIG simulations conducted here (referred to as *midHolocene* and *lig127k*, respectively, and collectively as the~~ warm climate simulations conducted here~~)~~, and ~~indeed~~ the *piControl* ~~PI~~

simulation (~~*piControl*,~~ conducted elsewhere as part of the UK's CMIP6 runs and used here for comparative purposes) were all run using the same fully-coupled GCM: the Global Coupled 3 configuration of the UK's physical climate model, HadGEM3-GC3.1. ~~-~~Full details on HadGEM3-GC3.1, and a comparison to previous configurations, are given in Williams *et al*. (2017) and Kuhlbrodt *et al*. (2018). Here, the model was run using the Unified Model (UM), version 10.7, and including the following components: i) Global Atmosphere (GA) version 7.1, with an N96 atmospheric spatial resolution (approximately 1.875° longitude by 1.25° latitude) and 85 vertical levels; ii) the NEMO ocean component, version 3.6, including Global Ocean (GO) version 6.0 (ORCA1), with an isotropic Mercator grid which, despite varying in both meridional and zonal directions, has an approximate spatial resolution of 1° by 1° and 75 vertical levels; iii) the Global Sea Ice (GIS) component, version 8.0 (GSI8.0); iv) the Global Land (GL) configuration, version 7.0, of the Joint UK Land Environment Simulator (JULES); and v) the OASIS3 MCT coupler. The official title for this configuration of HadGEM3-GC3.1 is HadGEM3-GC31-LL N96ORCA1 UM10.7 NEMO3.6 (for brevity, hereafter HadGEM3).

All of the above individual components are summarised by Williams *et al*. (2017) and detailed individually by a suite of companion papers (see Walters *et al*. 2017 for GA7 and GL7, Storkey *et al*. 2017 for GO6 and Ridley *et al*. 2017 for GIS8). However, a brief description of the major changes relative to its predecessor are given in the Supplementary Material ~~here~~. ~~Beginning with GA7 and GL7, a once-in-a-decade replacement of the model's dynamical core, implementing ENDGame, was undertaken for the previous version (GA6) and therefore remains the same in GA7 (Walters *et al.* 2017). In addition, a number of bottom-up and top-down developments were included in GA7. For the former, these include improvements to the radiation scheme to allow better treatment of gases absorption, improvements to how warm rain and ice clouds are treated, and an improvement to the numerics of the convection scheme (Walters *et al*. 2017). For the latter, these include further improvements to the microphysics as well as an incremental development of ENDGame (Walters *et al*. 2017). Together these led to reductions in four model errors that were deemed critical in the previous configuration: i) South Asian monsoon rainfall biases over India; ii) biases in both temperature and humidity in the tropical tropopause; iii) shortcomings in the numerical conservation; and iv) biases in surface radiation fluxes over the Southern Ocean (Walters *et al*. 2017). In addition to these developments, two new parameterisation schemes were introduced in GA7: firstly the UK Chemistry and Aerosol (UKCA) GLOMAP-mode aerosol scheme, to improve the representation of tropospheric aerosols, and secondly a multi-layer snow scheme in JULES, to allow the first time inclusion of stochastic physics in UM climate simulations (Walters *et al*. 2017).~~

~~For the GO and GIS components, a number of improvements to GO6 have been made since the previous version, the first of which was an upgrade of the NEMO base code (to version 3.6) which~~

~~allowed a formulation for momentum advection (from Hollingsworth *et al*. 1983), a Lagrangian icebergs scheme, and a simulation of circulation below ice shelves (Storkey *et al*. 2018). Other developments included an improvement to the warm SST bias in the Southern Ocean (as detailed by Williams *et al*. 2017), as well as tuning to various parameters e.g. the isopycnal diffusion (Storkey *et al*. 2018). For GIS8, along with improvements to the albedo scheme and more realistic semi-implicit coupling, the biggest development since its predecessor is the inclusion of multilayer thermodynamics, giving a heat capacity to the sea ice and allowing vertical variation of conduction (Ridley *et al*. 2018). Testing of these two components produced a better simulation compared to its predecessor, with more realistic mixed layer depths in the Southern Ocean and the aforementioned reduced warm bias, the latter of which was deemed primarily due to the tuning of the different mixing (e.g. vertical and isopycnal) parameters (Storkey *et al*. 2018).~~

When all of these components are coupled together to give GC3, there have been several improvements relative to its predecessor (GC2), most noticeably to the large warm bias in the Southern Ocean (which was reduced by 75%), as well as an improved simulation of clouds, sea ice, the frequency of tropical cyclones in the Northern Hemisphere as well as the AMOC, and the Madden Julian Oscillation (MJO) (Williams *et al*. 2017). Relative to the previous fully-coupled version of the model (HadGEM2), which was submitted to the last CMIP5/PMIP3 exercise, many systematic errors have been improved including a reduction of the temperature bias in many regions~~including a reduction in many regions to the temperature bias~~, a better simulation of mid-latitude synoptic variability, and an improved simulation of tropical cyclones and the El Niño Southern Oscillation (ENSO) (Williams *et al*. 2017).

Here, the *midHolocene* and *lig127k* simulations were both run on the UK National Supercomputing Service, ARCHER, whereas the *piControl* was run on a different platform based within the UK Met Office's Hadley Centre. While this may mean that anomalies computed against the *piControl* are potentially influenced by different computing environments, and not purely the result of different climate forcings, the reproducibility of GC3.1 simulations across different platforms has been tested (Guarino *et al*. 2020). It was found that, although a simulation length of 200 years is recommended whenever possible to adequately capture climate variability across different platforms, the main climate variables considered here (e.g. surface temperature) are not expected to be significantly different on a 100- or 50-year timescale (see, for example, Fig. 6 in Guarino *et al*. [2020~~19~~]) as they are not directly affected by medium-frequency climate processes~~ such as ENSO~~.

~~Not including queueing time, both simulations were achieving 3-4 model years per day during the spin-up phase, and 1-2 model years per day during the production run; see below for the differences in output, and therefore speed, between the two phases.~~

2.2. Experiment design

Full details of the experimental design~~,~~ and results from the CMIP6 *piControl* simulation~~,~~ are documented in Menary *et al*. (2018). Both the warm climate simulations followed the experimental design given by Otto-Bliesner *et al*. (2017), and specified at https://pmip4.lsce.ipsl.fr/doku.php/exp_design:index. The primary differences from the *piControl* were to the astronomical parameters and the atmospheric trace greenhouse gas concentrations, summarised in Table 1. For the astronomical parameters, these were prescribed in Otto-Bliesner *et al*. (2017) according to orbital constants from Berger & Loutre (1991). However, in HadGEM3, the individual parameters (e.g. eccentricity, obliquity, etc) use orbital constants based on Berger (1978), according to the specified start date of the simulation. For the atmospheric trace greenhouse gas concentrations, these were based on recent reconstructions from a number of sources (see Table 1 for values, and section 2.2 in Otto-Bliesner *et al*. [2017] for a full list of references/sources).

All other boundary conditions, including solar activity, ice sheets, topography and coastlines, volcanic activity and aerosol emissions, are identical to the CMIP6 *piControl* simulation. Likewise, vegetation was prescribed to present-day values, to again match the CMIP6 *piControl* simulation. As such, the *piControl* and both the warm climate simulations actually include a prescribed fraction of urban land surface. As a result of this, our orbitally- and greenhouse gas-forced simulations should be considered as anomalies to the *piControl*, rather than absolute representations of the MH or LIG climate.

Both the warm climate simulations were started from the end of the *piControl* spin-up phase (which ran for approximately 600 years), after which time the *piControl* was considered to be in atmospheric and oceanic equilibrium (Menary *et al*. 2018). To assess this, four metrics were used, namely net radiative balance at the top of the atmosphere (TOA), surface air temperature (SAT), ~~and~~ full-depth ocean temperature (OceTemp) and full-depth ocean salinity (OceSal) (Menary *et al*. ~~(~~2018). See Section ~~3.1~~ 2.4 (and in particular Table 2) for an analysis of the equilibrium state of both the *piControl* and the warm climate simulations. Starting at the end of the *piControl*, these were then run for their own spin-up phases, 400 and 350 years for the *midHolocene* and *lig127k* respectively. ~~During this phase, ~700 diagnostics were output, containing mostly low temporal frequency (e.g. monthly, seasonal and annual) fields.~~ Once the simulations were considered in an acceptable level of equilibrium (see Section ~~3.1~~ 2.4), a production phase was run for 100 and 200 years for the *midHolocene* and *lig127k* respectively, during which the full CMIP6/PMIP4 diagnostic profile ~~(totalling ~1700 fields)~~ was implemented to output both high and low temporal frequency variables.

2.3. Data

Recent data syntheses compiling quantitative surface temperature and rainfall reconstructions were used in order to evaluate the warm climate simulations.

For the MH, the global-scale continental surface mean annual temperature (MAT) and rainfall (or mean annual precipitation, MAP) reconstructions from Bartlein *et al*. (2011), with quantitative uncertainties accounting for climate parameter reconstruction methods, were used (see Data Availability for access details). They rely on a combination of existing quantitative reconstructions based on pollen and plant macrofossils and are inferred using a variety of methods (see Bartlein *et al*. 2011 for further details). At each site, the 6 ka anomaly (corresponding to the 5.5-6.5 ka average value), is given relative to the present day, and in the case where modern values could not be directly inferred from the record, modern climatology values (1961-1990) were extracted from the Climate Research Unit historical climatology data set (New *et al*. 2002). Further proxy data for the MH, such as SST reconstructions, are not included here, as an extensive model-data comparison is presented in a companion paper (Brierley *et al*. 2020).

For the LIG, two recent different sets of surface temperature data are available. Firstly, the Capron *et al*. (2017) 127 ka timeslice of SAT and sea surface temperature (SST) anomalies (relative to pre-industrial, 1870-1899), is based on polar ice cores and marine sediment data that are (i) located poleward of 40° latitude and (ii) have been placed on a common temporal framework (see Data Availability for access details). Polar ice core water isotope data are interpreted as annual mean surface air temperatures, while most marine sediment-based reconstructions are interpreted as summer (defined here as July-September, JAS) SST signals. For each site, the 127 ka value was calculated as the average value between 126 and 128 ka using the surface temperature curve resampled every 0.1 ka. Here, we use the SST anomalies only. Secondly, a global-scale time slice of SST anomalies, relative to pre-industrial (1870-1889), at 127 ka was built, based on the recent compilation from Hoffman *et al*. (2017), which includes both annual and summer SST reconstructions (see Data Availability for access details). This adds further novelty to this study, by using a new combined dataset based on this existing data. The 127 ka values at each site were extracted, following the methodology they proposed for inferring their 129, 125 and 120 ka time slices i.e. the SST value at 127 ka was taken on the provided mean 0.1 ka interpolated SST curve for each core location. Data syntheses from both Capron *et al*. (2014, 2017) and Hoffman *et al*. (2017) are associated with quantitative uncertainties accounting for relative dating and surface temperature reconstruction methods. Here, the two datasets are treated as independent data benchmarks, as they use different reference chronologies and methodologies to infer temporal surface temperature changes, and therefore they should not be combined. See Capron *et al*. (2017) for a detailed comparison of the two syntheses. A model-data comparison exercise using existing LIG data compilations focusing on continental surface temperature (e.g. Turney and Jones 2010) was not attempted, as they do no benefit yet from a coherent chronological framework, preventing the definition of a robust time slice representing the 127 ka terrestrial climate conditions (Capron *et al*. 2017).

A brand-new, recently-published dataset of proxy precipitation anomalies (again, relative to the preindustrial) is also used for model-data comparison purposes here, adding further novelty to this study. The proxy data are compiled from existing literature by Scusscolini *et al*. (2019), and the dataset includes 138 proxy locations from a number of paleoclimatic archives including pollen, fossils other than pollen, lacustrine or marine sediment composition, loess deposits, and other multi-proxy sources. Note that, as Scusscolini *et al*. (2019) observe, unlike temperature anomalies the majority of precipitation anomalies in the existing literature are not quantitative. To allow a quantitative comparison, Scusscolini *et al*. (2019) use a semi-quantitative scale, based on their expert judgement, to show a LIG that is 'much wetter', 'wetter', 'no discernible change', 'drier' and 'much drier', relative to the PI. The same scale is therefore used here. See Scusscolini *et al*. (2019) for further information, and see Data Availability for access details).

2.4. Spin-up simulations

As briefly mentioned above, both the warm climate simulations had a spin-up phase before the main production run was started.–, briefly discussed here. As an example of atmospheric equilibrium, Aannual global mean 1.5 m air temperature and TOA radiation from both warm climate simulations, compared to the *piControl*, are shown in Fig_atmos_equilib and summarised in Table 2; see Supplementary Material (SM2) for the timeseries of these fields. There is a clear increase in temperature during the beginning of this period, as the *piControl* slowly spins up from its original starting point; this levels off towards the end of the period, however, with a final temperature trend of 0.03°C century^{-1} (Table 2 and Fig_atmos_equilib a). For the warm climate simulations, despite considerable interannual variability and arguably more so than in the *piControl* (particularly halfway through the *lig127k* simulationsee SM2), both are showing small long-term trends of -0.06°C century^{-1} and -0.16°C century^{-1} for the last 100 years of the *midHolocene* and *lig127k*, respectively (Table 2 and Fig_atmos_equilib a).– The spatial patterns of these trends, also shown in the Supplementary Material (SM3), are similar in both warm climate simulations, with much of the statistically significant cooling occurring over high latitude regions in both Hemispheres, and particularly so over Antarctica in the *lig127k* simulation (SM3). The same is true for The TOA radiation balance is also showing long-term (and again slightly negative) trends by the end of the simulations, with -0.05 W m^{2} and -0.06 W m^{2} for the the *midHolocene* and *lig127k*, respectively, where the *piControl* has a slow downward trend towards zero until equilibrium was reached, whereas the *midHolocene* and *lig127k* are relatively stable (Fig_atmos_equilib b).

For the oceanAs an example of oceanic equilibrium, annual global mean full-depth OceTemp and OceSal are shown in Table 2 (and again visualised in the Supplementary Material, SM4)and Fig_ocean_equilib. There is again a clear increase in OceTemp during the *piControl* spin-up phase, which again stabilises at 0.035°C century^{-1} by the end of the period (Table 2). OceTemp is steadily increasing throughout the *piControl* , and this continues to increase in the *li g127k* until it stabilises within the last ~50 years in both warm climate simulations(Fig_ocean_equilib a), whereas there is a dramatic fall in ocean salinity in these simulations (SM4). A similar pattern is shown in OceSal, with a steady decrease in the *piControl* spin-up phase which continues during the *midHolocene* and, conversely, starts to increase before stabilising during the *lig127k* (Fig_ocean_equilib b). Concerning the long-term trends, Menary *et al*. (2018) considered values acceptable for equilibrium to be < +/-0.035°C century^{-1} and < +/-0.0001 psu century^{-1} (for OceTemp and OceSal, respectively); as shown in Table 2, although both warm climate simulations meet the temperature criterion, the *midHolocene* neither meet the it is not meeting the salinity criterion (-0.00047 psu and 0.006 psu for the *midHolocene* and *lig127k*, respectively, compared to a criterion of 0.0001 psu). However, running for several thousands of years (and > 5 years of computer time), which would be needed to reach true oceanic equilibrium, was simply unfeasible here given time and resource constraints.

3. RESULTS

As briefly mentioned above, both the warm climate simulations had a spin-up phase before the main production run was started. The results discussed here are therefore split into two sections: firstly, assessing the level of atmospheric and oceanic equilibrium during (and, in particular, at the end of) the spin-up phase, and secondly assessing the 100-year climatology from the production run.

3.1. Spin-up

Annual global mean 1.5 m air temperature and TOA radiation from both warm climate simulations, compared to the *piControl*, are shown in Fig_atmos_equilib and summarised in Table 2. Note that the *piControl* spin-up phase was run in three separate parts, to accommodate for minor changes/updates in the model as the simulation progressed. There is a clear increase in temperature during the beginning of this period, as the *piControl* slowly spins up from its original starting point; this levels off towards the end of the period, however, with a final temperature trend of 0.03°C century^{-1} (Table 2 and Fig_atmos_equilib a). For the warm climate simulations, despite considerable interannual variability (particularly halfway through the *lig127k* simulation) both are showing small long-term trends of -0.06°C century^{-1} and -0.16°C century^{-1} for the last 100 years of the *midHolocene* and *lig127k*, respectively (Table 2 and Fig_atmos_equilib a). The same is true for TOA, where the *piControl* has a slow downward trend towards zero until equilibrium was reached, whereas the *midHolocene* and *lig127k* are relatively stable (Fig_atmos_equilib b).

~~For the ocean, annual global mean OceTemp and OceSal are shown in Table 2 and Fig_ocean_equilib. There is again a clear increase in OceTemp during the *piControl* spin-up phase, which again stabilises at 0.035°C century^{-1} by the end of the period (Table 2). Whilst OceTemp stabilises in the *midHolocene* and indeed has a smaller trend than the *piControl* (Table 2), it continues to increase in the *lig127k* until it stabilises within the last ~50 years (Fig_ocean_equilib a). A similar pattern is shown in OceSal, with a steady decrease in the *piControl* spin-up phase which continues during the *midHolocene* and, conversely, starts to increase before stabilising during the *lig127k* (Fig_ocean_equilib b). Concerning the long-term trends, Menary *et al*. (2018) considered values acceptable for equilibrium to be < +/-0.035°C century^{-1} and < +/-0.0001 psu century^{-1} (for OceTemp and OceSal, respectively); as shown in Table 2, although both warm climate simulations meet the temperature criterion, neither meet the salinity criterion (-0.007 psu and 0.006 psu for the *midHolocene* and *lig127k*, respectively, compared to a criterion of 0.0001 psu). However, running for several thousands of years (and > 5 years of computer time), which would be needed to reach true oceanic equilibrium, was simply unfeasible here given time and resource constraints.~~

3.~~2~~1. Production runs results

The warm climate production runs were undertaken following the spin-up phase, with ~~a 100-year~~ the climatology of each simulation being compared to that from the *piControl*, as well as available proxy data, using either annual means or summer/winter seasonal means. For the latter, depending on the availability of the proxy data, Northern Hemisphere summer is defined as either June-August (JJA) or ~~July-September (~~JAS~~)~~, and Northern Hemisphere winter is defined as either December-February (DJF) or January-March (JFM); and vice versa for Southern Hemisphere summer/winter. ~~–~~ As briefly introduced in Section 1, ~~Using atmospheric diagnostics, the~~ the focus is on ~~three~~ two separate measures: i) to describe and understand the differences between the ~~current~~ two most recent ~~two~~ warm climate simulations and the *piControl* in terms of temperature, rainfall and atmospheric/oceanic circulation changes; and ii) to compare both current simulations, as well as simulations from previous versions of the UK model (where available), with ~~existing and~~ the aforementioned newly-available proxy data, to assess any improvements due to model advances. A final aim, discussed only briefly here but shown in the Supplementary Material, is to include previous CMIP5 models to address the question of whether any of the simulations produce enough rainfall to allow vegetation growth across the Sahara: the mid-Holocene 'Saharan greening' ~~and iii) to compare both current simulations with those from previous versions of the UK model (where available), such as HadGEM2-ES or HadCM3, in order to assess any improvements due to model advances. In this aim, previous CMIP3 and 5 versions of the UK model, alongside other CMIP5 models, will be assessed to address the question of whether simulations produce enough rainfall to allow vegetation growth across the Sahara: the mid-Holocene 'Saharan greening' problem~~.

3.~~2~~1.1. Do the CMIP6 HadGEM3 warm climate simulations show temperature, rainfall and atmospheric/oceanic circulation differences when compared to the pre-industrial era?

Here we focus on mean differences between the HadGEM3 warm climate simulations and the corresponding *piControl*. Calendar adjusted ~~Seasonal~~ annual and seasonal mean summer~~ and ~~/winter 1.5 m air temperature anomalies (relative to the *piControl*) from both warm climate simulations are shown in Figure 2.~~–~~ As an example and for comparative purposes, the same figure but where the data are based on the modern calendar is shown in the Supplementary Material (SM5); this suggests that the impact of the calendar adjustments on this field, and at this spatial and temporal scale, is negligible, with the only obvious impact occurring over the Northern Hemisphere polar regions during JJA in both simulations, but more so in the *lig127k* simulation (due to the larger changes in insolation resulting in a larger change to the calendar, relative to the MH). Consistent with the seasonality of the changes, the differences between either simulations are less at the annual timescale (Figure 2a and d) than during individual seasons, but are still nevertheless to statistically significant at the 99% level. During JJA, the *midHolocene* is showing a widespread statistically significant increase in temperatures of up to 2°C across the entire Northern Hemisphere north of 30°N, more in some places e.g. Greenland (Figure 2b), consistent with the increased latitudinal and seasonal distribution of insolation caused by known differences in the Earth's axial tilt (Berger & Loutre 1991, Otto-Bliesner *et al*. 2017). The only places showing a reduction in temperature are West and ~~central~~ Central Africa (around 10°N) and northern India; this, as discussed below, is likely related to increased rainfall in response to a stronger summer monsoon, but could also be due to the resulting increase in cloud cover (reflecting more insolation) or a combination of the two. During DJF, only the Northern Hemisphere high latitudes (north of 60°N) continue this warming trend, with the rest of continental Africa and Asia showing a reduction in temperature (Figure 2c). These patterns are virtually the same~~ during~~ in the *lig127k* simulation (Figure 2e and f), just much more pronounced (with statistically significant temperature increases during JJA of 5°C or more); again, this is consistent with the differences in the Earth's axial tilt, which were more extreme (and therefore Northern Hemisphere summer experienced larger insolation changes) in the LIG relative to the MH (Berger & Loutre 1991, Otto-Bliesner *et al*. 2017). Another clear feature of these figures, at either annual or seasonal timescales, is polar amplification, which is likely associated with changes in sea-ice; as shown in the Supplementary Material (SM6), statistically significant decreases in sea-ice are shown throughout the polar regions of both hemispheres in the *midHolocene*, relative to the *piControl*. The same is true for the *lig127k* simulation, just more pronounced (not shown).

Calendar adjusted seasonal mean summer and winter surface daily rainfall anomalies (again relative to the *piControl*) from both warm climate simulations are shown in Figure 3. In line with the aforementioned increased latitudinal and seasonal distribution of insolation, the largest differences in either simulation occur during Northern Hemisphere summer (Figure 3b and e). Both warm climate simulations are showing statistically against increases in rainfall around the monsoon regions, especially over northern India and equatorial Africa, more so in the *lig127k* (Figure 3e). Both simulations are also showing oceanic drying relative to the *piControl*, especially in the equatorial Atlantic and Pacific, again more pronounced in the *lig127k* (Figure 3e). In contrast, during DJF, less of an impact is seen in either simulation relative to the *piControl*, with a small but statistically significant increase in rainfall in oceanic equatorial regions but drying over tropical land regions e.g. southern Africa, central Brazil and northern Australia (Figure 3c and f). Again, consistent with the increased insulation changes during the LIG compared to the MH, these differences are stronger in the *lig127k* simulation (Figure 3f). Consistent with the temperature differences, these signals are again weaker at the annual timescale but are nevertheless statistically significant (Figure 3a and b).

A measure of oceanic circulation is also considered here, shown by the three HadGEM3 simulations of meridional overturning circulation (MOC) in the Atlantic basin and globally (Figure 4a-c and d-f, respectively). Although not identical, the differences are nevertheless negligible, with both warm climate simulations almost exactly reproducing the structures of weakly and strongly overturning MOC seen in the *piControl*; for example, the strongly overturning MOC in the upper levels of the Atlantic is marginally stronger in the *midHolocene* at ~30-40°N relative to the other two simulations, but the structures are very similar. This suggests that the changes to atmospheric fields such as P-E, energy fluxes and wind stress (in response to the insolation changes) are having a minimal impact on the overturning circulation, and this is consistent with other work (e.g. Guarino *et al*. [2020])

A key region of interest, concerning mean precipitation changes and changes to the extent and latitudinal distribution of monsoon regions, is northern Africa, primarily because of the aforementioned inability of previous models to reproduce the increases shown by the proxy data here (e.g. Braconnot *et al*. 2007, Braconnot *et al*. 2012). Therefore, Figure 5 reproduces the above precipitation changes but zooms into Africa and additionally includes ~~Mean~~ calendar adjusted mean JJA (the primary monsoon region) ~~rainfall and~~ 850mb wind anomalies (relative to the *piControl*) ~~from both warm climate simulations are shown in Fig_wafricarain_prod, which zooms into Africa~~. In response to the increased Northern Hemisphere summer insolation, the West African monsoon is enhanced in both simulations, with positive (negative) rainfall anomalies across sub-Saharan Africa (eastern equatorial Atlantic) suggesting a northward displacement of the ~~ITCZ~~ rainfall maxima. This is consistent with previous work, with a northward movement of the rainbelt being associated with increased advection of moisture into the continent (Huag *et al*. 2001, Singarayer *et al*. 2017, Wang *et al*. 2014). This increased advection of moisture is shown by the enhanced low-level westerlies at all latitudes but especially over the regions of rainfall maxima in Figure 5a and b~~Fig_wafricarain_prod~~, drawing in more moisture from the tropical Atlantic, which are consistent with previous work documenting the intensified monsoon circulation ~~associated with a greater land-sea temperature~~

~~contrast~~ (Huag *et al*. 2001, Singarayer *et al*. 2017, Wang *et al*. 2006). This pattern is enhanced in the *lig127k* relative to the *midHolocene*, again in response to the stronger insolation changes relative to the MH, and the northward displacement of the ~~ITCZ~~ central rainbelt is more pronounced in the *lig127k* simulation (Figure 5~~Fig_wafricarain_prod~~ c). ~~Interestingly, however, regarding very small anomalies (i.e. < 1 mm day^{-1}), the *midHolocene* is showing wetter conditions further north, throughout the Sahara and up to the Mediterranean, whereas the *lig127k* simulation has small dry anomalies in this region (Fig_wafricarain_prod a and b for the *midHolocene* and *lig127k*, respectively).~~

The change to the intensity and the spatial pattern (e.g. latitudinal positioning and extent) of the West African monsoon is further shown in Figure 6, which shows calendar adjusted daily JJA rainfall by latitude over West Africa (averaged over 20°W-15°E, land points only) from both warm climate simulations. This figure also includes MH and LIG simulations from previous generations of the same model. It should be noted that although LIG experiments have been conducted previously with both model-model and model-data comparisons being made (Lunt *et al*. 2013), all of these experiments were carried out using early versions of the models and were thus not included in CMIP5. Moreover, as part of their assessment Lunt *et al*. (2013) considered a set of four simulations, at 130, 128, 125 and 115 ka, none of which are directly comparable to the current HadGEM3 *lig127k* simulation. Instead, a LIG simulation has recently been undertaken using one of the original versions of the UK's physical climate model, HadCM3, and so this is used here to compare with the *lig127k* simulation.

Beginning with the recent paleoclimate HadGEM3 simulations, in line with the changes in insolation both warm climate simulations are showing higher absolute values at their peak (between ~7.5-10°N) than the *piControl* (Figure 6a). Concerning anomalies, both simulations are showing a large increase in rainfall relative to the *piControl* (of ~2 and 6 mm day^{-1} for the *midHolocene* and *lig127k*, respectively) over the monsoon region between ~10-12°N (Figure 6b). Relative to previous versions of the same model, the previous generation (HadGEM2-ES) is slightly drier then HadGEM3 over this region for its PI simulation and slightly wetter for its MH simulation; conversely, the version before that (HadCM3) is consistently wetter than HadGEM3, for all of its simulations (Figure 6a). There also appears to be a northward displacement in the oldest version, with the largest difference between the simulations and their corresponding PI simulations occurring at ~11°N in the two most recent versions of the model, whereas in HadCM3 this appears to be shifted northwards to ~12.5°N (Figure 6b). This northward displacement in certain models consistent with previous work (e.g. Huag et al. 2001, Otto-Bliesner et al. 2017, Singarayer et al. 2017, Wang et al. 2014). In terms of the latitudinal extent, the results suggest that all warm climate simulations (regardless of generation) are producing a wider Northern Hemisphere monsoon region (i.e. a greater northerly extent) relative to each version's

PI, with rainfall falling to near zero at ~18°N in the PI simulations but extending to 20°N (and above, in terms of the LIG simulations) in both warm climate simulations (Figure 6a). This is again consistent with previous work, where various theories are compared as to the reasons behind the latitudinal changes in the rainbelt's position, one which is a symmetric expansion during boreal summer (Singarayer & Burrough 2015, Singarayer et al. 2017).

3.~~2~~1.2. ~~Model~~ Simulation comparison and Model-Data comparison: Do the CMIP6 HadGEM3 simulations reproduce the 'reconstructed' climate based on available proxy data, and has there been any noticeable improvement relative to previous versions of the same model?

Although the above analysis is useful and confirms that the most recent warm climate simulations are responding consistently to the increased latitudinal and seasonal distribution of insolation, it does not give any information on which (if any) of the simulations is most accurate or which version of the model is better at reproducing proxy-observed conditions. Therefore, h~~H~~ere we ~~focus on~~ bring in a comparison with newly-available ~~recent~~ proxy data, comparing these to all versions of the model, focusing on surface air temperature, SST and rainfall (drawing direct comparisons, as well as using the root mean square error (RMSE,~~)~~ but without a cut-off threshold), between both proxy ~~and~~ vs simulated data and HadGEM3 vs previous versions~~, summarised in Table 4a),~~). The aim of this is to firstly ~~to~~ see how well the current warm climate simulations are reproducing the 'observed' approximate magnitudes and patterns of change, and secondly to assess any possible improvement from previous versions of the same model. It is worth noting that both simulated and proxy anomalies contain a high level of uncertainty (as measured by the standard deviation), and in many locations the uncertainty is ~~often~~ larger than the anomalies themselves (not shown). The following results should therefore be considered with this caveat in mind.

Before the spatial patterns are compared, it is useful to assess global means from the three HadGEM3 simulations (focusing on 1.5 m air temperature, calculated both annually and during Northern and Southern Hemisphere summer, JJA and DJF respectively) ~~for model-model comparisons~~. Table 3 shows these global means, where it is clear that when annual means are considered, the *midHolocene* simulation is actually cooler than the *piControl*. This discrepancy with the palaeodata, which ~~in general~~ at many locations suggests a warmer MH relative to PI, and this is consistent with previous work using other models (e.g. ~~also exists in previous models, and is termed the 'Holocene temperature conundrum' by~~ Lui *et al*. ~~(~~2014). The *lig127k* simulation is, however, warmer than the *piControl* simulation. Given the seasonal distribution of insolation in these two simulations, it is expected that the largest difference to the *piControl* occurs during boreal summer, and indeed it does; during JJA, there is a warmer *lig127k* and a slightly warmer *midHolocene* (1.69°C and 0.07°C, respectively). The opposite is true during DJF.

Concerning the spatial patterns during the MH, Fig_proxy_mh_loc shows simulated surface MAT and MAP anomalies from the *midHolocene* simulation versus MH proxy anomalies from Bartlein *et al*. (2011), both of which have over 600 proxy locations in total (Table 4), although mostly confined to the Northern Hemisphere. For MAT, globally the simulation looks reasonable (RMSE = 2.45°C), and appears to be able to reproduce the sign of temperature change for many locations, with both simulated and proxy anomalies suggesting increases in temperature North of 30°N (Fig_proxy_mh_loc a and b). This is not true everywhere, such as across the Mediterranean where the simulation suggests a small warming but the proxy data indicates cooling (Fig_proxy_mh_loc a and b). However, regarding the magnitude of change, the *midHolocene* simulation is underestimating the temperature increase across most of the Northern Hemisphere, with for example increases of up to 1°C across Europe from the simulation compared to 3-4°C increases from the proxy data (Fig_proxy_mh_loc a and b). In the simulation, temperature anomalies only reach these magnitudes in the Northern Hemisphere polar region (i.e. north of 70°N), not elsewhere. A similar conclusion can be drawn from MAP (RMSE = 280 mm yr^{-1}), where again the *midHolocene* simulation is correctly reproducing the sign of change across most of the Northern Hemisphere, but in some places not the magnitude. Over the eastern US, for example, rainfall decreases of up to 200 mm yr^{-1} are being shown by the simulation whereas the proxy data suggests a much stronger drying of up to 400 mm yr^{-1} (Fig_proxy_mh_loc c and d). Elsewhere, such as over Europe and Northern Hemisphere Africa, the simulation more accurately reproduces the magnitude of rainfall increases; both simulated and proxy anomalies show increases of 200-400 mm yr^{-1} (Fig_proxy_mh_loc c and d).

Concerning the spatial patterns during the MH, Figure 7 shows simulated surface MAT anomalies from the current *midHolocene* simulation and those from two previous versions of the same model, versus MH proxy anomalies from Bartlein *et al*. (2011). Note that, here, statistical significance of the simulated anomalies has not been shown, because firstly the aim here is to assess all differences regardless of significance and secondly because a measure of statistical significance (for HadGEM3) has already been presented in Figure 2; statistical significance from the other versions of the same model is virtually identical (not shown). Globally, all three models are showing a reasonable level of agreement to the proxy data, with RMSE = 2.45°C, 2.42°C and 2.37°C for HadGEM3, HadGEM2-ES and HadCM3, respectively (Table 4a). Using this metric, the oldest version of the model (HadCM3) is doing marginally better than the other models, relative to the proxy data. Spatially, however, there are differences to the proxy data and between model generations. Although all three generations appear to be able to reproduce the sign of temperature change for many locations, with both simulated and proxy anomalies suggesting increases in temperature North of 30°N and especially over northern Europe, the Arctic Circle increases are not as homogenous in HadCM3 (Figure 7d) and indeed this model shows cooling over the Greenland Sea. Although this cannot be corroborated by the proxy data, due to a lack of coverage, neither of the later generation models show this to the same extent

(Figure 7b and c). Discrepancies with the proxy data also occur in all three simulations across the Mediterranean region, where all three simulations suggest a small warming but the proxy data indicates cooling (Figure 7). Moreover, regarding the magnitude of change, all three simulations are underestimating the temperature increase across most of the Northern Hemisphere, with for example increases of up to 1°C across Europe from the simulations compared to 3-4°C increases from the proxy data. In the simulations, temperature anomalies only reach these magnitudes in the Northern Hemisphere polar region (i.e. north of 70°N), not elsewhere. Further equatorward, all three simulations are identifying a slight cooling over the West African monsoon region (as discussed above), but the accuracy of this relative to the proxy data is difficult to ascertain given the lack of coverage across Africa and, where there are data locations, a highly variable sign of change (Figure 7a).

A similar conclusion can be drawn from MAP, shown in Figure 8, where all three simulations are correctly reproducing the sign of change across most of the Northern Hemisphere, although more so in the two most recent generations of the model (HadGEM3 and HadGEM2-ES), but in some places not the magnitude. Over the eastern US, for example, rainfall decreases of up to 200 mm yr^{-1} are being shown by the simulations (Figure 8b-d) whereas the proxy data suggests a much stronger drying of up to 400 mm yr^{-1} (Figure 8a). Elsewhere, such as over Europe and Northern Hemisphere Africa, the simulations more accurately reproduce the magnitude of rainfall increases; both simulated and proxy anomalies show increases of 200-400 mm yr^{-1}. Globally, Table 4a suggests that the most recent generation model, HadGEM3, is doing better than the others, relative to the proxy data (RMSE = 285.9 mm yr^{-1}, 293.5 mm yr^{-1} and 304.7 mm yr^{-1} for HadGEM3, HadGEM2-ES and HadCM3, respectively). In terms of how the spatial patterns change according to model version, during the MH the two most recent simulations generally agree (RMSE = 90.8 mm $year^{-1}$, Table 4a) and show similar spatial patterns; focusing again on the African monsoon region (for the aforementioned reasons), both simulations show a drier equatorial Atlantic during the MH and then increased rainfall around 10°N (Figure 8b and c for HadGEM3 and HadGEM2-ES, respectively). Both simulations also suggest that the increases in rainfall extend longitudinally across the entire African continent, with the largest changes not only occurring across western and central regions but also further east. In contrast, globally HadCM3 agrees less with HadGEM3 (RMSE = 121.8 mm $year^{-1}$, Table 4a) and only suggests a wetter MH over West Africa, not further east. HadCM3, and indeed HadGEM2-ES, also differs from the most recent simulation over the equatorial Atlantic, showing a region of drying that is not only stronger in magnitude but also larger in terms of spatial extent; whilst still present in HadGEM3, this feature that is much weaker (Figure 8b-d).

~~Concerning the spatial patterns during the LIG, Fig8_proxy_lig_loc shows simulated mean SST anomalies (calculated both annually and during JAS/JFM) from the *lig127k* simulation and LIG proxy~~

anomalies from two sources, Capron *et al*. (2017) and Hoffman *et al*. (2017). When annual anomalies are considered, despite the lack of reconstructions in the Capron *et al*. (2017) data (Table 4), there is relatively good agreement (RMSE = 2.44°C and 2.94°C for the Capron *et al*. (2017) and Hoffman *et al*. (2017) data, respectively, and which is within the average uncertainty range), between simulated and observed SST anomalies in the Northern Hemisphere (and in particular in the North Atlantic), with both suggesting increased temperatures during the LIG of up to 3°C (Fig_proxy_lig_loc a). There are discrepancies, such as in the Norwegian Sea, where the Hoffman *et al*. (2017) reconstructions suggest a cooler LIG than preindustrial, whereas the *lig127k* simulation shows a consistent warming; this is, however, consistent with previous work, and earlier climate models have also failed to capture this cooling (Capron *et al*. 2014, Stone *et al*. 2016). Note that, over Greenland and Antarctica, the Capron *et al*. (2017) proxy data show SAT, not SST, and are therefore not compared in this figure; comparison with simulated SAT, however, suggests that the model is capturing the sign, if not the magnitude, of annual change over these regions (not shown). During Northern Hemisphere summer, JAS (during which period Capron *et al*. [2017] has the most proxy locations [Table 4]), the simulated anomalies are in agreement with many, but not all, of the proxy locations (RMSE = 3.11°C and 2.06°C for the Capron *et al*. (2017) and Hoffman *et al*. (2017) data, respectively); examples of where they differ, not just in magnitude but also sign, again include the Norwegian and Labrador Seas (Fig_proxy_lig_loc b). In Southern Hemisphere summer, JFM, the model suggests a general (but weak) cooling in the South Atlantic relative to preindustrial and a general (but weak) warming in the Southern Ocean (Fig_proxy_lig_loc c). However, certain proxy locations (such as off the coast of southern Africa) suggest a much warmer LIG than preindustrial (RMSE = 1.94°C and 4.24°C for the Capron *et al*. (2017) and Hoffman *et al*. (2017) data, respectively), which in stark contrast to the cooling in the same region from the *lig127k* simulation (Fig_proxy_lig_loc c) . In the Southern Ocean, the majority of simulated anomalies reproduce the observed sign of change, but not the magnitude; the *lig127k* simulation suggests temperature increases of up to 1°C, whereas both proxy datasets suggest SST increases of 2-3°C depending on location (Fig_proxy_lig_loc c).

Concerning the spatial patterns during the LIG, Figure 9 shows simulated mean SST anomalies (calculated both annually and during JAS/JFM) from the current *lig127k* simulation and that from the oldest version of the same model, versus LIG proxy anomalies from two sources, Capron *et al*. (2017) and Hoffman *et al*. (2017). No LIG simulation using HadGEM2-ES is currently available. When annual anomalies are considered, there is relatively good agreement globally between HadGEM3 and the proxy data where RMSE = 3.03°C and 2.42°C for the Capron *et al*. (2017) and Hoffman *et al*. (2017) data, respectively (Table 4b). HadCM3 performs marginally better when compared to the Capron *et al*. (2017) data, but worse when compared to the Hoffman *et al*. (2017) data (Table 4b). Similarly varying results also occur when JAS and JFM anomalies are considered, with HadGEM3 comparing slightly better or worse than HadCM3 according to season and proxy dataset used; all of the values, however, show relatively good agreement, with no simulation exceeding RMSE = 4.5°C in any season or with any dataset (Table 4b). Spatially, HadGEM3 is showing a general agreement between simulated and proxy annual and JAS anomalies in the Northern Hemisphere (and in particular in the North Atlantic), with both suggesting increased temperatures during the LIG of up to 5°C (Figure 9a and b). HadCM3 is not capturing these magnitudes at the annual timescale (Figure 9d) and, despite showing greater warming during JAS, is still lower than HadGEM3; this is more in agreement with the proxy data at higher latitudes (e.g. the western Norwegian Sea at ~70°N) but less so further south (Figure 9e). This might suggest that, in this region, HadGEM3 is actually overestimating the degree of warming. Nevertheless, in both versions of the model there are discrepancies concerning not just in the magnitude but also in the sign of change, such as in the eastern Norwegian Sea or the Labrador Sea, where reconstructions suggest a cooler LIG but both versions show a consistent warming (Figure 9b and e). This is, however, consistent with previous work, and earlier climate models have also failed to capture this cooling (Capron *et al*. 2014, Stone *et al*. 2016). In Southern Hemisphere summer, JFM, both versions agree on a general (but weak) cooling in the South Atlantic relative to preindustrial and a weak warming in the Southern Ocean (Figure 9c and f). In contrast certain proxy locations (such as off the coast of southern Africa) suggest a much warmer LIG than preindustrial, which is opposite to the simulated cooling in the same region (Figure 9c and f). Further south, the majority of simulated anomalies reproduce the observed sign of change, but not the magnitude; here, the simulations suggest temperature increases of up to 1°C, whereas both proxy datasets suggest SST increases of 2-3°C depending on location (Figure 9c and f).

For rainfall changes during the LIG, Figure 10 shows simulated annual mean surface rainfall anomalies from the current *lig127k* simulation and that from the oldest version of the same model, versus LIG proxy anomalies from Scusscolini et al. (2019). Note that the simulated anomalies shown here are annual anomalies, as opposed to daily anomalies in Figure 3, to be consistent with the proxy data. Note also that, for these proxy reconstructions, a semi-quantitative scale is used by Scusscolini et al. (2019) rather than actual anomalies and is therefore reproduced here; this ranges from a unitless -2 to 2, corresponding to 'Much wetter LIG anomaly', 'Wetter', 'No noticeable anomaly', 'Drier' and 'Much drier LIG anomaly'. It is for this reason that RMSE values have not been calculated here. As was suggested from the MH simulations (Figure 8), both versions of the model are showing similar patterns of rainfall changes, along the same lines as those seen during the MH but again enhanced (Figure 10). Both versions are showing enhanced rainfall across the Northern Hemisphere equatorial zone and in particular the monsoon regions during the LIG, often exceeding 500 mm $year^{-1}$ in some places. In the Northern Hemisphere, both versions of the model are generally in agreement with the proxy data, with most proxy locations showing 'Wetter' or 'Much wetter' conditions. There are, however, some discrepancies elsewhere, such as the regions of tropical drying over e.g. Brazil and southern Africa in the simulations being in stark contrast to the 'Wetter' conditions suggested by the proxy data (Figure 10). Concerning the differences in the spatial patterns between the model versions, although both generations qualitatively show similar patterns, there are subtle differences. Again focusing on the African monsoon region, HadGEM3 shows greatly increased rainfall across all of sub-Saharan Africa, centred on 10°N but extending from ~5°N to almost 20°N and longitudinally across the entire African continent (Figure 10a). In contrast, and similar to the MH results, in HadCM3 the largest rainfall increases are less apparent over East Africa (Figure 10b).

It would therefore be reasonable to say that, for both ~~warm climate~~ MH and LIG simulations, whilst the most recent version of the model is capturing the sign and magnitude of change relative to proxy reconstructions (for either temperature or rainfall) in some locations, this is highly geographically dependent and there are locations where the current simulation fails to capture even the sign of change. Compared to previous versions of the same model, any improvement also appears to be highly variable according to metric, proxy reconstruction used for comparison and geographical location, with for example HadGEM3 showing some improvement relative to previous versions for rainfall during the MH, but not surface air temperature. The accuracy of the most recent ~~The~~ model, and indeed previous generations, also appear~~s~~s to be seasonally dependent, with the most recent *lig127k* simulation ~~(but not the *midHolocene* simulation)~~ correctly reproducing both the sign and magnitude of change during Northern Hemisphere summer in some locations, but not during Southern Hemisphere summer or annually. It would also appear that, for both the MH and LIG simulations, whilst there is less difference between the most recent two configurations of the model, they are nevertheless quite different to the oldest version. For global mean annual rainfall during the MH, Table 4a shows a linear progression of improvement across the three versions of the model, as well as more agreement between the two most recent model generations. This is also true when just the region of rainfall maxima in northern Africa is considered, with both of the two most recent generations, and especially HadGEM2-ES, being marginally closer to the proxy data than HadCM3 (RMSE = 463.7 mm yr^{-1}, 424.5 mm yr^{-1} and 468.4 mm yr^{-1} for HadGEM3, HadGEM2-ES and HadCM3, respectively). In all simulations, although spatial patterns of rainfall are similar, there are discrepancies especially over the African monsoon region; the oldest version of the model, for example, only shows rainfall increases over West Africa, whereas the two most recent versions imply Africa-wide rainfall increases at this latitude. If a comparison is made with satellite-derived rainfall data for the modern West African monsoon (not shown), results suggest that rainfall maxima are not just limited to West Africa but also occur over the central region and East Africa, more consistent with the two most recent versions of the model. One reason for HadCM3 not identifying this longitudinal extent might be connected to the very coarse spatial resolution of this model, relative to the others, impacting any topographically-induced rainfall, especially over the East African Highlands.

3.2.3. Model-Model comparison: Do the CMIP6 HadGEM3 simulations show an improvement compared to older CMIP versions of the UK model?

Here we focus on model-model intercomparisons, comparing the HadGEM3 warm climate simulations with firstly those from previous versions of the UK model and secondly with those from other models included in CMIP5. It should be noted that although LIG experiments have been conducted previously with both model-model and model-data comparisons being made (Lunt *et al.* 2013), all of these experiments were carried out using early versions of the models and were thus not included in CMIP5. Moreover, as part of their assessment Lunt *et al.* (2013) considered a set of four simulations, at 130, 128, 125 and 115 ka, none of which are directly comparable to the current HadGEM3 *lig127k* simulation. Instead, a LIG simulation has recently been undertaken using one of the original versions of the UK's physical climate model, HadCM3, and so this is used here to compare with the *lig127k* simulation. As discussed above, this section is divided into two parts: firstly the mean climate state of the warm climate simulations will be compared to the model's predecessors, focusing again on hydroclimate of the West African monsoon (given the known problem of simulated rainfall underestimation in this region, see e.g. Braconnot *et al.* [2007]). Here, both direct comparisons and RMSE values will again be examined, this time calculating the RMSE between the simulated rainfall anomaly from two older versions of the UK model versus the current HadGEM3 *midHolocene* and *lig127k* simulations (summarised in Table 4b).

Secondly, previous generation simulations (from all available models included in CMIP5) will be compared to see whether the most recent HadGEM3 *midHolocene* simulation is now providing enough rainfall to allow vegetation growth across the Sahara; something which previous generations of models from CMIP5 did not (Braconnot *et al.* 2007).

3.2.3.1. Mean climate state from predecessors of HadGEM3

Regarding the magnitude and latitudinal extent of the West African monsoon, Fig_latrain_gen shows the JJA rainfall differences averaged over West Africa from the current *midHolocene* and *lig127k* simulation versus two of the model's predecessors. During the MH, the two most recent generations of the model (HadGEM3 and HadGEM2-ES) generally agree on drier conditions over the equatorial Atlantic and then wetter conditions over West Africa, however the oldest generation model (HadCM3) does not reproduce the Atlantic drying. Likewise the two most recent generations share a similar latitudinal distribution of rainfall above ~5°N, with a wetter MH over land, peaking at ~2-3 mm day^{-1} at ~11-12°N. Interestingly, the previous version of the model (HadGEM2-ES) shows the strongest and most northwardly displaced rainfall peak, as discussed in previous work (e.g. Huag *et al.* 2001, Otto-Bliesner *et al.* 2017, Singarayer *et al.* 2017, Wang *et al.* 2014); the most recent version, HadGEM3, has lower northward displacement compared to the two older versions of the model. Both recent versions suggest that the monsoon region extends to ~17°N, above which the differences between the MH and PI reduce to near zero. In contrast, HadCM3 suggests a generally weaker, but latitudinally more extensive, monsoon region, suggesting a wetter MH (by ~1 mm day^{-1}) as far north as 20°N and beyond. For the LIG, HadGEM3 is showing a much stronger monsoon region relative to the *piControl*, compared to HadCM3. However, in terms of extent, similar results are shown to those for the MH, with HadCM3 showing a generally weaker, but more northwardly displaced, monsoon region. In this older generation model, positive rainfall anomalies of ~2-3 mm day^{-1} extend as far north as 17-18°N, whereas in HadGEM3 they fall to ~1 mm day^{-1} at these latitudes.

In terms of the spatial patterns of the West African monsoon, Fig_wafricarain_gen_mh and Fig_wafricarain_gen_lig show the JJA daily rainfall climatology differences from the same three model generations for the MH and LIG, respectively. During the MH, consistent with Fig_latrain_gen, the two most recent simulations generally agree (RMSE = 0.46 mm day^{-1}) and show similar spatial patterns, with a drier equatorial Atlantic during the MH and then increased rainfall around 10°N (Fig_wafricarain_gen_mh a and b for HadGEM3 and HadGEM2-ES, respectively). Both simulations also suggest that the increases in rainfall extend longitudinally across the entire continent, with the largest changes not only occurring across western and central regions but also further east. In contrast, HadCM3 is less consistent than HadGEM3 (RMSE = 0.53 mm day^{-1}) and only suggests a wetter MH over West Africa; moreover, again consistent with Fig_latrain_gen, HadCM3 suggests that although the West African monsoon region is longitudinally narrower, it is latitudinally wider than the other two simulations (Fig_wafricarain_gen_mh c). HadCM3 also differs from the other simulations over the equatorial Atlantic, showing a region of drying that is not only stronger in magnitude (with the MH being over 5 mm day^{-1} drier than the PI in HadCM3, compared to ~2-3 mm day^{-1} in the two most recent simulations), but also larger in terms of latitude and longitude extent (Fig_wafricarain_gen_mh c).

During the LIG, only the most recent and oldest version of the model can be compared, as a LIG simulation using HadGEM2-ES is unavailable. In Fig_wafricarain_gen_lig there is a noticeable difference between generations and the level of agreement is the lowest across all simulation combinations (RMSE = 1.57 mm day^{-1}), with the most recent HadGEM3 showing greatly increased rainfall across all of northern Africa, centred on 10°N but extending from ~5°N to almost 20°N and beyond (Fig_wafricarain_gen_lig a), again consistent with Fig_latrain_gen. In contrast, and similar to the MH results, in HadCM3 the largest rainfall increases are confined to Western Africa only, rather than extending longitudinally across the continent (Fig_wafricarain_gen_lig b). However, in terms of latitudinal extent, HadCM3 is showing weak wet anomalies all the way to the Mediterranean, whereas the monsoon region diminishes further south (at ~30°N) in HadCM3 and dry anomalies are suggested North of this. Another noticeable difference is the region of drying, with the most recent generation

~~model placing this over the equatorial Atlantic (consistent with the MH) but HadCM3 shifting this further east, over most of central Africa (Fig_wafricarain_gen_lig b). The region of equatorial Atlantic drying shown by the more recent versions of the model is actually wetter during this HadCM3 LIG simulation.~~

~~It would therefore appear that, for the MH, whilst there is less difference between the most recent two configurations of the model (in terms of a more localised West African monsoon region), there nevertheless has been improvement since the oldest version of the UK's physical climate model. For the LIG, where unfortunately there is no intermediate generation, it would be reasonable to say that again considerable change has occurred since the oldest generation model, with the suggestion that, although HadCM3 is identifying an enhanced monsoon which extends to the Mediterranean (albeit with very weak anomalies), at lower latitudes it is not showing the level of northward displacement as the most recent version, apart from in the far western regions.~~

3.~~2~~1.3. ~~Rainfall across the~~ Saharan greening

Finally, a brief discussion is given on the 'Saharan greening' question. Given that the warm climate simulations, and indeed the *piControl*, did not use interactive~~, but rather prescribed,~~ vegetation, it is not possible to directly test if the model is reproducing the 'Saharan greening' that proxy data suggest. For example, Jolly *et al*. (1998a, 1998b) analysed MH pollen assemblages across northern Africa and suggested that some areas south of 23°N (characterised by desert today) were grassland and xerophytic woodland/scrubland during the MH (Joussaume *et al*. 1999). To circumvent this caveat, Joussaume *et al*. (1999) developed a method for indirectly assessing Saharan greening, based on the annual mean rainfall anomaly relative to a given model's modern simulation. Using the water-balance module from the BIOME3 equilibrium vegetation model (Haxeltine & Prentice 1996), Joussaume *et al*. (1999) calculated the increase in mean annual rainfall, zonally averaged over 20°W-30°E, required to support grassland at each latitude from 0 to 30°N, compared to the modern rainfall at that latitude. This was then used to create maximum and minimum estimates, within which bounds the model's annual mean rainfall anomaly must lie to suggest enough of an increase to support grassland (Joussaume *et al*. 1999).

Therefore, an adapted version of Figure 3a in Joussaume *et al*. (1999) is shown in the Supplementary Material (SM7), which shows mean annual rainfall anomalies by latitude (to be consistent with the proxy data-based threshold) from not only the current *midHolocene* simulation, but also all previous MH simulations from CMIP5. Concerning the threshold required to support grassland, it is clear that although the current *midHolocene* simulation is just within the required bounds at lower latitudes (e.g. up to 17°N), north of this the current *midHolocene* simulation is not meeting the required threshold, neither are any of the other CMIP5 models after ~18°N (SM7). It would therefore appear that the

'Saharan greening' problem has yet to be resolved, and may well only be reproduced once interactive vegetation, and indeed interactive dust, is included in the simulation; given the current lack of an interactive vegetation/dust model, vegetation-related climate feedbacks (e.g. albedo) on the system are therefore currently missing.

4. SUMMARY AND CONCLUSIONS

This study has conducted and assessed the mid-Holocene and Last Interglacial simulations using the latest version of the UK's physical climate model, HadGEM3-GC3.1, comparing the results firstly with the model's preindustrial simulation and secondly with previous versions the same model, against ~~with~~ available proxy data~~, previous versions of the same model, and other models from CMIP's previous iteration, CMIP5~~.~~–~~ Therefore this study is novel, being the first time this version of the UK model has been used to conduct any paleoclimate simulations and therefore the first time we are in a position to include them as part of the UK's contribution to CMIP6/PMIP4. Both the *midHolocene* and *lig127k* simulations followed the experimental design defined in Otto-Bliesner *et al*. (2017) and ~~under the auspices of~~ and the CMIP6/PMIP4 protocol~~, –~~. Both simulations were run for a 350-400 year spin-up phase, during which ~~time~~ atmospheric and oceanic equilibrium ~~was~~ were assessed, and once an acceptable level of equilibrium had been reached, the production runs were started.

~~Concerning the results from the spin-up phase, comparison to the metrics used to assess the CMIP6 *piControl* suggest that both warm climate simulations reached an acceptable state of equilibrium, in the atmosphere at least, to allow the production runs to be undertaken. From these, both simulations are showing global temperatures consistent with the latitudinal and seasonal distribution of insolation, and with previous work (e.g. Otto-Bliesner *et al*. 2017).~~ Globally, whilst both the recent simulations are mostly capturing the sign and, in some places, magnitude of change relative to the PI, similar to previous model simulations this is geographically and seasonally dependent. It should be noted that the proxy data (against which the simulations are evaluated) also contain a high level of uncertainty in both space and time (in terms of both seasons and geological era), and so it is encouraging that the simulations are generally reproducing the large-scale sign of change, if not at an individual location. Compared to previous versions of the same model, this appears to vary according to metric, proxy reconstruction used for comparison and geographical location. In some instances, such as annual mean rainfall in the MH, there is a clear and linear improvement (relative to proxy data) through the model generations when rainfall is considered globally; likewise there is more accuracy in the two recent versions (again relative to proxy data) than the oldest version when only the West African monsoon region is considered (see Table 4a and the RMSE values discussed in the concluding paragraph of Section 3.1.2).

Likewise, when zooming into Africa, the behaviour of the West African monsoon in both HadGEM3 warm climate simulations is consistent with current understanding (e.g. Huag et al. 2001, Singarayer et al. 2017, Wang et al. 2014), which suggests a wetter (and possibly latitudinally wider, and/or northwardly displaced) monsoon during the MH and LIG, relative to the PI. Regarding model development in simulating the West African monsoon, there are differences between model generations; the oldest version of the model, for example, limits the rainfall increases to over sub-Saharan West Africa only, whereas the two most recent versions imply Africa-wide (i.e. across all longitudes) rainfall increases at this same latitude~~a~~. ~~Although there has been an improvement since the oldest version of the UK's physical climate model (HadCM3), the two most recent version of the model yield similar results in terms of both intensity and position.~~ Lastly, regarding the well-documented 'Saharan greening' during the MH, results here suggest that the most recent version of the UK's physical climate model is consistent with all other previous models to date.

In conclusion, the results suggest that the most recent version of the UK's physical climate model is reproducing climate conditions consistent with the known changes to insolation during these two warm periods~~, and is consistent with previous versions of the same model, and other models~~. Even though the *lig127k* simulation did not contain any influx of Northern Hemisphere meltwater, shown by previous work to be a critical forcing in LIG simulations (causing regions of both warming and cooling, according to location), it is still nevertheless showing increased temperatures in certain regions. ~~A potential caveat of this conclusion, however, is the matter of spin-up and the fact that neither of the current warm climate simulations were in oceanic equilibrium when the production runs were undertaken. The production runs were undertaken nevertheless because the resources required to run for several thousands of years (needed to reach true oceanic equilibrium) would have been impossible to obtain, but future simulations using this model should endeavour to obtain a better level of oceanic equilibrium.~~ Another limitation of using this particular version of the model is that certain processes, such as vegetation and atmospheric chemistry, were prescribed, rather than allowed to be dynamically evolving. Moreover, for ~~reasons of necessity~~ practical reasons some of the boundary conditions were left as PI, such as vegetation, ~~surface like,~~ anthropogenic deforestation and aerosols; a better simulation might be achieved if these were prescribed for the MH and LIG. Processes and boundary conditions such as these may be of critical importance regarding climate sensitivity during the MH and the LIG, and therefore ongoing work is underway to repeat both of these experiments using the most recent version of the UK's Earth Systems model, UKESM1. Here, although the atmospheric core is HadGEM3, UKESM1 contains many other earth system components (e.g. dynamic vegetation), and therefore in theory should be able to better reproduce these paleoclimate states.

DATA AVAILABILITY

The model simulations will be uploaded in the near future to the Earth System Grid Federation (ESGF) WCRP Coupled Model Intercomparison Project (Phase 6), located at https://esgf-node.llnl.gov/projects/cmip6/, but are not yet publicly available. The simulations are, however, available to the public by directly contacting the lead author. For the MH reconstructions, the data can be found within the Supplementary Online Material of Bartlein *et al*. (2011), at https://link.springer.com/article/10.1007/s00382-010-0904-1. For the LIG temperature reconstructions, the data can be found within the Supplementary Online Material of Capron *et al*. (2017), at https://www.sciencedirect.com/science/article/pii/S0277379117303487?via%3Dihub, and the Supplementary Online Material of Hoffman *et al*. (2017), at https://science.sciencemag.org/content/suppl/2017/01/23/355.6322.276.DC1. The LIG temperature reconstructions created here, based on the above Hoffman *et al*. (2017) data, are currently available by directly contacting the lead author. For the LIG precipitation reconstructions, the data can be found within the Supplementary Online Material of Scusscolini *et al*. (2019), at https://advances.sciencemag.org/content/suppl/2019/11/18/5.11.eaax7047.DC1.

COMPETING INTERESTS

The authors declare that they have no conflict of interest.

AUTHOR CONTRIBUTION

CJRW conducted the *midHolocene* simulation, carried out the analysis, produced the figures, wrote the majority of the manuscript, and led the paper. MVG conducted and provided the *lig127k* simulation, and contributed to some of the analysis and writing. EC provided the proxy data, and contributed to some of the writing. IMV provided the HadCM3 LIG simulation. PJV provided the HadCM3 MH simulation. JS contributed to some of the writing. All authors proofread the manuscript and provided comments.

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SM2 - Annual global mean atmospheric fields from HadGEM3 *piControl*, *midHolocene* and *lig127k* spin-up phases: a) 1.5 m air temperature; b) TOA radiation balance. Thin lines in b) show annual TOA radiation balance, thick lines show 11-year running mean. Note that the *piControl* spin-up phase was run in three separate parts, to accommodate for minor changes/updates in the model as the simulation progressed. Note also that the first ~50 years of the *lig127k* simulation have been deliberately removed from this figure, because a number of model crashes caused the model to be initially unstable and give highly varied global mean temperatures.

SM3 – Centennial trends in 1.5m temperature for HadGEM3 warm climate simulations' spin-up phases, last 100 years only: a) *midHolocene* ; b) *lig127k*. Stippling shows statistical significance (as calculated by a Mann-Kendall test) at the 99% level

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SM6 – Annual mean sea-ice climatology differences, HadGEM3 *midHolocene* production run versus HadGEM3 *piControl* production run. Stippling shows statistical significance (as calculated by a Student's T-test) at the 99% level

SM7 – Annual mean rainfall over West Africa (averaged over 20°W-30°E, consistent with Joussaume *et al*. [1999]), HadGEM3 *midHolocene* simulation minus corresponding *piControl*, and likewise for previous models from CMIP5. Solid line shows HadGEM3, dotted lines show CMIP5 simulations. Grey dashes show maximum and minimum bounds of the increase in rainfall required to support grassland at each latitude, within which simulations must lie if producing enough rainfall to support grassland (adapted from Figure 3a in Joussaume *et al*. [1999])

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	piControl	*midHolocene*	*lig127k*
Astronomical parameters			
Eccentricity	0.016764	0.018682	0.039378
Obliquity	23.459	24.105°	24.04°
Perihelion-180°	100.33	0.87°	275.41°
Date of vernal equinox	March 21 at noon	March 21 at noon	March 21 at noon
Trace gases			
CO_2	284.3 ppm	264.4 ppm	275 ppm
CH_4	808.2 ppb	597 ppb	685 ppb
N_2O	273 ppb	262 ppb	255 ppb
Other GHG gases	CMIP DECK *piControl*	CMIP DECK *piControl*	CMIP DECK *piControl*

Table 1 - Astronomical parameters and atmospheric trace gas concentrations used in HadGEM3 simulations

Variable	*piControl*	*midHolocene*	*lig127k*
TOA (W m^2)	-0.002	-0.05	-0.06
1.5 m air temp (°C)	0.03	-0.06	-0.16
OceTemp (°C)	0.035	0.03	0.03
OceSal (psu)	0.0001	-0.0004	0.00007

Table 2 - Trends (per century) in global mean measures of climate equilibrium for the last hundred years of the simulations, adapted from and including *piControl* results from Menary *et al*. (2018)

Time period	Means (°C)			Anomalies (°C)	
	piControl	*midHolocene*	*lig127k*	*midHolocene – piControl*	*lig127k – piControl*
Annual	13.8	13.67	14.29	-0.12	0.49
JJA	15.68	15.75	17.37	0.07	1.69
DJF	11.86	11.55	11.39	-0.31	-0.47

Table 3 - Global 1.5 m air temperature means and anomalies from HadGEM3 *piControl*, *midHolocene* and *lig127k* production runs

a)

Metric	Simulations vs proxy data			Simulations vs simulations	
	HadGEM3	HadGEM2-ES	HadCM3	HadGEM2-ES v HadGEM3	HadCM3 v HadGEM3
MAT (°C)	2.45	2.42	2.37	0.65	0.57
No. of locations	*638*			*Global coverage*	
MAP (mm year^{-1})	285.9	293.5	304.7	90.8	121.8
No. of locations	*651*			*Global coverage*	

b)

Metric	Simulations vs proxy data					
	Yearly		JAS		JFM	
	HadGEM3	HadCM3	HadGEM3	HadCM3	HadGEM3	HadCM3
SST from Capron *et al*. (2017)	3.03	3.04	3.03	2.98	2.81	2.62
No. of locations	*3*		*24*		*15*	
SST from Hoffman *et al*. (2017)	2.42	3.02	1.99	2.78	4.28	3.97
No. of locations	*86*		*12*		*6*	

Table 4 - RMSE values (for various metrics) between simulations from different generations of the same model versus proxy data, and versus each other: a) MAT and MAP from the MH simulations versus proxy data from Bartlein et al. (2011); b) SST from the LIG simulations versus proxy data from Capron et al. (2017) and Hoffman et al. (2017). Regarding the proxy data comparisons in b), for JAS the simulated SST anomalies are compared to Northern Hemisphere summer reconstructions and for JFM the simulated SST anomalies are compared to Southern Hemisphere summer reconstructions

FIGURES

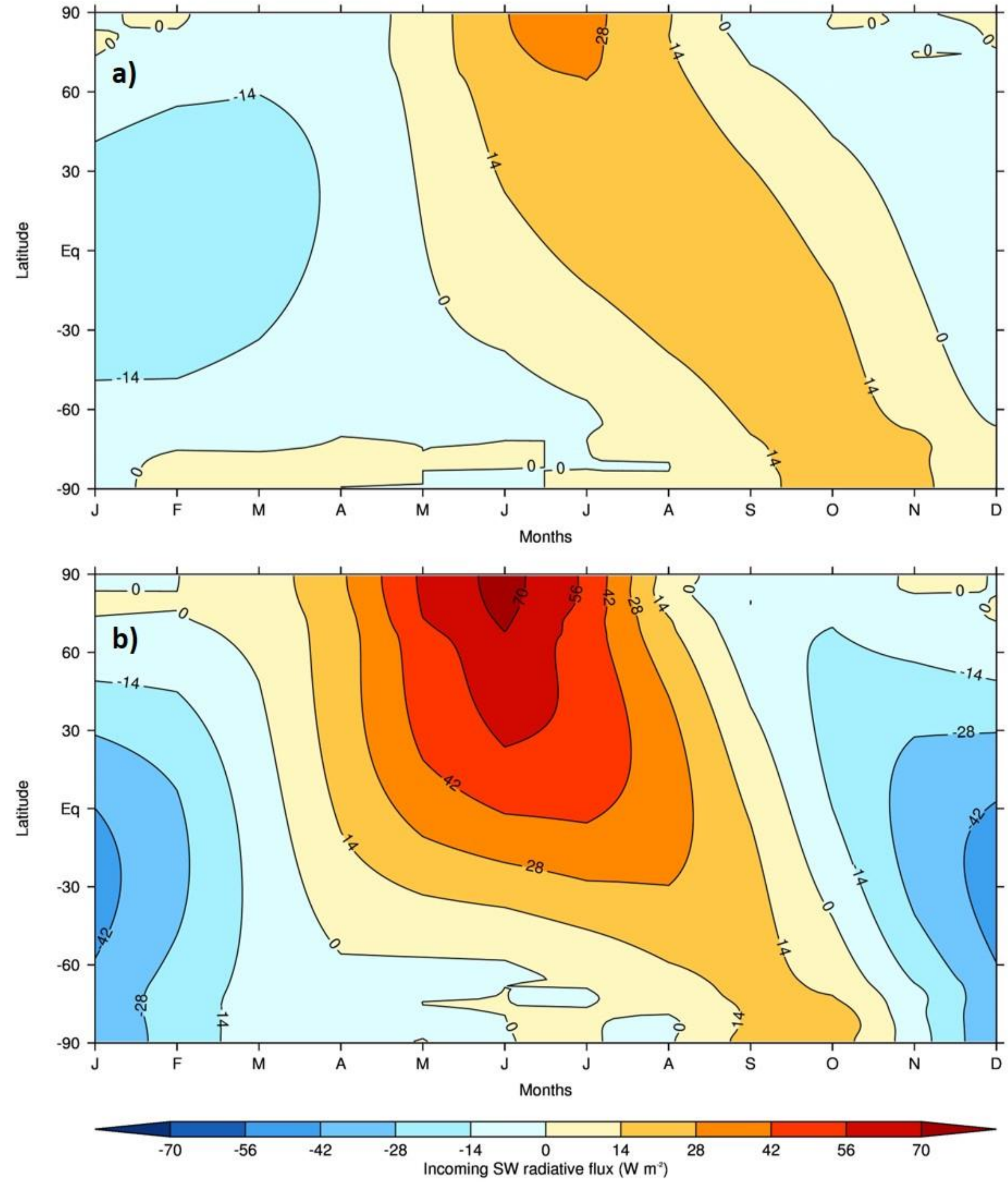
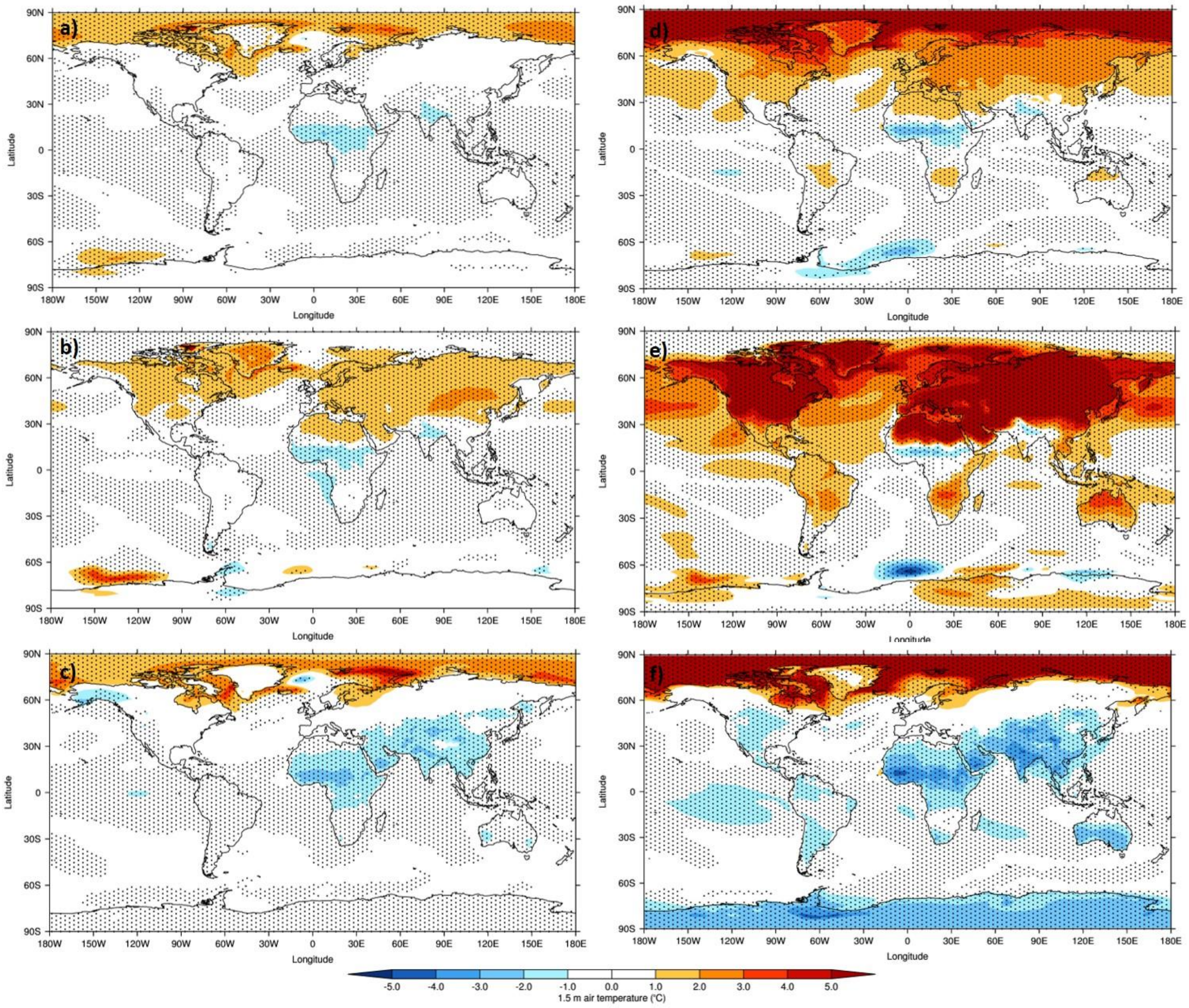


Figure 1 - Calendar adjusted ~~Latitude~~latitude-month insolation (incoming SW radiative flux) anomalies: a) *midHolocene* - *piControl*; b) *lig127k* - *piControl*



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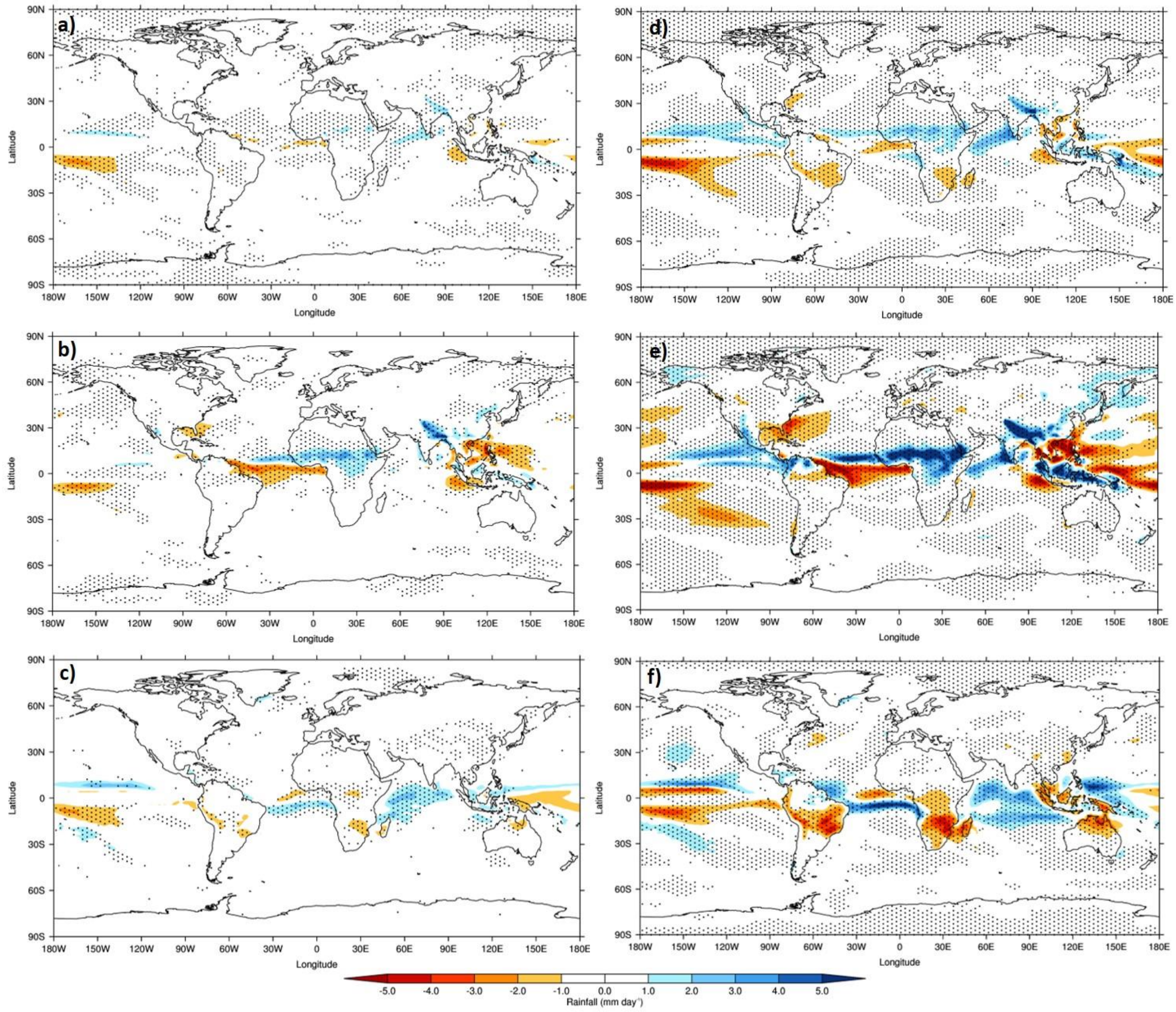
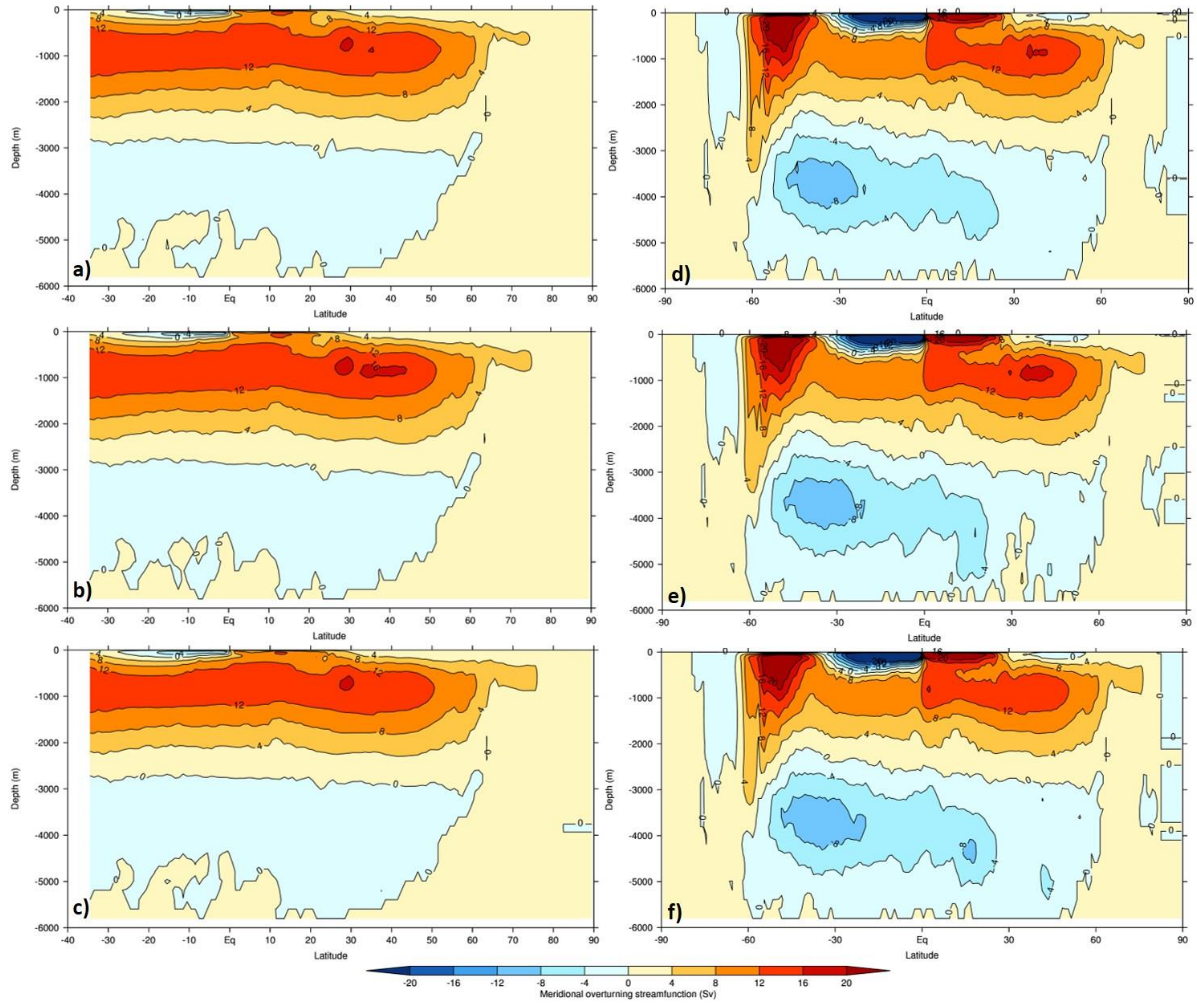


Figure 3 – Same as Figure 2, but for daily surface rainfall differences



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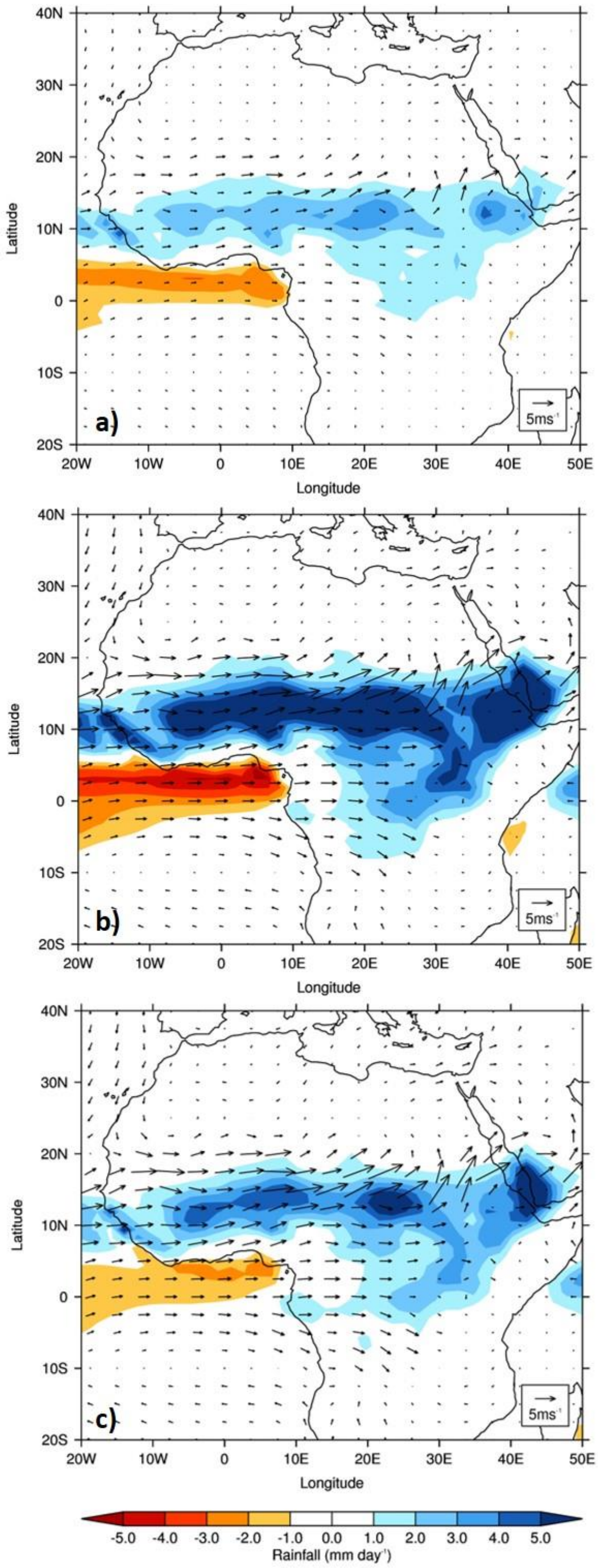

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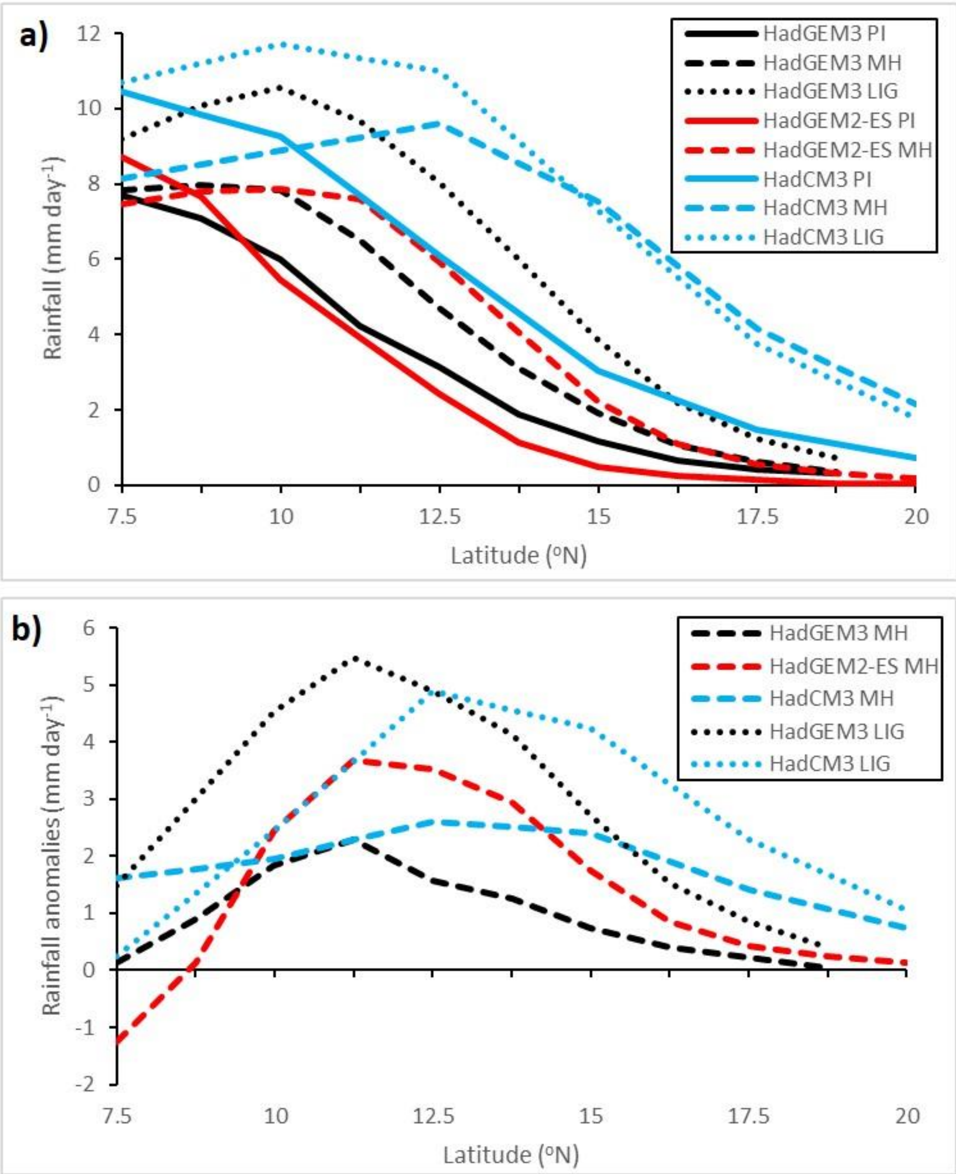

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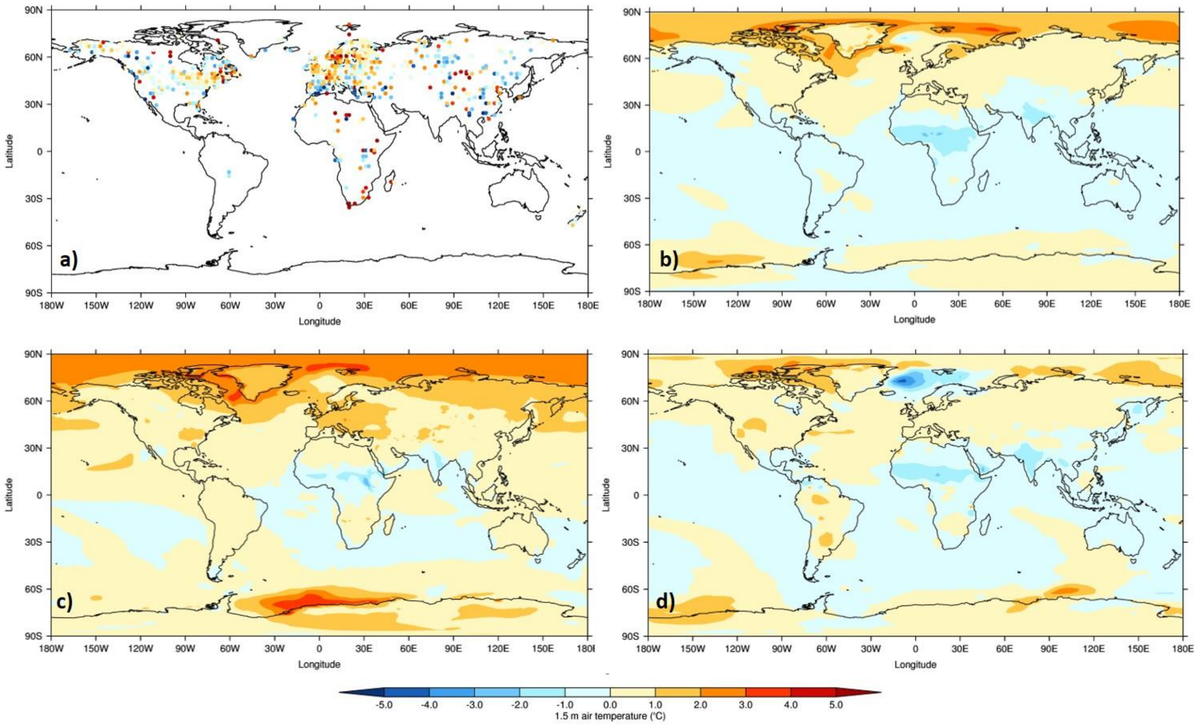

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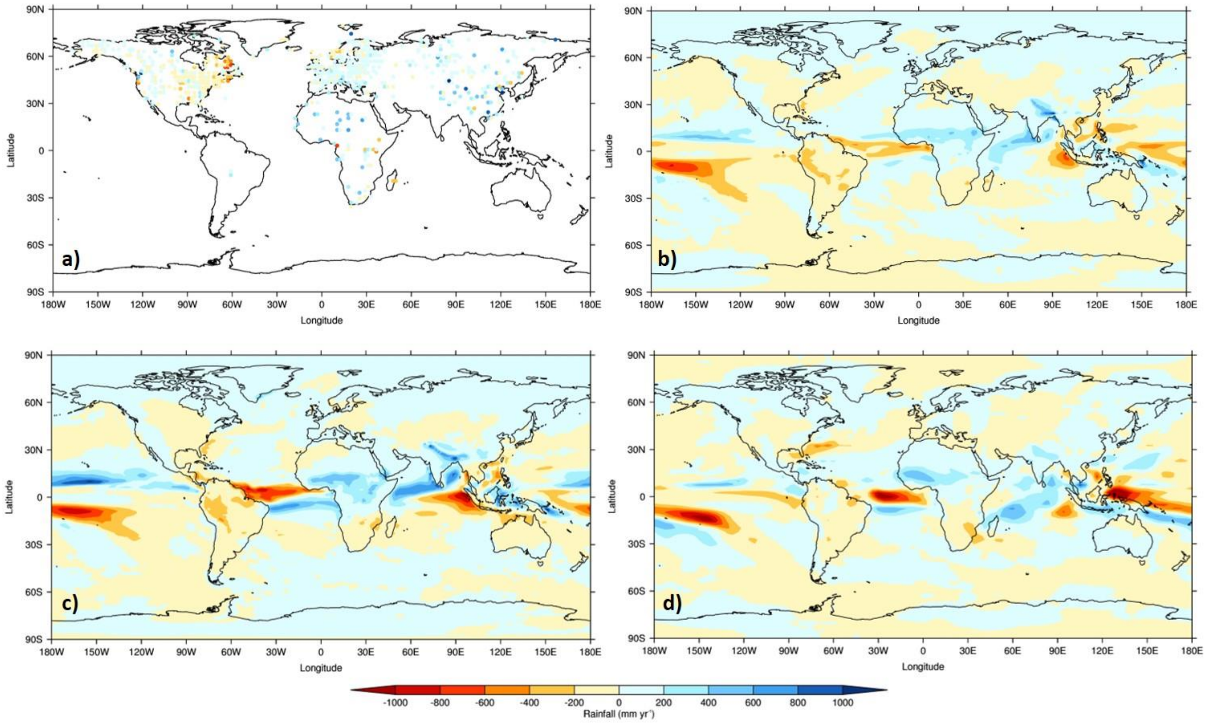
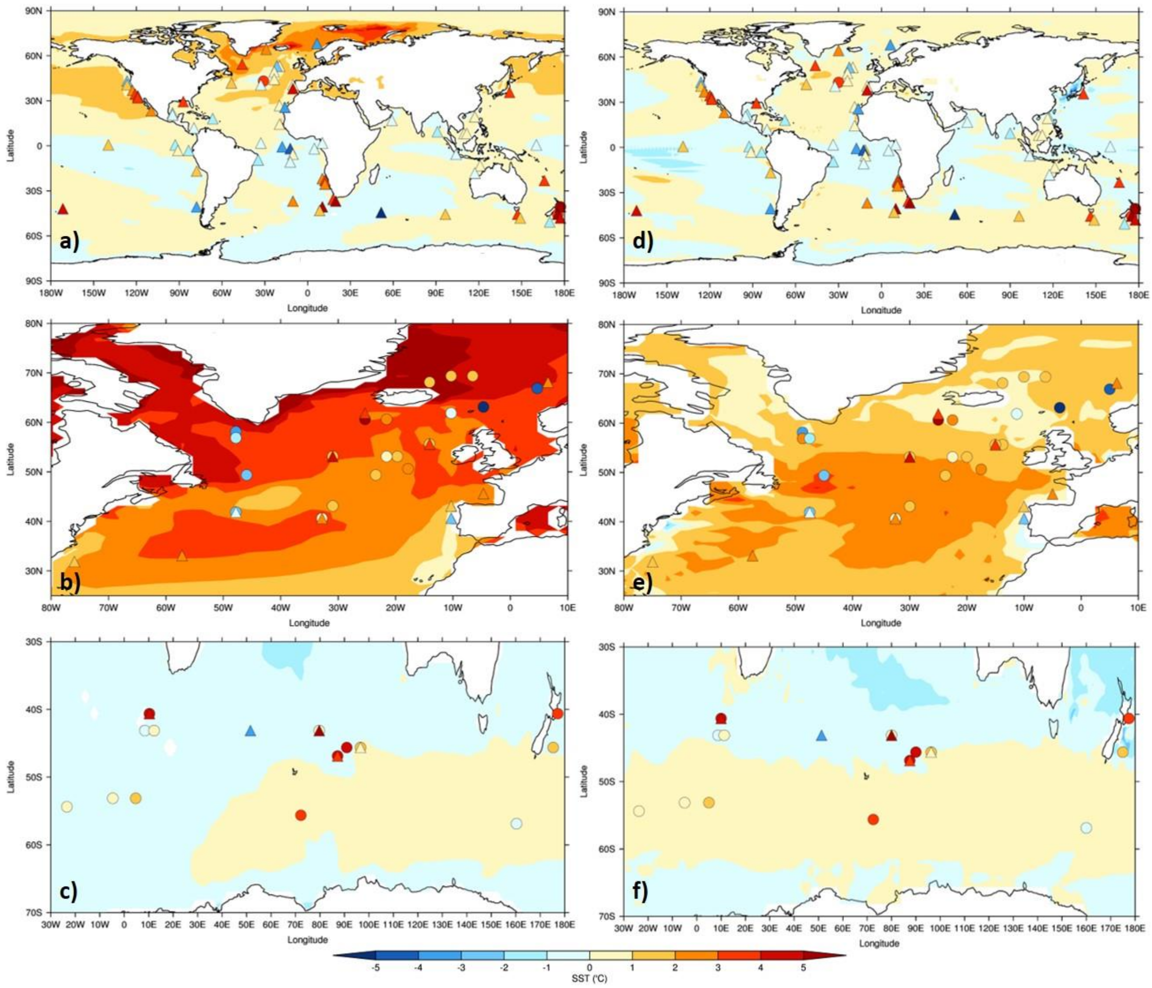


Figure 8 – Same as Figure 7, but for rainfall anomalies



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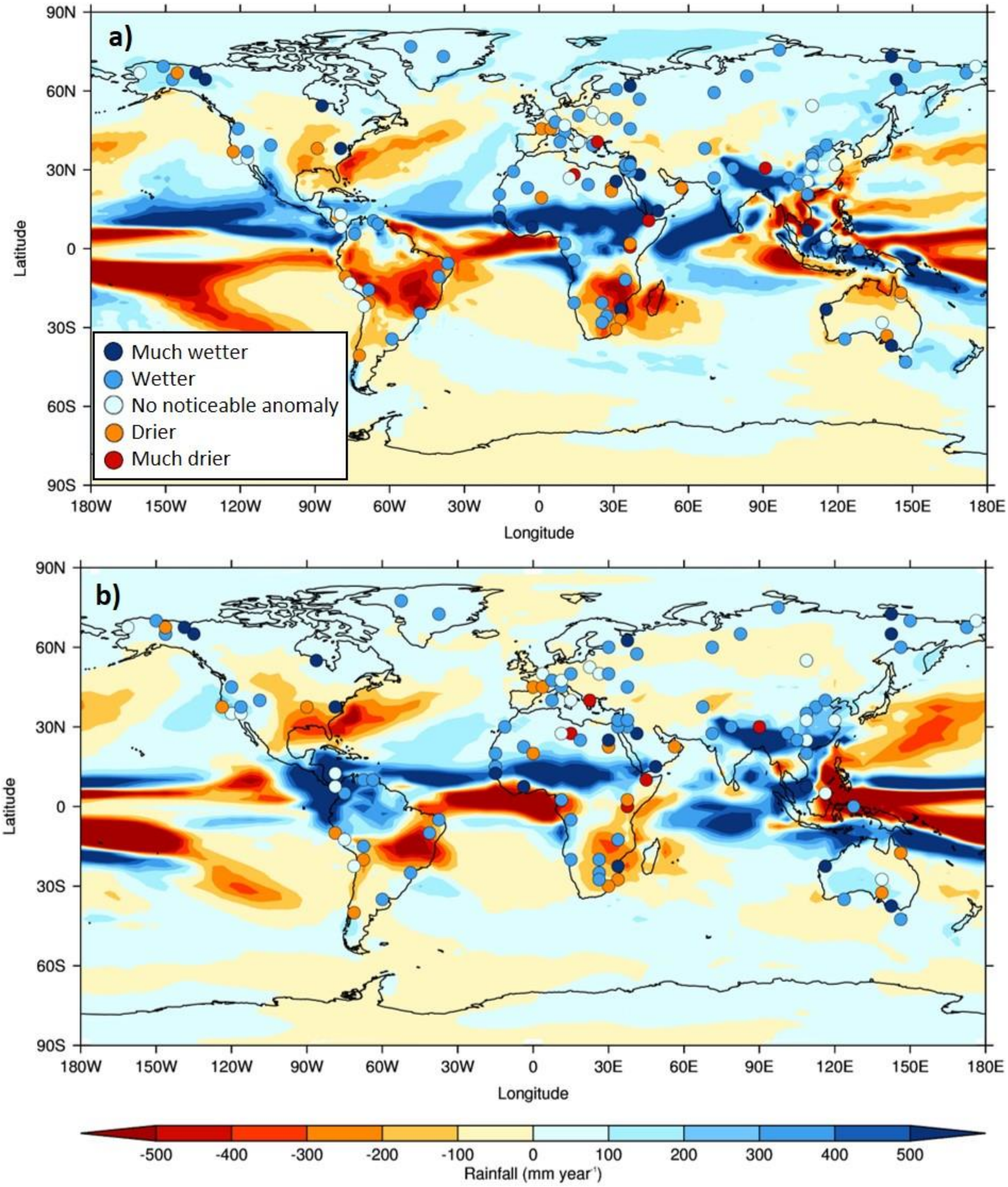

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CMIP6/PMIP4 simulations of the mid-Holocene and Last Interglacial using HadGEM3: comparison to the pre-industrial era, previous model versions, and proxy data

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SUPPLEMENTARY MATERIAL

TEXT

Model description

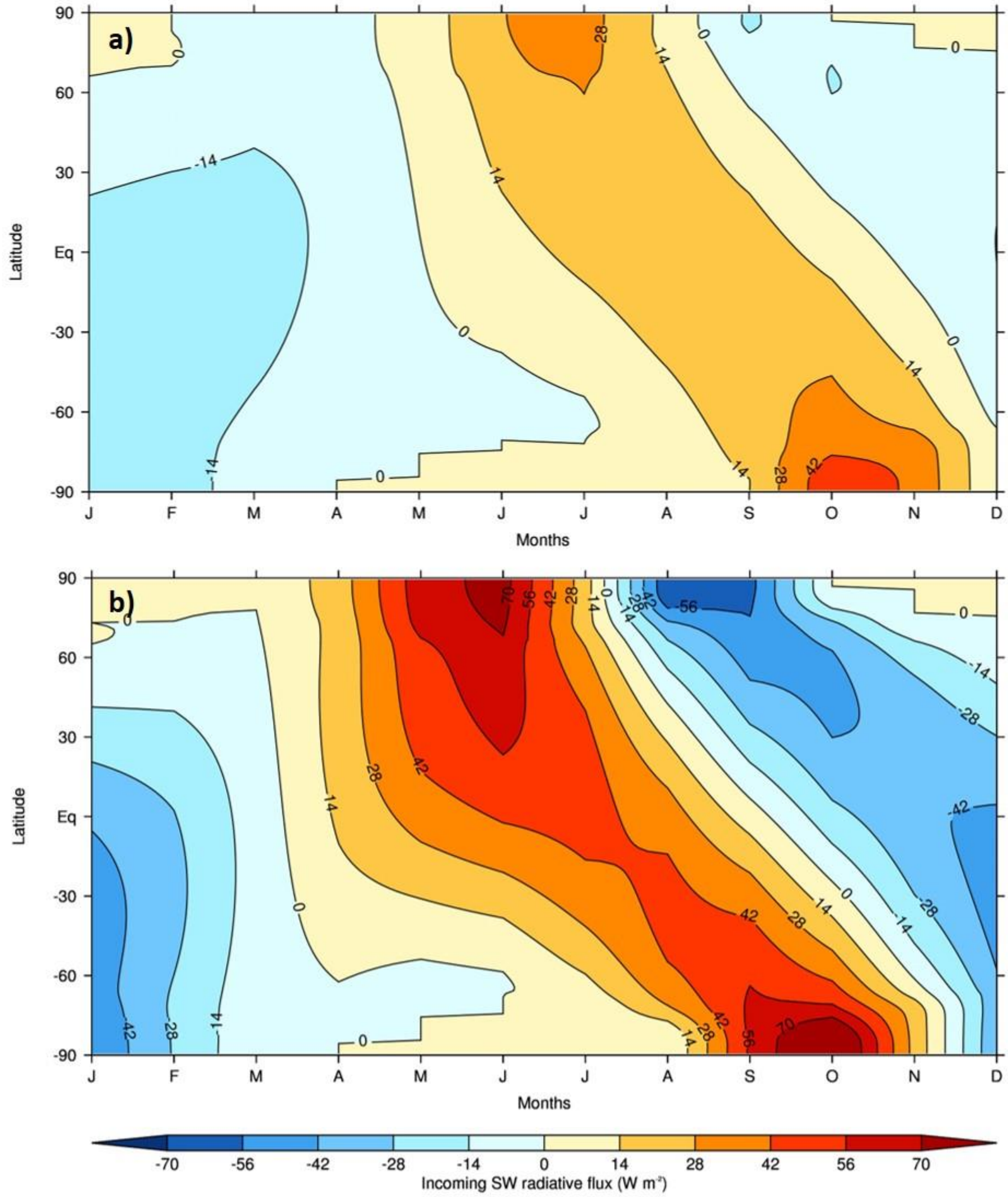
~~However~~Here, a ~~brief~~ description of the major changes in the latest version of UK's physical climate model, HadGEM3-GC3.1 ~~GC 3.1~~, relative to its predecessor, ~~are~~ is given, following on directly from Section 2.1.2 in the main manuscript ~~in the here~~. Beginning with Global Atmosphere (GA7) and Global Land components (GL7), a once-in-a-decade replacement of the model's dynamical core, implementing ENDGame, was undertaken for the previous version (GA6) and therefore remains the same in GA7 (Walters *et al*. 2017)[1]. A number of other developments, since the previous version of the model, have also been included. ~~In addition, a number of bottom-up and top-down developments were included in GA7. For the former, these include improvements~~Improvements were made to the radiation scheme to allow better treatment of gases absorption, as well as improvements to how warm rain and ice clouds are treated, ~~and~~ an improvement to the numerics of the convection scheme, and ~~(Walters *et al*. 2017). For the latter, these include further~~ improvements to the microphysics as well as an incremental development of ENDGame (Walters *et al*. 2017). Together these led to reductions in four model errors that were deemed critical in the previous configuration: i) South Asian monsoon rainfall biases over India; ii) biases in both temperature and humidity in the tropical tropopause; iii) shortcomings in the numerical conservation; and iv) biases in surface radiation fluxes over the Southern Ocean (Walters *et al*. 2017). In addition to these developments, two new parameterisation schemes were introduced in GA7: firstly the UK Chemistry and Aerosol (UKCA) GLOMAP-mode aerosol scheme, to improve the representation of tropospheric aerosols, and secondly a multi-layer snow scheme in the Joint UK Land Environment Simulator (JULES) ~~JULES~~, to allow the first time inclusion of stochastic physics in UM climate simulations (Walters *et al*. 2017).

For the ~~-~~ Global Ocean (GO) and Global Sea Ice (GIS) components, a number of improvements to GO6 have been made since the previous version, the first of which was an upgrade of the NEMO base code (to version 3.6) which allowed a formulation for momentum advection (from Hollingsworth *et al*. 1983), a Lagrangian icebergs scheme, and a simulation of circulation below ice shelves (Storkey *et al*. 2018). Other developments included an improvement to the warm SST bias in the Southern Ocean (as detailed by Williams *et al*. 2017), as well as tuning of various parameters e.g. the isopycnal diffusion (Storkey *et al*. 2018). For GIS8, along with improvements to the albedo scheme and more realistic semi-implicit coupling, the biggest development since its predecessor is the inclusion of multilayer thermodynamics, giving a heat capacity to the sea ice and allowing vertical variation of conduction (Ridley *et al*. 2018). Testing of these two components produced a better simulation compared to its predecessor, with more realistic mixed layer depths in the Southern Ocean and the

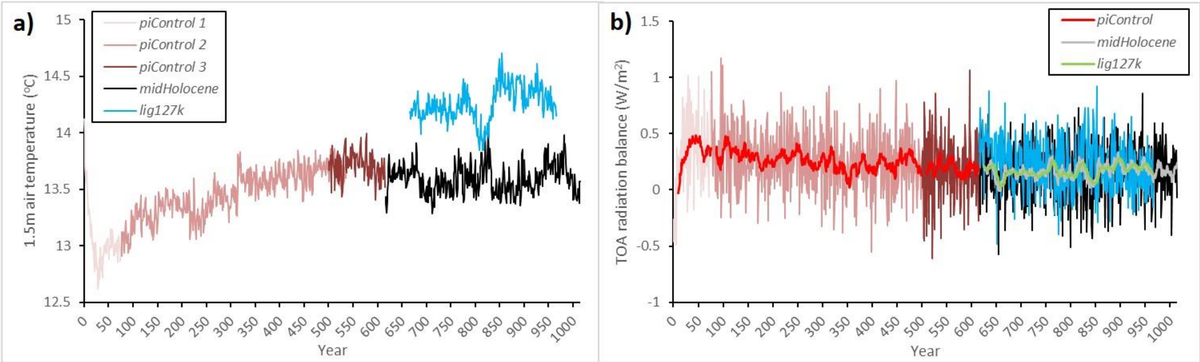
[1] Please see Reference section in main manuscript for citations

aforementioned reduced warm bias, the latter of which was deemed primarily due to the tuning of the different mixing (e.g. vertical and isopycnal) parameters (Storkey *et al*. 2018).

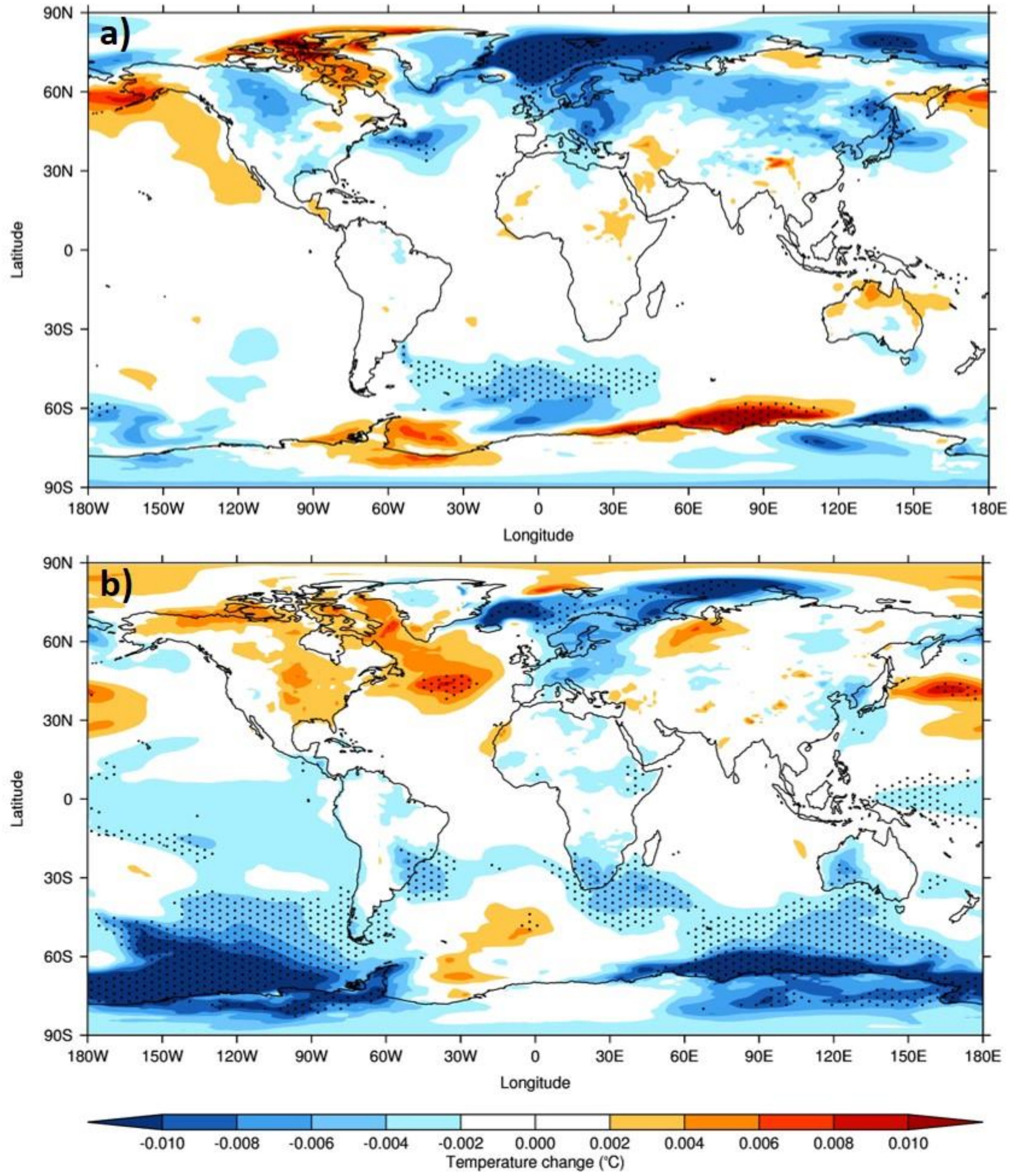
FIGURES



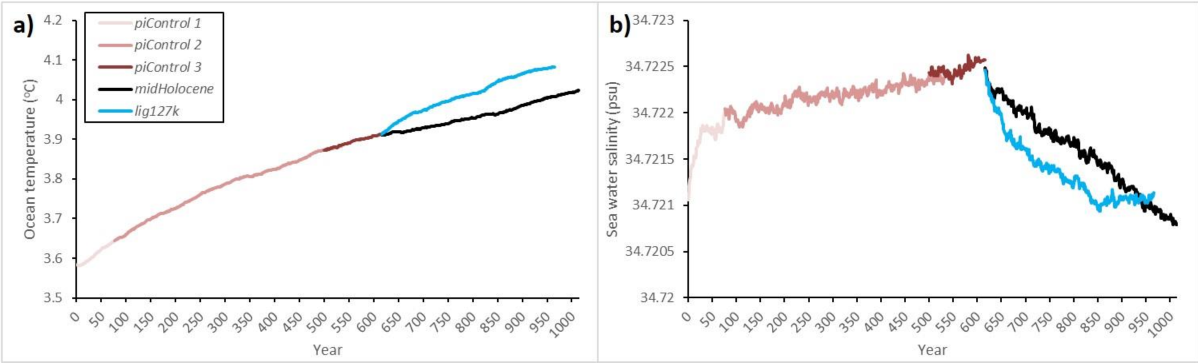
SM1 - Latitude-month insolation (incoming SW radiative flux) anomalies, using modern calendar: a) *midHolocene* - *piControl*; b) *lig127k – piControl*



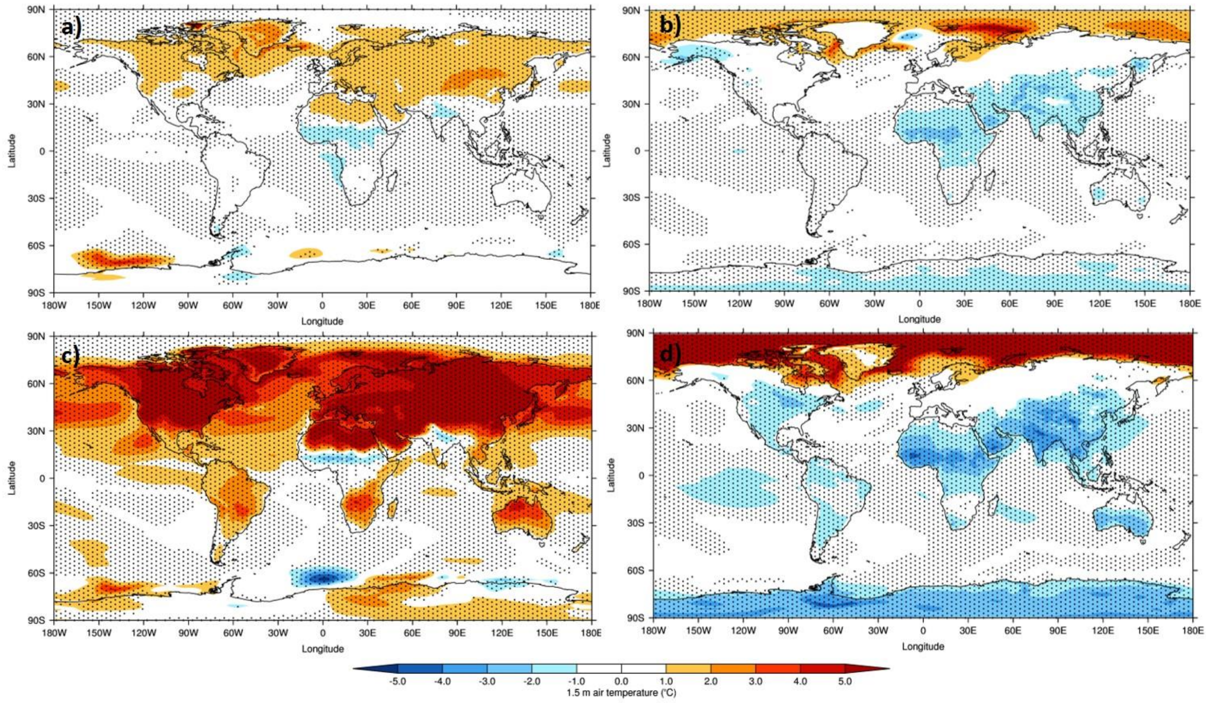
SM2 - Annual global mean atmospheric fields from HadGEM3 *piControl*, *midHolocene* and *lig127k* spin-up phases: a) 1.5 m air temperature; b) TOA radiation balance. Thin lines in b) show annual TOA radiation balance, thick lines show 11-year running mean. Note that the *piControl* spin-up phase was run in three separate parts, to accommodate for minor changes/updates in the model as the simulation progressed. Note also that the first ~50 years of the *lig127k* simulation have been deliberately removed from this figure, because a number of model crashes caused the model to be initially unstable and give highly varied global mean temperatures.



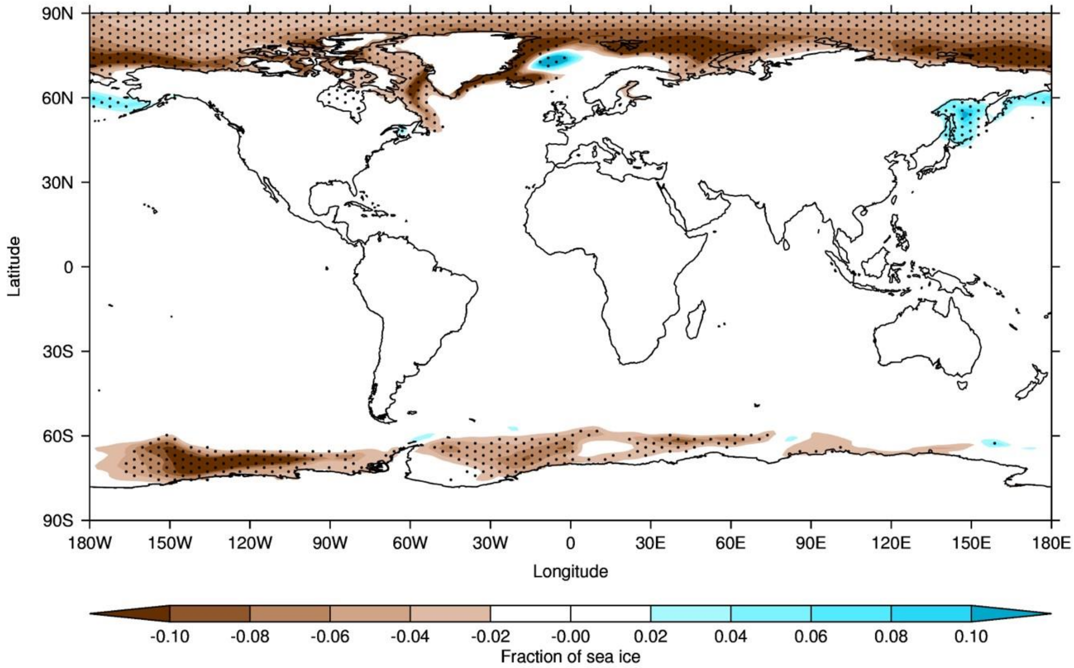
SM3 - Centennial trends in 1.5m temperature for HadGEM3 warm climate simulations' spin-up phases, last 100 years only: a) *midHolocene* ; b) *lig127k*. Stippling shows statistical significance (as calculated by a Mann-Kendall test) at the 99% level



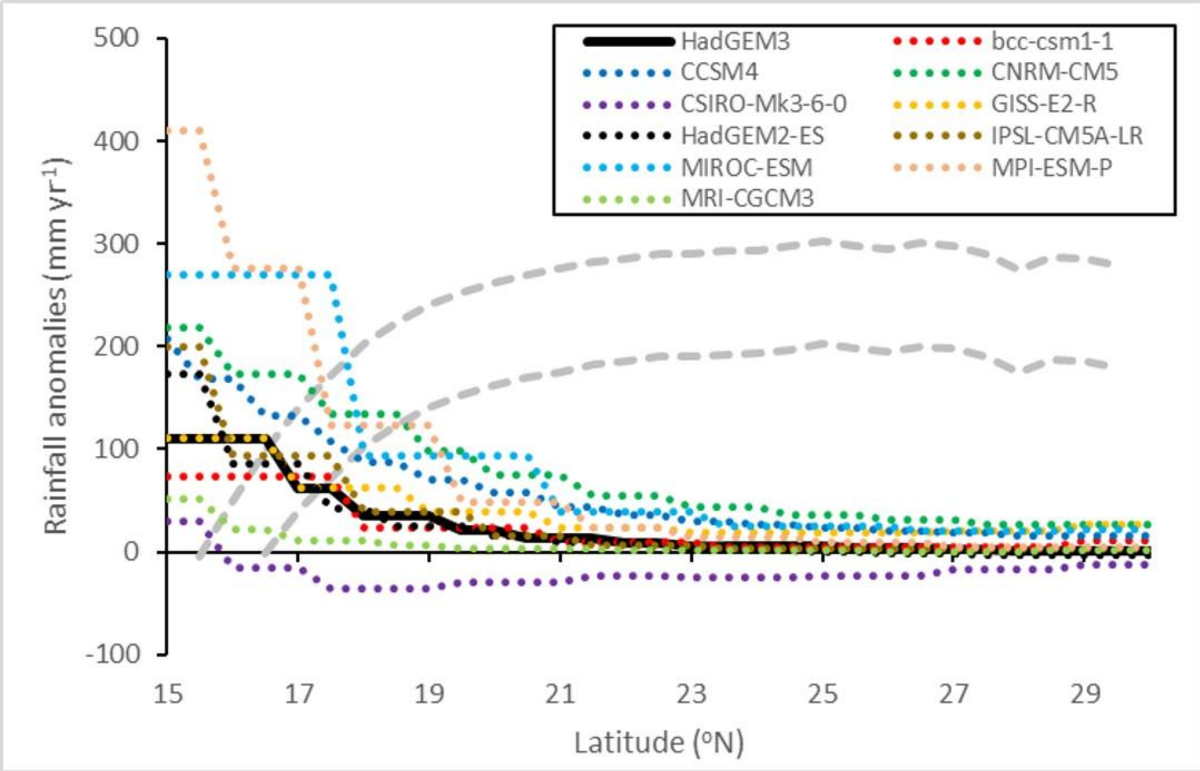
SM4 - Annual global mean (full depth) oceanic fields from HadGEM3 *piControl*, *midHolocene* and *lig127k* spin-up phases: a) OceTemp; b) OceSal



SM5 - Modern calendar 1.5 m air temperature climatology differences, HadGEM3 *midHolocene* and *lig127k* production runs versus HadGEM3 *piControl* production run: a) *midHolocene – piControl*, JJA; b) *midHolocene – piControl*, DJF; c) *lig127k – piControl*, JJA; d) *lig127k – piControl*, DJF. Stippling shows statistical significance (as calculated by a Student's T-test) at the 99% level



SM6 - Annual mean sea-ice climatology differences, HadGEM3 *midHolocene* production run versus HadGEM3 *piControl* production run. Stippling shows statistical significance (as calculated by a Student's T-test) at the 99% level



SM7 - Annual mean rainfall over West Africa (averaged over 20°W-30°E, consistent with Joussaume *et al*. [1999]), HadGEM3 *midHolocene* simulation minus corresponding *piControl*, and likewise for previous models from CMIP5. Solid line shows HadGEM3, dotted lines show CMIP5 simulations. Grey dashes show maximum and minimum bounds of the increase in rainfall required to support grassland at each latitude, within which simulations must lie if producing enough rainfall to support grassland (adapted from Figure 3a in Joussaume *et al*. [1999])