Cp-2018-180 Authors response

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* Please note the interupt and restart of page numbers of the Annotated Manuscript

Anonymous Referee #1

We thank the reviewer for their helpful comments and considerable time spent working on this manuscript. The contribution of reviewer has added substantially to the quality of the manuscript, this is greatly appreciated particularly by the lead author. The level of detail within the review was sincerely appreciated as was the significant amount of time that the reviewer spent on commenting. With regards to the comments, these are addressed in sequence by SJH with input from the co-authors. I (SJH) will start with the general comments and then finish with the line-by-line comments.

1. Remarks regarding the model and simulation description

Could the authors provide in their text on page 3 details regarding the employed model version of the oasis coupler and include the respective reference?
I have removed the term "using the oasis coupler" as this was incorrectly stated for this version of the model. I am working on another project using the coupler so a bit of laziness crept in.

Furthermore shortly after that: I think the description of coupling "every model day" is ambiguous. Do the authors mean that the coupling occurs exactly once per model day? Please clarify the text accordingly I have clarified this sentence by changing it to "The model has a time-step of 30 minutes and is coupled to the ocean model (Section 2.2) at the end of every model day."

On page 3, lines 29/30, the authors state that MOSES2 introduced "improved representation of surface and land processes". Could the authors please elaborate this statement in their text to make clear what kind (and to which degree of detail) respective processes are represented in their model? Giving some respective references would be appreciated.
I expanded the text so that it now reads:
"The land surface scheme is MOSES 2.1 (Met Office Surface Exchange Scheme; Cox et al. (1999); Essery et al. (2003)) which principally deals with the hydrology of the canopy to the subsurface and the surface energy balance (including subsurface thermodynamics). Within the scheme there are 5 plant functional types (PFTs: broadleaf and needleleaf trees, C3 and C4 grasses, and shrub) as well as soil (desert), lakes and ice. Each non-glaciated terrestrial grid cell can take fractional values of each surface type.
The HadCM3 PlioMIP1 study of Bragg et al. (2012) used an earlier version of MOSES (MOSES1) which treats each model grid cell as a homogeneous surface and uses effective parameters to calculate the grid cell's energy and moisture flux. However, MOSES2 introduced subgrid (tiled) heterogeneity and improved representation of surface and plant processes such that hydrological partitioning and energy balance is computed for each subgrid tile. A comparison of MOSES1 and MOSES2.1 can be found within Valdes et al. (2017). In this study we incorporate a software update taken from the HadGEM2 climate model (Good et al., 2013) which corrects the temperature control of plant respiration and improves forest resilience to elevated temperatures (making the model MOSES2.1a in the nomenclature of Valdes et al. (2017)."

The meaning of the statement "upper layer of ocean" on page 3, line 32 is not clear. Do the authors state that the runoff is somehow vertically distributed over the layers of the upper ocean, or is it given exclusively to the uppermost ocean layer? Please clarify the text accordingly.
The phrase "the coastal outflow point in the upper layer of ocean" has been changed to "the coastal outflow point in the uppermost layer of ocean"

On page 4 the authors describe that the ocean model employs z-type cells with bottom topography represented by "full" cells. Does this mean that bathymetry is adjusted so that at the border between ocean and sediment the lowermost "wet" ocean grid cell has always the standard

thickness defined in the model, rather than a thickness adjusted to represent bathymetry as closely as possible – an approach, that is employed in the case of the "partial grid cell" scheme applied by some other models? If indeed the layer thickness is not adjusted to bathymetry, I would imagine that, in addition to the various approximations involved in the generation of the Pliocene bathymetry, there is another substantial approximation in that for deeper regions of the ocean, where the layer thickness is assumedly relatively large, the modified Pliocene bathymetry is significantly changed to fit it to the layer thickness. Could the authors please explain this a bit more detailed in the text?
You are correct in that the bottommost ocean grid cell has a standard thickness (1 of 20 standard thicknesses). When the Pliocene bathymetry anomaly is applied to the modern bathymetry, there will be circumstances when we see changes in the bathymetry (due to the discrete thickness of the ocean grid cells). A similar discretisation occurred when the pre-industrial bathymetry was originally generated for the model using the ETOPO5 data. Therefore, the representation of the Pliocene (and pre-industrial) bathymetry has lower fidelity at greater depths (where the layer thickness is greatest). I have added an additional sentence to the description of the ocean model
"The model uses z co-ordinate vertical layers with bottom topography represented by "full" cells. This leads to a discontinuous representation of the bathymetry which has poorer fidelity at greater depths (where the thickness of levels is greatest)."

Could the authors please add a remark whether the ocean grid is aligned in such way that one atmosphere grid cell covers exactly 6 ocean grid cells (the term "exactly") is not clear to me.
I have clarified the sentence so that it now reads "Horizontal spatial resolution is 1.25 ^{o} x 1.25^{o} (288 x 144 cell geographic grid) and the grid is aligned so that there are six ocean grid cells to each atmosphere grid cell (3.75 x 2.5^{o}).

Furthermore, does the statement "The land-sea mask is effectively 3.75x2.5° resolution in the top 200 m, but beneath increases to 1.25° resolution." imply that there is some kind of horizontal interpolation of vertical fluxes occurring at critical depths? If so, what is the nature of this interpolation?
There is no horizontal interpolation of vertical fluxes as I was referring to the bathymetry. I meant that the land sea boundary (isodepth) at the ocean levels <200m was 3.75 x 2.5° resolution and at >200m it is 1.25 x 1.25° resolution. It is confusing to describe in text and superfluous to the description, so I have clarified the sentence and it now reads
"To simplify coupling with the atmosphere model, the ocean model's coastline has a resolution of 3.75 ^{o} x 2.5^{o}"

The authors describe that they employ a prescribed time-invariant freshwater iceberg field that is omitted for Pliocene simulations. What is not clear to me is whether such omission is also done for simulations E400 and E560, where the climate state is as well much different from the one simulated in E280, for which the modern iceberg conditions are probably optimized or derived. This could be explained, and the respective impact on the interpretation of results could be discussed later on.
This is a good question. I did apply the time-invariant freshwater flux rate (fixed in intensity and geographic distribution) to the E^{400} and E^{560} experiments as it is commonly done when using models of this era within historical and future experiments (e.g. within CMIP3). As you correctly identify, this is not ideal. With increasing CO_2, ocean currents, winds, and ocean and boundary-layer temperatures will change, which will modify the iceberg melt trajectories away from the pre-industrial (altering the geographical distribution of the fresh-water correction). In addition, precipitation patterns (wrt. terrestrial ice and inland drainage basins) will alter, which will subsequently change the extent to which the hydrological cycle requires closure. These components (ice-berg trajectories and precipitation patterns) will act to modify the geographic distribution and magnitude of the required

freshwater correction. I have clarified the text describing the time-invariant freshwater iceberg field as follows (note the emphasis is mine):

"The fresh water budget of the ocean is balanced by fluxes from the river routing scheme and a freshwater correction applied to the uppermost ocean level. Within the pre-industrial (and associated CO_2 sensitivity experiments) the freshwater correction field is prescribed (time-invariant). The correction field had been derived to provided closure of the model's modern hydrological cycle and consists of a uniform background component correcting internal-drainage (Section 2.1) and an iceberg component whose geographic distribution is derived from modern observations (Gordon et al., 2000; Pardaens et al., 2003). Within the Pliocene experiments we omit the time-invariant correction (including the iceberg component) and instead use an annual model-derived geographically-invariant freshwater correction to reduce residual salinity drifts to zero. We justify this as we currently do not have a priori knowledge of the geographic distribution of iceberg melt consistent with the ice sheet distribution within the PlioMIP2 enhanced boundary conditions. In the Northern Hemisphere we do not expect significant iceberg calving given the configuration of the Greenland Ice Sheet and the lack of marine terminating margins specified within the PRISM4 boundary conditions. "

Related to this topic, regarding the artificial closing of the water budget for Pliocene simulations: Is the artificial budget term somehow regionally distributed, potentially weighted with regard to (a modern) salinity distribution of the ocean? Or is it rather a globally distributed residual term? This should be explained in more detail as I expect that depending on how this correction is applied a significant impact on buoyancy-driven ocean circulation cannot be excluded. Furthermore, it may be interesting to state the amplitude of the freshwater flux that is applied in order to close the water budget.
In the Pliocene the correction is applied as a globally distributed residual term. I have expanded the description from
"...use an annual model-derived freshwater correction to reduce residual salinity drifts to zero."
To
"... use an annual model-derived geographically-invariant freshwater correction to reduce residual salinity drifts to zero."
Although I recognise the that this correction will have an impact on buoyancy-driven flow, I think that it is beyond the scope of this manuscript to explore it further. The fresh-water correction is a historic-feature of the model and its impact on the ocean flow is a given

At the bottom of page 4 the authors describe that "Ice drifts only by the action [of] surface ocean current." Does this imply that wind stress has no direct influence on sea ice transport? Please clarify in the text.
Within the model, wind stress acts indirectly on sea-ice drift via its action of the surface ocean current. I have clarified the sentence such that it now reads "Ice drifts only by the action of surface ocean current, hence within the model, surface wind stress indirectly influences sea ice drift via its influence on the surface ocean current."

On page 5, line 9, the authors write that "pre-industrial experiments are run at 280, 400, and 560 ppm". I think this statement may be a bit misleading, as pre-industrial is characterized by CO_2 of around 280 ppm. Would it make sense to rephrase this pointing out that "simulations based on a pre-industrial geography" are run with differing levels of CO_2?
That is a very good point (and the confusion was also picked up by the second reviewer). As you have suggested I have clarified the terminology used to describe these CO_2 sensitivity experiments with "... Within the pre-industrial (and associated CO_2 sensitivity experiments) ..." etc within the manuscript.

On page 6 the authors write that corrections were applied "using a model resolution river routing model". Could details of this procedure be included into the text? Does this, for example, imply eliminating internal drainage basins?
I have added the following text to the manuscript

Within Section 3.2.1 in which you refer to I have expanded the text so that it now reads
"River basins and outflow points were derived from the pre-industrial routing scheme (Section 3.1) but corrected in regions of LSM, topographical and ice-bedrock change using a model-resolution river routing model based on the D8 method (Tribe, 1992) This was then followed by manual correction in regions when model resolution fails to capture important orography or where the regridded Pliocene orography is flat."

And within Section 2.1 (Atmosphere model) I have expanded the description so that it now reads
"Internally-draining basins are present but the associated water loss is not explicitly modelled within the routing scheme. Instead, the loss of freshwater in the hydrological cycle is corrected using an artificial freshwater correction field applied to the uppermost surface of the ocean (Section 2.2). This freshwater closure also acts to correct the freshwater loss due to terrestrial snowfall accumulation.

The authors write on page 6 that a BIOME4-to-MOSES2 lookup table has been employed. I think it is important for the less experienced reader to point out that the PRISM4 boundary condition is based on BIOME4, if I am not mistaken.
You are correct. I have clarified the sentence by expanding it to "The PRISM4 vegetation scheme (represented by BIOME4 biomes) was regridded by combining a BIOME4-to-MOSES2 lookup table with a bespoke LSM-guided regridding relying on an area-weighted survey of underlying biomes."

Could the authors give a reference that explain details of the xancil and um2nc tools mentioned on page 6?
Very good point. I have added a reference to the website that provides access to these tools so that the sentence now reads "All boundary conditions were generated within a bespoke Matlab framework using the MOHC-developed and National Centre for Atmospheric Sciences, Computing Modelling Services (NCAS-CMS) supported xancil and um2nc tools (NCAS 2019)."
I have also subsequently moved this block of text to the acknowledgements.

On page 7 it is described that the CO2 is adjusted via a 1% CO2 ramp like in the respective CMIP6 simulation. Is there a specific reason for this methodology of creating a Pliocene models setup? Please explain.
The described spin-up methodology was implemented as it is consistent with other modelling we have done in the group. For the *modest* CO_2 values used within this manuscript (cf. deep time) we could have used instantaneous changes in CO_2, the impact being on how the model then approaches a state of equilibrium towards the year 2500. Given that the CORE simulations reach a satisfactory state of equilibrium the implementation method for CO2 change is somewhat arbitrary. Our high CO_2 experiments did have higher TOA radiative imbalances and may have benefitted slightly from an instantaneous CO_2 change (as they could have benefitted from a longer integration time). Nevertheless, all our experiments had TOA imbalance which compare favourably to previous Pliocene experiments (e.g. compare our Table 2 to the PlioMIP1 TOA summary provided by Haywood et al. (2013)[1] Table 2)

[1] Haywood, A. M., Hill, D. J., Dolan, A. M., Otto-Bliesner, B. L., Bragg, F., Chan, W.-L., Chandler, M. A., Contoux, C., Dowsett, H. J., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Abe-Ouchi, A., Pickering, S. J., Ramstein, G., Rosenbloom, N. A., Salzmann, U., Sohl, L., Stepanek, C.,

On page 7 the authors explain that the final 50 model years are used for computing climatological averages. Considering the potential presence of slow variability in the model simulations, could the authors state whether results would look different if instead 100 model years are employed? What is the official time period over which PlioMIP2 climatologies shall be aggregated?
I am not sure why we didn't include this in the PRISM4 protocol paper (Haywood et al., 2016[2]), as we did specify a minimum integration length. The MRI-CGCM2.3 study of Kamae et al. (2016)[3] used a 50 year averaging period and the CCSM4 study of Chandan and Peltier (2017)[4] used 30 years. Internally we have looked at the difference between using 50 years and 100 years as averaging periods and it didn't make a big difference.
I have expanded the text within Section 4 to include
"We derive climatological averages from the final 50 years (model years 2450 through to 2499) and climatic oscillations from the final 100 years. The final 50 years of output is used for climatological averaging to remain consistent with the HadCM3 PlioMIP submission (Exp. 2 of Bragg et al. (2012)). The PlioMIP2 protocol (Haywood et al., 2016) does not state a standardised time length for climatological means although the PlioMIP2 website (USGS, 2018) does request 100 years of monthly climatology. We therefore make the 50 year climatological average and 100 years of monthly climatology available on the PlioMIP2 data repository."

2. Remarks regarding derived results and interpretations made by the authors

Regarding Fig. 2: It is not clear to me which simulation is represented by the data – or is it an average over various simulations? Please add this information to the text.
I have clarified Figure 2 caption so that it now reads "Time-evolution of the globally-integrated temperature for the ocean layers within Eoi^{400} experiment."

On page 9, lines 4 and five one could add to the results of Climate Sensitivity (CS) the statement that due to the overlap of variability ranges there is no significant difference between the model CS for the different climate states. Furthermore, based on rough calculations of presented numbers: Should the result 2.9°C for Pliocene CS should rather read 2.8°C?
This has been corrected.

Significant digits: I think the ESS/CS ratio should be 1.9°C rather than 1.90°C to honour the limited precision of the value used to compute that ratio. I agree.
This has been corrected

On page 9 the authors write that they "neglect" changes in topography and land sea mask. Would the meaning of the sentence get clearer if it was changed to: "... hence assuming consistency of ice sheet topography and land sea mask with the (simulated or in the boundary condition assumed) climate state"?

Ueda, H., Yan, Q., and Zhang, Z.: Large-scale features of Pliocene climate: results from the Pliocene Model Intercomparison Project, Clim. Past, 9, 191-209, https://doi.org/10.5194/cp-9-191-2013, 2013.

[2] Haywood, A. M., Dowsett, H. J., Dolan, A. M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M. A., Hunter, S. J., Lunt, D. J., Pound, M., and Salzmann, U.: The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: scientific objectives and experimental design, Clim. Past, 12, 663-675, https://doi.org/10.5194/cp-12-663-2016, 2016.

[3] Kamae, Y., Yoshida, K., and Ueda, H.: Sensitivity of Pliocene climate simulations in MRI-CGCM2.3 to respective boundary conditions, Clim. Past, 12, 1619-1634, https://doi.org/10.5194/cp-12-1619-2016, 2016.

[4] Chandan, D. and Peltier, W. R.: Regional and global climate for the mid-Pliocene using the University of Toronto version of CCSM4 and PlioMIP2 boundary conditions, Clim. Past, 13, 919-942, https://doi.org/10.5194/cp-13-919-2017, 2017.

I have made the sentence more specific so that it now reads
"It must be noted, however, that this calculation assumes that the PlioMIP2 enhanced boundary condition *represents* the equilibriated Earth System under a contemporary doubling of CO2, hence neglecting non-glacial elements of the PRISM4 retrodicted palaeogeography."

On page 11, line 28 it is stated that sea ice extent is significantly suppressed within the Weddell Sea – is the significance of the change really shown?
I think Figure 10(f and h) shows adequately the reduction in sea ice in the Weddell Sea (to the East of the Antarctic Peninsula) due to the change in palaeogeography. I have enlarged Figure 10. It is untidy if subfigures are referenced within the text e.g. "..(Figure 10h vs.10d and 10f vs. 10b).."

In the context of Section 4.2.3 I believe Fig. 11 should be referred, otherwise the textual description of results is difficult to follow.
This has been corrected so that the sentence now reads
"The mixed layer depth (MLD) for E^{280}, Eoi^{280} and Eoi^{400} is shown within Figure 11."

The statement on page 12, line 16, that the difference in AMOC can be ascribed to the earlier use of HadCM3 MOSES 1 seems to be a bit uncertain. As there are no variability ranges given by Bragg et al. (2012), one can only speculate whether there are significant differences between the AMOC values, or whether there is an overlap of both results. The authors elaborate later on that the original time series of AMOC by Bragg et al. (2012) are lost, impeding the computation of the old error ranges. Yet, this problematic should be mentioned here when ascribing a change in a result to a difference in the model version.
I agree this is unsatisfactory. The lack of temporal data from the Bragg et al., 2012 study did cause me problems. I have removed reference to the Bragg paper within this paragraph (Section 4.2.4) and the Discussion (Section 5)

On page 12, line 17, it is stated that the maximum AMOC strength is at about 1000 m depth. By eye Figure 12 suggests a rather shallower depth. Please verify and correct if necessary.
This has been corrected to ~650 m depth.

In the same line the authors write about "Fluctuations of the order in the AMOC", without specifying the order of the fluctuations. It is also not clear what the difference in Mid-Pliocene and PI fluctuations should be. I at least do not see an obvious difference from the presented results. Please clarify.
My apologies for this omission. Currently I am unsure what is causing this difference in AMOC behaviour. Nevertheless, I have corrected and restricted the sentence so that it now reads "Multidecadal to centennial fluctuations, including a dominant ~225 year oscillation, within the $AMOC_{max}$ are present within the Pliocene experiment but not in the pre-industrial experiment."

On page 13, line 12, the authors state that ACC strength appears significantly reduced in Pliocene experiments. Looking at the conveyed data, I get the impression that also the variability over time is reduced in the simulations. Is this impression correct? If so, I would state that as well in the text, and maybe discuss the implications for the Pliocene circulation regime in the Southern Hemisphere.
That is an interesting point. Table 8 does indeed show higher variability within the ACC for lower CO_2 levels. I am hesitant to discuss the ACC in more detail within the manuscript as I have written a lot about the ACC already. Also, there are some interpretational difficulties associated with the ACC model output (which I discuss) and so I think that discussing its variability (to CO_2 sensitivity) is beyond the sections scope.

In sections 4.3.1 and 4.3.2 the authors elaborate on the statistical significance of differences between simulations with differing orbital configuration and TSI. I have to admit that I got a bit lost here. While the statement seems to be that there are statistical differences, my impression from the values given in the various tables is that simulations with different orbital parameters and TSI indeed show different mean values of respective quantities, but that in many (if not all) cases there is an overlap of the given variability around the mean value. Based on this observation I would assume that there is no statistical difference. Could the authors please clarify this in the text? I might have misunderstood their reasoning, but the matter is not yet clear to me.
For orbit and solar insulation there are no statistical differences within the standard climatic fields (MASAT, MAP, MASST etc. and PMOC) I have clarified Sections 4.3.1 and 4.3.2 to make this point clear. The simulation data does suggest the possibility that that there is statistical difference within the AMOC

In the discussion the authors state that the primary control on ESS/CS ratio is the reconstructed ice distribution and global vegetation coverage. Assuming a prescribed vegetation, this is certainly the case. Yet, there are also modelling groups that will likely provide simulations with dynamic vegetation. Hence, the statement made by the authors could be explicitly tested in PlioMIP2. I would add some according remarks to the discussion section.
I agree and have added the following sentence to the Discussion section '"The implementation of dynamic global vegetation models by PlioMIP2 participant groups will allow investigation of the sensitivity of ESS/CS to vegetation-climate feedbacks."

On page 15, line 19 following. I am not sure whether details and results of simulation Ei280, that is not considered in the manuscript, should be discussed here. Either, the relevant results should be explicitly shown somewhere before, or the results and discussion should go into the follow-up manuscript. Similar statement holds for the mentioned simulation Eo400.
My sincere apologies for the confusion as these were simply spelling mistakes. These have been corrected to Eoi^{280} and Eoi^{400} respectively.

The statement on page 15, line 26/27, that the findings are in contrast to Zhang et al. (2013): Is there really a contrast? Zhang et al. (2013) shows various models that have a stronger Mid-Pliocene AMOC. So aren't your results somehow in line with findings by Zhang et al. (2013)? AND On page 15, line 30, you state that "looking at typical HadCM3 (MOSES2) AMOC variability within Table 7". Where do I find this information in Table 7 (or somewhere else)? The understanding of the whole sentence in reference to PlioMIP1 is lacking to me.
I agree, this was a co-authors suggestion for inclusion but they had incorrectly remembered the premise of this paper. I have removed reference to Zhang et al., 2013. As discussed previously I have also removed reference to Bragg et al., 2012 wrt. AMOC within the Discussion (Section 5).

3. Remarks regarding quality of the presentation of results

Regarding labels (a, b, c, ...) of subfigures: All subfigures are clearly labelled, which is very good. Yet, in very few cases the caption clearly defines what simulation, time average, etc. a label refers to. Instead, in many cases a heading is given for the subfigure that illustrates that information. As far as I know the use of labels is the preferred option for publications in Climate of the Past, rather than a subfigure heading that often reduces the space available for the illustrations themselves. If the authors choose to keep subfigure labels (which I strongly support), I would make sure that the meaning of a label is clearly defined in the figure caption.

I have ensured that the Figure caption clearly identifies each subfigure. I have also left in the subfigure label. In accordance with the second reviewer I have also made the text larger within each subfigure graphic.

There is a prominent switch in the terminology employed in the various tables of the manuscript. In Table 1, the first column is headed "ID", but in following tables it is headed "model". One may argue which is the better term (I would opt for ID to avoid potential overlap with the term 'climate model', which is consistently HadCM3 for all simulations) – but at least the employed term should be consistent across tables.
I agree with you. To remain consistent with the PlioMIP2 protocol (e.g. Table 3. Within Haywood et al., 2016) I have used "ID" within all the tables.

The authors state at the beginning of Section 4.1.2 that MAP is influenced principally by geography and land surface changes and is relatively insensitive to Pliocene CO2 changes. Is this statement supported by the presented results (difference between results for Eoi^{280} and E^{280} is only 0.07 mm/d, which is somehow in the range of the change created by modifications in CO_2)?
I agree, a good point. I was originally trying to refer to the geographic distribution of the precipitation. I have rephrased the Section on precipitation so it now starts
"The globally integrated Mean Annual Precipitation metric (MAP; Table 4) is influenced by both Pliocene geography and CO_2 changes. Pliocene geography acts to increase globally integrated MAP although this appears sensitive to the background CO_2 level (e.g. Pliocene geography increases MAP by 0.07 and 0.05 mm day^{-1} at 280 and 400 ppm respectively). The geographical distribution of MAP change can be seen within Figure 5."

In the same section, it is stated that regions with little change in precipitation are regions that receive little precipitation in E280. Isn't this statement in contrast to the results derived for the rather large region of Eurasia?
Eurasia within E280 receives a fair amount of precipitation (it is not dry like the North Africa or the East Antarctic Ice Sheet). The statement therefore doesn't refer to Eurasia. The ordering of statements within my sentence was the source of confusion, so I have changed it from
"Regions that have little (<0.1 mm day-^{1}) change in precipitation under increasing Pliocene CO_2 are regions that receive little precipitation within E^{280} e.g. North Africa and the East Antarctic Ice Sheet"
To
"Regions that receive little precipitation within E^{280} e.g. North Africa and the East Antarctic Ice Sheet have little (<0.1 mm day^{-1}) change in precipitation under increasing Pliocene CO_2."

On page 9, at the bottom, and on Page 10 up, the authors describe the simulated monsoon. I have to admit that the statements were difficult for me to verify and to follow based on the presented anomaly results. Am I right that showing an additional Figure with (seasonal) absolute fields of precipitation (MAP) for E280 would help to solve this problem?
We removed the monsoon text as we believe that this would be more appropriate in a separate paper that allows the complexities of monsoon systems to be fully articulated and investigated.

The change in the northern cell (by +10.8%) is difficult to identify in Figure 7, even when zooming in on the screen. This should be fixed if possible.
I have made the subfigure axis labels larger and have made this figure within the manuscript. I have also expanded the description of the figure by indicating the Polar, Ferrel and Hadley cells. Within E280 the stronger northern Hadley cell can be seen as a stronger shade of red.

The stated moving of the jet stream mean path from northern to southern Europe is very difficult to see in Figure 8.
Within the text I have pointed the reader to compare Figure 8b vs. 8f. I have also made Figure 8 a little larger within the manuscript.

The statement on the more continuous counter current in the Pliocene (Fig. 14, stated on page 13, line 29) is difficult to interpret from the illustrations as individual arrows of the streamlines are difficult to see.

I have enlarged slightly the figure so that the reader can see the enhanced Pliocene counter current between 90 and 180^{o}E

I would like to point out that in my opinion the discussion provided by you regarding uncertainties due to setup of the Pliocene boundary condition – despite a common modelling protocol – is very important. In addition, I think one could elaborate (a bit more than already done) why the question after analogy or non-analogy of the Pliocene climate to modern or future conditions is so important in the context of Pliocene for future (P4F). I think references could be cited, e.g. Hill (2015) may be of relevance here.
I have expanded the within the final paragraph of the discussion.
Palaeogeographic induced changes in mean state, for example the path of the Antarctic Counter Current around the Peninsula island (Section 4.2.5) represent non-analogous characteristics imposed by the PRISM4 Pliocene reconstruction. Other potentially non-analogous changes are associated with palaeogeographical changes to the Maritime continent and subsequent changes in Indonesian throughflow configuration, the closure of the Bering Strait and Canadian Archipelago, and the withdrawal of the Baltic Sea and Hudson Bay. These palaeogeographical changes should be considered alongside those described within Hill (2015) such as the suggestion of extensive uplift in the Barents Sea (e.g. Knies et al. (2014)) and the rerouting of major rivers (e.g. within North American) which may be currently unrepresented within the model. These important regional changes must be considered when considering the KM5c time slice as an equilibrium state analogue to contemporary climate change (i.e. a 400 ppm world).

Page 21, Figure 1: I would add the term “streamfunction” after (the non-capitalized) term “barotropic” for consistency with the heading of section 3.2.2.
I have corrected the text within the Figure 1 description

Page 22, Figure 2: It is not clear which simulation is shown here. Add space between the subfigures. Maybe enlarge them and put them on top of each other. Would it be possible to give the depth information in addition to the layer information? Regarding the caption: I would add a “various” before “ocean layers”, make the comma after “spin-up stages” a colon, change “souther” to “southern”, and remove the hyphen of “high-latitudes”. “Incorporation”, “Correction”, and “Ocean layers” should in my opinion not be capitalized.
I have altered Figure so that only the first figure is shown. I have also changed the figure description so that it now reads
“Figure 2. Time-evolution of the globally-integrated temperature for the ocean layers within the Eoi400 experiment. Whole ocean volume indicated by the thick red line and the top 200 m indicated by the thick green line. Vertical lines indicate key spin-up stages; (a) adding the barotropic physics to the ocean model, (b) incorporation of barotropic streamfunction islands into the barotropic solver, and (c) correction to the barotropic streamfunction island in the southern high-latitudes and incorporation of full PRISM4 vegetation boundary conditions into the model. The mid points to the ocean layers are 5 m (L1), 15 m (L2), 15 m (L3), 35 m (L4), 48 m (L5), 67 m (L6), 96 m (L7), 139 m (L8),

204 m (L9), 301 m (L10), 447 m (L11), 447, 666 m (L12), 996 m (L13), 1501 m (L14), 2116 m (L15), 2731 m (L16), 3347 m (L17), 3962 m (L18), 4577 m (L19) and 5195 m (L20)."

Page 23, Figure 3: The physical unit is not given. Should "MAT" read "MASAT"? Should "student" be capitalized? There is no reference in the caption to subfigures a) to f), and there is no information in the caption that also two different Mid-Pliocene realisations are shown here.
Page 24, Figure 4: May it be that the figure is not explicitly referenced and used in the text? Could it be that captions of Fig. 3 and Fig. 4 where mixed up? Please check and correct if necessary. The physical unit is missing. Add reference to subfigures.
I have corrected the text within the Figure 3 description to read MASAT and capitalised "student". I have added physical units to all Figure color scales. I have also edited the caption to refer to the subfigures. Note also the Figure 3 and Figure 4 graphics were incorrectly swapped over within the manuscript.

Page 25, Figure 5: Add reference to subfigures in the caption and fix capitalization of "Mean Annual Precipitation".
I have corrected the text within the Figure 5 descriptions and references the subfigures within the Figure caption.

Page 26, Figure 6: I noticed that there is a gap in the stipples around the 0°E meridian (also the case for at least Fig. 5). Are stipples shifted or is there a data gap, and what does that mean for the interpretation of stipples in comparison to the shaded values? Add reference to subfigures in the caption.
I have added reference to the subfigures within the Figure caption. The small gap at the 0E meridian is a NCL problem and I am currently unable correct this.

Page 27, Figure 7: The plots are too small, maybe put on top of each other and enlarge. Add reference to all subfigures in the caption. Replace "every" by "shown for intervals of". Is the statement "ascending air moves southward" only true for counter-clockwise flow?
I have enlarged the axis text within each subfigure to make it more clear. I have also made the figure larger and identified the cells within the first subfigure (described within the Figure caption)

Page 28, Figure 8: Is there any way to enlarge the figure a bit more? Some details are difficult to decipher from the rather small plots. Point out in the caption that left is Northern Hemisphere, and right is Southern Hemisphere. Remove space in the superscript of simulation E280. Employ the defined abbreviations consistently throughout the caption. Add "by" after "typology", "the" after "Note", and "but" before "instead".
I have made the Figure larger and have enlarged the text. In response to reviewer 1 I have made the latitudinal extent of the north pole plots the same (and similar for the south pole)

Page 29, Figure 9: The physical unit is missing. Could you explain (and correct if necessary) why there are two definitions for the warm pools applied (28°C and 28.5°C), also with respect to Table 6? Remove the "s" from "indicates", add a "the" before E280, capitalize "Pliocene", and change "have contrasting land surface" to "have land-sea contrast". Add information on the criterion for the decision on statistical significance of anomalies.

Within the literature the global warm pool was defined as the 28.5°C isotherm whereas the regional warm pools were defined as 28 °C. For internal consistency I have recomputed the global warm pool as 28 °C (Figure 9 and Table 6)

Page 10, Figure 10: I think the labelling and the respective reference in the caption is incomplete (that is certain) and potentially also wrong. Capitalize "Southern Ocean".
I have corrected the subfigure referencing within the caption and capitalized "Southern Ocean". I have also increased the subfigure heading text size and increased the size of the Figure within the manuscript.

Page 31, Figure 11: The unit is missing. Give details of subfigure-label relation in the caption. Could you please elaborate (in the main text) why March and September means where shown in the plots, rather than, for example, boreal spring and boreal autumn?
I have added the unit to the colour scale. March and September were chosen to keep consistent with other modelling studies looking at the MLD that I had read. These months were chosen to correspond with the maximum in sea ice extent.

Page 32, Figures 12 and 13: The figures are too small, maybe combine them on top of each other. Add an "N" to the x-axis labels. The units are missing. Please specify the time interval that the data average represents (100 yr multiannual means? Maybe also consider this for other figurs). Note the flow direction (e.g. clockwise circulation given for positive values). Maybe put the subfigure captions at a different location, they are difficult to read for PMOC plots. Add a space after (PMOC). Add the term "Meridional" before "Overturning".
I have enlarged Figures 12 and 13 and modified them so superfluous axis elements are removed. I have added the units to the colour scale bar. I have corrected the text of the figure captions and included the definition of the flow direction. Within the introduction to the results I removed the "We derive … climatic oscillations from the final 100 years" as this was now unused. This now reads "We derive climatological averages from the final 50 years of each simulation (model years 2450 through to 2499)." This clears up uncertainty associated with the averaging period.

Page 33, Figure 14: The physical unit is missing (maybe cm/s?). Do not capitalize "Mean Annual". Remove the "the" before (c).
I have added the unit, decapitalized "Mean Annual" and removed the "the".

Page 34, Figure 15: Define abbreviation MAT, and do not capitalize the words for a), b); c), d); e), f). The units are missing.
I have added units to the colour scale bars to each sub plot. I have also used the abbreviations MASAT, MAP and SST to remain consistent with the manuscripts

Page 35, Table 1: There is a problem with the text below the table ("our standard a discussion ...").
I have corrected the Table 1 sub caption text.

Page 35, Table 2: Do not capitalize "Climatological". Consider to use "ID" as heading for the first column (also for all subsequent tables).
I have decapitalised "Climatological". I agree with the use of "ID" and so have corrected this within all the tables.

Page 36, Table 3: Do not capitalize the m of "1.5 M". Could you provide the definition of polar and tropical regions as used in the analysis? Do the terms follow standard definitions? Add the

physical unit to the third column. I am a bit puzzled that the standard deviation of the third column is 0.7 °C for all simulations. Is this correct or is this a mistake?
I have corrected the table and added definitions to Polar and tropical MASAT within the table caption

Page 36, Table 4: Do not capitalize "Annual".
I have corrected the Table 4 caption text.

Page 36, Table 5: Define abbrevation StJ in the first line of the caption, and apply it in the second line of the caption.
I have corrected the Table 4 caption text to include the abbreviation

Page 37, Table 6: Fix the typo in "charactersistics". Below the table, clarify why the warm pool criterion is 28°C (rather than 28.5°C as given for the respective SST figure). In the first line below the table, there is a word missing towards the end of the line (maybe 28°C-criterion?). In the third line, I think one should adjust the text to "mean area that is at 28°C or above".
I have corrected the typo. Within the literature the GWP had been defined by the 28.5°C isotherm. To avoid confusion within the manuscript I have made the definition of the warm pools consistent within the manuscript so that they all are defined by the 28°C isotherm. Tables and Figures have been recomputed to reflect this change.

Page 37, Table 7: In the column headings, fix the superfluous space between "AMOC" and the subscript "max", add °-symbols to "N" and "S", and maybe change ">500 m" to "below 500m" . Specify the meaning of values given in rectangular brackets of the last column. Define +ve and -ve PDW. Fix typo in "meriodonal". Is the abbreviation MOI used? Link the incomplete sentence "Pacific Meridional Overturning Circulation (PMOC)" to the rest of the text.
I have removed the superfluous spacing in the heading caption, corrected the symbology and changed ">" to "below". I have removed the Delworth et al., 1993 citation as the MOI abbreviation is not used within the manuscript. I have rewritten the Table caption.

Page 38, Table 8: Fix naming of the current (see my discussion at a different location). Do not capitalize "Mean" and "Barotropic". Make sure that the plus-minus sign is not separated from the 50% value via a line break.
I have corrected the naming of the ACC and the capitalisation within the Table caption

Page 38, Table 9: Fix capitalization.
I have corrected the capitalisation

4. Referencing

There are various references in the text that do not appear in the list of references at the end of the manuscript, which makes it unlikely for the reader to find the referenced literature. Respective references are often also wrongly formatted (e.g. with respect to use of comma between authors and publication year). I have found at least the following references that definitely need to be added to the list of references:
Johns et al. (2001); Matthews et al. (2016); Levitus and Boyer (1994); Edwards (1989); Wilson and Henderson-Sellers (1985); Randall et al. (2007); Stachnik and Schumacher (2011); Archer and Caldeira (2008); Koch et al. (2006); McCarthy et al. (2015); Jackson and Vellinga (2012); Delworth et al. (1993)
All the references have been corrected and doi's have been included in as much as possible.

The Lie and Xie (2014) is now not cited.

5. Language- and nomenclature-related remarks

The authors employ various abbreviations, which is fine. Yet, not all of the abbreviations are defined in the text, and respective definitions are even rarer in the captions to figures and tables. While it is difficult to decide which abbreviations can be assumed to be understood by the readership, I would suggest to strictly define them all – in particular to ease understanding of the work by non-experts of the subjects of Pliocene, PlioMIP, CMIP/PMIP, and IPCC, that hopefully will also be attracted to reading this work in the context of informing themselves about the potential relevance of Pliocene climate for projections of the climate of the future. I would suggest to make sure that the following abbreviations are defined: HadCM3, PRISM4, GCM, CMIP3, IPCC, AR4/5. I may have overlooked some more, so ask the authors to once more check the completeness of the definition of abbreviations used throughout the text.
Another important remark regarding abbreviations: Please define abbreviations at the first occurrence of the text and only there, and, once defined, use them in all cases. Exceptions are the abstract, figure and table captions where abbreviations used in the respective text unit should be redefined regardless of their appearance in the main text (the latter is not everywhere the case). One case, where abbreviations are not consistently used, are the terms Figure (also used as Fig. and Fig) and Table (also used as Tab.). Another example is the abbreviation LSM for land sea mask, that is defined for the first time on page 6, while the full term is used various times on preceding and following pages. Similar problems are with polar jet (PJ) and Subtropical Jet (StJ) as well as with the term sea surface temperature (SST).
I agree. At the first instance if have defined the abbreviation in full. Where required, I have also defined the abbreviations within the table captions, so that the tables can be considered stand-alone and self-describing.

Nomenclature regarding simulations: It must be made more clear what the authors mean with the term 'control' Pliocene experiment. In the abstract that term is used without explanation. While I assumed that 'control' stands for 'CORE' (the Eoi400 simulation), and then was surprised by the apparently rather small difference in global mean surface air temperatures that the HadCM3 Eoi400 CORE simulation assumedly provides if compared to E280, digging deeper into the text reveals that 'control' rather refers to simulation Eoi280. This is confusing even if one has the list of simulations (and simulation names) as proposed by Haywood et al. (2016) at hand. Maybe avoid the term 'control' altogether to avoid confusion and rather refer to the standard simulation names. Or, if you intend to use the term, make sure that it is clearly defined.
Within the Experiment Design section (Section 3), in which I use PlioMIP2 terminology, I tie the PlioMIP2 CORE experiments to the standard use of the term "control"
"These experiments are labelled the *control* Pliocene experiment Eoi^{400} (PlioMIP2 CORE), $Eoi^{350,450}$ (Tier 1; P4F+P4P), and Eoi^{280} (Tier 2; P4F)." [...] "These are identified as the *control* pre-industrial experiment E^{280} (CORE), E^{400} (Tier 2; P4F) and E^{560} (Tier 1; P4F). "

I use the term CORE when in sections discussing the PlioMIP2 experiment but stick to "control'" within the text describing the results.

It is not fully clear to me what climatic quantity the authors refer to when they talk about "air temperature". At one point of the text an air temperature at 1.5 m height above the ground is mentioned, but it is not clear to me whether all results in the text, in tables, and all air temperature illustrations in the various figures refer to this height (or maybe to a different height, like 2 m, or even to the surface skin temperature). This could be clarified if the height above the ground was specified together with a definition of the term surface air temperature at the earliest convenient location of the text, and if subsequently that definition is consequently applied throughout the text.
There are various definitions of SAT (MAT, MASAT, SAT?) – my feeling is that they all refer to the same quantity – if so, please use only one abbreviation.
At the earliest opportunity I have defined MASAT as the mean annual 1.5 m surface air temperature (Section 4.1.1 Surface Air Temperature and Climate Sensitivity). The abbreviation MASAT is then used throughout the manuscript.

There is a problem with the term Antarctic Circumpolar Current (ACC) in Section 4.2.5 and related text. The section is headed "Antarctic Circumglobal Current", and that term appears to me at least to be unusual. Furthermore, at some locations the term Antarctic Circumpolar Current is used then anyway, although not abbreviated. Last but not least, understanding the text becomes even more complicated due to the appearance of the terms Antarctic Counter current and counter current, the former one could equally be abbreviated as ACC. The latter terms are to my knowledge different from the former terms, and rather refer to the near-coast flow in opposite direction to the ACC. This section left me puzzled with regard to the currents that were referred to in the various locations of the text. May I kindly ask the authors to overhaul this part of the text in order to clearly define ACC, Antarctic Circumpolar Current, and counter current?
My embarrassing and somewhat random use of the term "circumglobal" in relation to the ACC is due to my focus on Cretaceous climates (as in the *Tethys circumpolar current*). I have corrected this within the manuscript. With regards to my use of the term "Antarctic counter current", I have changed this to its formal name, "Antarctic Coastal Current".

Definition of time periods: There are at least two versions of the term pre-industrial period employed in the manuscript (pre-industrial and preindustrial). I would use only one, and in addition define once that it refers to simulation E280 (this has not been done if I am not mistaken). Furthermore, within PlioMIP there are various terminologies regarding the Pliocene time slice: Mid-Piacenzian (e.g. Dowsett et al., 2016), Mid-Pliocene (e.g. Haywood et al., 2016), and Pliocene (employed by the authors of this manuscript). If the term is defined clearly in the manuscript at the earliest available convenience, then in my opinion all three are suitable choices. Yet, the reference to the alternative term in the discussion on page 15 is in my personal opinion a bit late.
All instances of "preindustrial" and "Pre-industrial" have been corrected to "pre-industrial". I have ensured that the pre-industrial referred to the E^{280} experiment only once. Within the introduction of Section 1 we now explain our use of the term "Pliocene" with the following:
"PlioMIP2 focuses on a 'time slice' centred on an interglacial peak (MIS KM5c; 3.205 Ma) within the mid Piacenzian, for convenience we refer to this as the *Pliocene*."
In the results section I have then used the term Pliocene throughout. An exception to this is when there is a requirement to be more specific in a temporal sense (e.g. discussing uncertainty in the CO_2 record or orbital configuration).

There is quite a variety of the use (or non-use) of spacing of physical or geographical units from the respective value (X) and within the units themselves. I think the text would look much cleaner after a respective overhaul. I think that there should never be a space within physical units, also to avoid that part of the unit is separated and put into the next line in the proximity of line breaks. Here some of the examples that I found: […]

I have made the following corrections
All double spaces have been changed to single space
All instances of $W\ m^{-2}$ changed to Wm^{-2}
All instances of X % changed to X%
All instances of space between ~ and X removed
All instances of X^{0} corrected to X^{o}
All instances of "-hPa" corrected to " hPa"
All instance of "~ X" changed to "~X"
All instance of "> X" changed to ">X" and "< X" changed to "<X"
All instances of "preindustrial" and "Pre-industrial" changed to "pre-industrial"
All instances of "Core" or "core" in reference to PlioMIP2 experiments has been changed to "CORE"
Instances of "ice-sheet" changed to "ice sheet"
"Northern/Southern Hemisphere" capitalised
The "sea" in "Barents Sea" capitalised
The "south" in "South Pacific" capitalised
The "polar" in "Polar cell" capitalised
"warm pool" decapitalised throughout
"mixed layer depth" decapitalised throughout
"Nordic Seas" capitalised
"Drake Passage" capitalised
"barotropic/baroclinic" and derivatives decapitalised
Instances of "through flow" and "through-flow" have been changed to "throughflow"

<additional>
I have replaced all instances of "*ppmv"* with "ppm"
I have replaced all instances of "sub grid" with "subgrid"
I have replaced all instances of "hand corrections" to "manual corrections"
For consistency I have replaced all instances of "Tab." With "Table"

P1L1 Changed "*athe"* to "*the"*
P1L4 Added a comma after "*ocean state*"
P1L5 Added "*and various related sensitivity studies*" after "*Pliocene experiments* "
P1L7/8 I have added "*(*Eoi^{400}*)"* and "*(*E^{280}*)"* to clarify the stated experiments
P1L9 I have added a "*of*" between "*ratio*" and "*~1.90*"
P1L10 The text "*wet-get-wetter*" has been removed from the manuscript.
P1L15 Comma deleted after PlioMIP2
P1L17 I have changed the occurrence of "*the total solar irradiance choice"* to " *the choice in total solar irradiance value*" [and also altered within P6L13 and P27L20]
P1L18 I agree with Reviewer1 here and have changed "climatic systems" to "components of the climate system"
P1L20 I have removed the superfluous space and have changed the semicolon to a colon

P1L21 I have changed "*uses*" to "*use*", added a "as", and changed "c*ontemporary*" to "*future*" so that the sentence now reads "*...has dual focus: to serve as a means to improve understanding of Pliocene climate and also, through its use as a potential analogue for future climate, as a means to evaluate climate model uncertainty."*
P1L22 This section has been rewritten.
P1L24 I have removed the definitions of abbreviations T1 and T2 as the abbreviations are only used within Table 1 in which they are described within the caption
P2L3 I agree. I have added "*model*" between "*additional*" and "*sensitivities*"
P2L9 I agree. I have changed "*This leads onto the .."* to "*This leads onto to descriptions of the .."*
P2L11 I have inserted "*section*" after "*results*" and rephrased "atmospheric and surface climatology" to "*atmospheric circulation and surface climatology*". I have also inserted "focussing on", so that the sentence now reads "*...with the atmospheric circulation and surface climatology (Section 4.1 and then focussing on the oceanic realm (Section 4.2)."*
P2L14 I have capitalised "*Model*"
P2L14,15,16 I have removed the sentence (referring to CMIP3 and CMIP5) as it was surplus to its two bracketing sentences.
P2L17 I have added an apostrophe to "*models*"
P2L18 I have removed "*compared to similar generation models*" . I have altered "*...well suited to long-integration palaeoclimate studies."* to "*...well suited to conduct long-term integration palaeoclimate studies.*"
P2L21 I have changed "*..models, these.."* to "*.. models, and these.."*
P2L22 I have broken the sentence up after the initial "*Pliocene*"
P2L24 I have capitalised "*seaway*"
P2L27/28 I have added "*in which*" , so that the sentence so that it now reads "*This body of work therefore represents the first published record in which HadCM3 has been reconfigured with a bespoke global Pliocene palaeogeography*."
P3L7 I have added an "*at*" between "*and*" and "*45°*", and a comma making "*latitude, respectively*"
P3L9 I have added a space between "*CH_4*" and "*760*"
P3L10 I have added "*as reference*" after "*PMIP2*"
P3L13 This is correct, your replacement is more factually complete. I have replaced "*based upon the modern*" with "*based upon modern climatological conditions*"
P3L18 My preference is not to use a comma in these circumstances as it looks messy when the TSI is initially presented to 1 d.p (1365.0 rather than 1,365.0)
P3L19 see P1L17
P3L22/23 I have reworded "*..may depend upon if the group is participating within CMIP6."* to "*..may depend upon if the group is a participant of CMIP6."*
P3L24 I have added a comma after "..AMOC strength"
P3L25 I have kept the sentence as "The land surface scheme is MOSES 2.1 (Met Office Surface Exchange Scheme; Cox et al., 1999)
P3L26 I have decapitalised "*Broadleaf*" and "*Needleleaf*"
P3L28 The reviewer is correct in that this sentence belongs in the description of the experiment design. I have therefore removed the sentence "*We hold vegetation fixed through the entirety of each experiment."*
P3L29 The comma was removed within *"..subsurface, and.."*

P4L5 as suggested by the reviewer I clarified the sentence by changing "*..giving 6 grid cells per..*" to "*...equivalent to six grid cells per ..*"
P4L9 "archipelago" was capitalised
P4L10 A comma was added after "*...region*"
P4L11 Changed "*...mixing; important for the ..*" to "*..mixing that improves the..*"
P4L12 "A similar scheme is not present for Antarctic Bottom Water." was changed to " The scheme is not used for Antarctic Bottom Water."
P4L17 The "..(specifically, virtual -ve salinity fluxes).." is superfluous and so was removed.
P4L19 "*artificiality*" was corrected to "*artificially*"
P4L25 I removed the hyphen in "high-latitudes"
P4L27 I added "*on the other hand*" to make "*An advantage of the rigid lid scheme on the other hand...*"
P4L30 I agree. I added a hyphen to make "*Observation-derived upper-boundaries to..*"
P4L33 I have kept is within "Sublimation is represented .."
P4L34 I really failed here. I've corrected the spelling of "parameterisation", and "of" was added to make ".. action of surface ..". An "a" was added to "..by a parameterisation ..". I changed "The effects of snow age and melt pond formation on surface albedo is .." to "The effects of snow age and melt pond formation on surface albedo are .."
P5L1 corrected.
P5L4 "*experiment*" changed to "*experiments*".
P5L4/6 The sentence "*specified by the PlioMIP2 protocol, and a 3.205 Myr orbit consistent with the KM5c time slice.*" changed to *"specified by the PlioMIP2 protocol. A second set of Pliocene experiments were run with identical CO_2 values but with a 3.205 Myr orbit consistent with the KM5c time slice."*
P5L8 I added "*consideration of*" to make *"..the o and i indicate consideration of PRISM4 orography..*"
P5L9 New sentence started, to make "*The former (o) includes PRISM4 orography includes vegetation, soil, and lakes.*"
P5L10 Changed "*giving*" to "*providing*", I added "*the*" before "*PlioMIP2*", and then changed "*experiment design*" to "*simulation ensemble*"
P5L11 I changed " *.. a sensitivity outside the ...*" to *"..a sensitivity study that is beyond the..."*
P5L12 I removed "the" and added " *the subscript*" to "*..by the subscript orb, such..*"
P5L13 I added "*sensitivity studies*" to make "*..and total solar irradiance sensitivity studies*"
P5L15 Correct – I added the "*vs.*" to make "*(Eoi^{280} vs. E^{280})*"
P5L16 I agree, I changed the heading from "*Pre-industrial experiment description ..*" to "*Pre-industrial and CO_2 sensitivity experiments description...*"
P5L17 "year" was changed to "years"
P5L18 I have changed the sentence from "..Levitus observed ocean state (Levitus and Boyer 1994)" to "...the observed ocean state of Levitus and Boyer 1994".
P5L20 Good point. I have added a "runoff" before "basin" to avoid confusion with ocean basin.
P5L23 the " .. *is 280, 400 and 560 ppmv*" was changed to " *..are 280, 400 and 560 ppmv.*"
P5L25 Another good point. I have changed "*..total solar irradiance..*" to "*..TSI ..*"
P5L25 I have clarified the use of a hyphen within the Experimental design subsection with the sentence "*Here we use a comma separated list in the superscript to indicate 2 or more experiments or a hyphen to indicate all inclusive experiments (e.g. $Eoi^{280,350,400,450}$ is equivalent to $Eoi^{280\text{-}450}$).*"

P5L30 I have capitalised "Pliocene"
P6L5 I have inserted "regions of the " before " Eurasian Arctic."
P6L6/7 I have changed *"..the MOHC developed pre-industrial boundary conditions we .."* to *"..the pre-industrial boundary conditions developed by MOHC we..".* I have also changed *"..omit.."* to *"..removed.."*, changed *"subaerial extensions"* to *"subaerial exposure"*, and added *" Pliocene "* within *".. the Strait.."* to clarify that I was referring to the Pliocene. I have also replaced *"..the same as .."* to *"..identical to the..".*
P6L9 I agree, I added the hyphen to make *"..model-resolution .."*
P6L10 I agree – the "*..was interpolated using similar methodology."* was a vague and lazy phrase. I have replaced this with *"..generated using area-weighted regridding."*
P6L13 I have changed *"..manual correction in corrected regions in circumstances when.."* to *"..manual correction in regions when.."*
P6L14 I have changed *"..new.."* to *"..the regridded Pliocene .."*
P6L15 I have added a hyphen to make *"..model-resolution.."*
P6L17 I have added an apostrophe to make "*model's*"
P6L21 I have removed capitalisation of "*island*"
P6L24 I have added *"(Section 3.2.1)"* after "*aforementioned* "
P6L27 "*represent fully*" changed to "*fully represented*"
P6L30 Good point. I have changed this the two sentences "*Figure 1 compares the pre-industrial and PRISM4 HadCM3 island specification. Within PRISM4, 8 islands have been specified."* To "*Figure 1 compares the pre-industrial and PRISM4 Pliocene HadCM3 island specification in which the latter has 8 islands specified."*
P6L31 To clarify this sentence I have changed "*..within pre-industrial HadCM3 experiment the Bering Strait*" to *"..within the pre-industrial HadCM3 model setup the Bering Strait*".
P6L32 This was a Latex error. I have corrected this reference to *"(Section 2.2)"*
P6L34 To avoid plural "conditions" I have changed "*… the PRISM4 boundary conditions specifies these throughflow regions as closed"* to "*… the PRISM4 Pliocene geography has these throughflow regions closed*". I agree that "..we will not see.." is informal so have changed this to "..our simulations do not resolve.."
P7L1 I agree that this model limitation will be apparent within absolute quantities too, so I have removed the "*,when we look at climatological anomalies*" as it is now necessary.
P7L3 I have added "*from*" after "*as well as*"
P7L4 I have corrected the spelling of "rigid lid". I am incredibly sorry to RC1 for the time she/he has had to spend on spelling and grammatical errors.
P7L5 I have changed "*channels*" to "*gateways*" as it is more terminology
P7L8 I have removed capitalisation on "atmosphere"
P7L9 I changed the sentence "*..sea mask, pre-industrial CO_2.."* to "*..sea mask, as well as pre-industrial CO_2.."*
P7L10 I added "*distribution"* to make *"..sea ice distribution.."*
P7L12 I removed *"the"* and changed *"PRISM4"* to *"Pliocene" to make "100 year AOGCM run with Pliocene bathymetry and river scheme*". In the next sentence I replaced "*Here .."* with "*So far .."*
P7L16 I removed the erroneous "(1" and surplus "then"
P7L17 I have split this sentence up so that I now have "*At stage five we have an AOGCM incorporating full barotropic physics. CO_2 is then ramped up at 1% per year to 400 ppm and then held fixed."*
P7L18 I changed "*vegetation boundary conditions*" to "*vegetation boundary condition*".

P7L20 I corrected the phrasing and expanded on the description of the artefact such that the sentence went from " *..Peninsula following a persistent and unsatisfactory model artefact in this region"* to *"..Peninsula to resolve a persistent numerical mode within the barotrotopic solver in this region*"

P7L21 I have left in the repeated mention of CO_2 being held fixed at 400 ppm as it useful for the reader when then read the next sentence regarding forking off experiments at the other CO_2 values.

P7L22 I have since changed the breakdown of the modelling stages to a numbered list. I have kept the bracketed statement to remind the reader of the CO2 value.

P7L23 I understand the confusion. I have clarified the sentence by adding a "configured" so that the sentence now reads "*At the final stage, stage eight, the models are run for the final 100 years configured with full climatological output."* This is because the model when it is spinning-up doesn't generate full climatological output.

P7L24 I have changed the sentence from "The final 50 years is used for climatological averages" to "*The final 50 years of output is used for climatological averaging*"

P7L25 The number of Pliocene experiments within the paper is nine, this has been corrected within the text.

P7L26/27 This paragraph has been clarified in relation to the total combined 7500 model years (recalculated to reflect the correct number of experiments). I have also moved the plural of "*achieve*" to before "*with full physics.."*

P7L32 I agree with the reviewer and so have changed the sentence "*..and the upper 200 m and globally integrated ocean potential temperature trends are -0.026 ^{o}C century $^{-1}$ and +0.041 ^{o}C century-1 respectively." To "..and ocean potential temperature trends within the upper 200m and globally integrated are -0.026 ^{o}C century $^{-1}$ and +0.041 ^{o}C century^{-1}*"

P8L1 The superfluous sentence has been removed

P8L2-3 The sentence has been clarified to "*Positive TOA imbalance is indicative of a warming of the earth system, the small heat capacity of the atmosphere and land means that residual energy is predominantly taken up by the ocean, which is reflected in the volume averaged ocean temperature evolution."*

P8L4 I have changed the term "*..volume averaged.."* to "*..volume integrated.."*, and have added a space after these sentence closure.

P8L6 I agree, I have changed the *"..>2000 m.."* to *" ..deeper than 2000m.."* and the occurrence of *"..greater.."* to *"..deeper.."* to clarify.

P8L7 I have changed the sentence from "All experiments are satisfactory, although E^{560} has above average warming within the deep ocean" to "*All experiments are deemed to be in a satisfactory state of equilibrium, although the outlier high TOA simulations Eoi^{450} and E^{560} present above average warming within the deep ocean."*

P8L8 I agree, I have changed "*inconsistent*" to "*not meaningful*"

P8L13 I have changed the sub heading from "*Atmospheric and surface climatology*" to "*State of the atmosphere and earth surface climatology*"

P8L15 Within the file naming of Figure 3 and Figure 4 were incorrect. This has been corrected and the sentence now correctly refers to the correct Figure 3. Figure 4 now correctly refers to the Seasonal plots.

P8L17 I agree that the term "*..regions of Pliocene ice sheet retreat (and topographical reduction)"* is incorrect and confusing, I have replaced this with your suggestion "*..regions where Pliocene ice sheets and the respective elevation are smaller than pre-industrial*."

P8L19 "*.. is in a similar distribution to HadCM3..*" to "*..is similar to results derived with HadCM3..*"
P8L24 I have replaced "*UK*" with "*Ireland and Scotland*".
P8L25 This has been corrected with the correction of Figure 3 and Figure 4 pdf filenames.
P8L26 I have replaced *"..in the present).."* with "*..during the pre-industrial)..*"
P8L27 *"..he.."* corrected to *"..the.."*
P9L1 "..pre-industrial E^{280}" has become "pre-industrial (E^{280})"
P9L7 *"(Table 2; Haywood et al., 2013)"* replaced with *"(Table 2 of Haywood et al., 2013)"*
P9L19 hyphen replaced with "*e.g.*"
P9L20 "*models*" changed to "*model's*"
P9L23 have added "(not shown)"
P9L25 "*is*" changed to "*are*" to make "*..although changes in seasonal latitudinal distribution are not evident*."
P9L26 I have inserted a reference to Figure 6 (c-f)
P9L27 Comma replaced by a period.
P9L28 I have removed the end of sentence from ",for example .." as this was surplus.
P9L30 superfluous "the" removed
P9L29-P10L4 I have removed these two paragraphs as this level of specificity is inappropriate to the scope of the manuscript
P10L28 changed "*stable latitudinally*" to "*latitudinally stable*"
P10L29,31,34 spaces removed from " *-E^{280}* "
P10L32 "*summer*" changed to "*southern*"
P11L1 All instances of "*equaterward*" replaced with "*equatorward*"
P11L2 I agree, I have changed the reference to "*Figure 6e and f*"
P11L3 The subheading has been changed from "*Ocean state: Description of the gross hydrographic, circulation features, Overturning and ocean heat transports*." to *"State of the Ocean climatology*" to remain consistent with subsection heading (see P8L13)
P11L8 hyphen added to make "*CO_2-induced*"
P11L9/10 These incomplete sentence has been corrected to make "*The greatest warming occurs within the North Atlantic subpolar gyre where Eoi^{400} – E^{280} reaches 9.3 ^oC*"
P11L25 "*A complex picture emerges in the geographic and CO_2 sensitivity of seasonal sea ice distributions as..*" changed to " *A complex picture emerges in the sensitivity of seasonal sea ice distribution to geographic and CO_2 as ..* "
"*winters*" changed to "*winter*". The term "*the <u>paleaogeographic</u> and vegetation changes*" has been changed to "*the <u>paleaogeography</u> changes*". I have removed "*extent*" and "*suppresses*" corrected to "*suppress*".
P11L30 2 commas were added.
P11L31 "*ice*" removed before *"..concentration."*
P12L6 "*the*" added before "*HadCM3L*", "*s*" added to make "*occurs*". "Greenland Seas" capitalised. "*off of the Antarctic Peninsula*" changed to "*near the Antarctic Peninsula*"
P12L14 "*AMOC of*" added to make "*consistency between E^{280} and E^{400} and the observed AMOC of 17.2 +/- 4.6 Sv*"
P12L15 The Sv unit was corrected to "*10^6 m^3 s^{-1}*", "..differs to.." replaced with "..differs from..". I have added a comma to make "..(RAPID array 26.5^o N, Apr 2004 - Oct 2012 ; McCarthy et al., 2015)..". The citation has also been corrected
P12L30 I have changed the sentence to "..level (for simulation Eoi^{400} the circulation pattern is 22% and 6 % stronger than E^{280})."

P13L3 The transect definition has been fixed so that it now reads "..across a 64.375 - 56.875°S, 65°W transect.."
P13L4 After consideration I left it as "..the positive aspect of the U component.."
P13L7 I changed "..had an ACC.." to "..simulated an ACC.."
P13L9 I removed the "s" to make "gradient"
P13L10 I replaced "..on the equator side.." with ".. towards low latitudes.."
P13L14 Corrected "interpreting"
P13L16 After consideration, I left the sentence as "..so is dominantly barotropic in nature."I switched "island Peninsula" to "Peninsula island"
P13L18/19 Comma added after "line-integral configuration". The sentence was reorganised and also split into two such that the two sentences read "Also, the model's barotropic solver, given a more complex line-integral configuration, may not be converging to a solution. This requires further investigation."
P13L21 Comma changed to "to" and corrected "latitudinal"
P13L21 Reordered so that it now reads "..and an equatorward shift of its centroid."
P13L29 Changed to "..a more continuous counter current in the Pliocene.."
P13L33 Provided more consistent capitalisation such that it now reads "The Weddell Sea sub-polar gyre is weakened and restructured whilst the Ross Sea gyre is less intense and extends more equatorward"
P13L29 The repeated block of text has been removed.
P14L9 Space added after "modern"
P14L10 "Tab. 6 SST" replaced by "Tab. 6 MASST"
P14L11 I have changed "warm pool dynamics" with "warm pool areal extent". "difference" added after "statistical". I have corrected "$AMOC_{max}$"
P14L12 Corrected "26.5°N"
P14L18 "(TSI)" removed from subsection title
P14L23 Text changed to "(Pliocene minus pre-industrial) for simulations based upon 1365 to 1361 W m^2 for .."
P15L5 I agree, I changed it to "..atmosphere and ocean state of these simulations."
P15L10 I added "results of" to make "..are similar to results of PlioMIP.."
P15L12 Significant digits of numerical results corrected.
P15L13 Changed to "..demonstrates an insensitivity of these quantities to the degree.."
P15L18 Again my apologies. I added an "in", a comma and "the variation" to make the sentence "We find an AMOC which is more intense in the Pliocene than in the pre-industrial, the variation driven principally by the change in geography"
P15L19 I corrected the sentence by adding E280 so that it is now "We determine this by comparing AMOC strength of E^{280} against Eoi^{400} and Eoi^{280}"
P15L34 Comma added after "KM5c"
P16L10 Comma added after "grid type"
P16L16 "subariel" changed to "subaerial"
P16L23 I have added a "palaeogeographical changes to" before "..the Maritime continent"
P16L30 italic font removed from Web address
P17L9 Full stop added to end of line
P18L5 I cannot find the error with author Peterchmitt, J.-Y., the bibtex bibliography text was copied from Climates of the Past. My apologies if I have missed something.
P18L16 Cox(1984) bibliography information corrected (changed to book)
P18L18 Removed duplicate doi information

P18L25 spaces around page number hyphen removed
P18L31 Bibliography information corrected
P18L34 Dowsett reference corrected
P18L35 Flato et al., 2013 reference removed
P18L21,P19L5, P19L18, P19L28
No page numbers available for these papers as they are from GRL:Oceans. < Note to editor> The correct bibliography information is present within the provided paper.bib file but it seems the Copernicus.bst bibliography style file doesn't incorporate the "number" field for references.
P19L10/11 Bibliography information corrected
P19L16 spaces around page number hyphen removed
P19L20 Download link added to Li and Shine (1995)
P19L34-35 Roether et al.,1994 changed to inbook
P19L36 Semtner (1974) entry was not required for the ocean model description – so this was removed. A more suitable Semtner (1976) reference was used for sea ice model.
P20L1 reference to IPCC AR4 was removed from the manuscript and so the bibliography information was now not required.

Bragg, F. J., Lunt, D. J., and Haywood, A. M.: Mid-Pliocene climate modelled using the UK Hadley Centre Model: PlioMIP Experiments 1 and 2, Geosci. Model Dev., 5, 1109-1125, https://doi.org/10.5194/gmd-5-1109-2012, 2012.

Chandan, D. and Peltier, W. R.: Regional and global climate for the mid-Pliocene using the University of Toronto version of CCSM4 and PlioMIP2 boundary conditions, Clim. Past, 13, 919-942, https://doi.org/10.5194/cp-13-919-2017, 2017.

Haywood, A. M., Hill, D. J., Dolan, A. M., Otto-Bliesner, B. L., Bragg, F., Chan, W.-L., Chandler, M. A., Contoux, C., Dowsett, H. J., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Abe-Ouchi, A., Pickering, S. J., Ramstein, G., Rosenbloom, N. A., Salzmann, U., Sohl, L., Stepanek, C., Ueda, H., Yan, Q., and Zhang, Z.: Large-scale features of Pliocene climate: results from the Pliocene Model Intercomparison Project, Clim. Past, 9, 191-209, https://doi.org/10.5194/cp-9-191-2013, 2013.

Haywood, A. M., Dowsett, H. J., Dolan, A. M., Rowley, D., Abe-Ouchi, A., Otto-Bliesner, B., Chandler, M. A., Hunter, S. J., Lunt, D. J., Pound, M., and Salzmann, U.: The Pliocene Model Intercomparison Project (PlioMIP) Phase 2: scientific objectives and experimental design, Clim. Past, 12, 663-675, https://doi.org/10.5194/cp-12-663-2016, 2016.

Anonymous Referee #2

We thank the reviewer for their helpful comments and considerable time spent working on this manuscript. The contribution of the reviewer has added substantially to the quality of the manuscript, this is greatly appreciated particularly by the lead author. We sincerely appreciate the considerable time that the reviewer spent on the review. With regards to the reviewer comments, these are addressed in sequence by SJH with input from the co-authors. We will start with the general comments and then finish with the line-by-line comments.

Confusion over the number of experiments

It seems that the authors themselves are unsure how many experiments they have performed.[...]

i. Lines 4—5 on page 5 suggest that the authors have conducted two sets of “Pliocene experiments” with CO_2 at 280, 350, 400 and 450 ppmv (for a total of 8 Pliocene experiments) and where one set uses modern orbit whereas the other uses orbit for 3.205 Mya.
ii. In Lines 12–13 on the same page the authors talk about two new insolation sensitivity simulations E^{280} and Eoi^{400} therefore giving a total of 10 simulations so far. If we include the obligatory PI control, then we should be currently at 11 simulations.
iii. Further down that page, under section 3.1, new control experiments E^{400} and E^{560} are introduced. That brings us to 13 simulations which appear in Table 1. So far all good.
iv. On page 7 at the end of first paragraph under section 3.3, the authors talk about 8 experiments which are the two sets of orbit based simulations. That’s fine. But the following line at the start of next paragraph talks about “the ten Pliocene experiments”. How can that be? In the author’s nomenclature, the Eoi experiments are Pliocene, so we have 8 experiments and the experiment ! Eoi^{400} giving 9 Pliocene experiments.
v. In the same line, to give an accounting for the ten experiments the authors say “(Core and Tier 1 detailed in Table 1 as well as Eoi^{400}, E^{280} and Eoi^{400})” but if we look at Table 1, there are 5 Core and Tier 1 experiments, so those five along with the three experiments $_{orb}Eoi^{400}$, $_{1361}E^{280}$ and $_{1361}Eoi^{400}$ add to 8 experiments! Not 10!!! Furthermore not all Core and Tier 1 experiments are Pliocene

This has been corrected within the manuscript. Table 1 describes the 10 experiments, which consists of 7 PlioMIP2 protocol experiments (4 Pliocene based and 3 pre-industrial based) and 3 additional sensitivity experiments (2 Pliocene and a pre-industrial based experiment). This correct counting has been pulled through into the manuscript. Section 3 Experiment Design has been corrected and now concludes with the following paragraph

“In total 6 Pliocene experiments were run: the CORE (Eoi^{400}), two Tier 1 (Eoi^{350} and Eoi^{450}), one Tier 2 (Eoi^{280}) as well as an orbital ($_{orb}Eoi^{400}$) and TSI sensitivity experiment ($_{1361}Eoi^{400}$). These are accompanied by 4 pre-industrial experiments: the CORE (E^{280}), a Tier 1 (E^{560}) and Tier 2 (E^{400}) as well as a TSI sensitivity experiment ($_{1361}E^{280}$). These 10 simulations are detailed within Table 1.”

Lack of significant connection to existing literature

A notable shortcoming of the paper is the general absence of connection between the author's own work and the literature on the Pliocene. One can get that sense even without reading the paper by simply looking at the length of their reference section. There are several missed opportunities in the paper for the authors to connect their findings to those from other studies — published results from other groups for PlioMIP2, published results from PlioMIP and other studies outside of these collaborations. As it currently stands, the authors almost exclusively compare, whenever they do, to their results from PlioMIP. While that is obviously required and good, they should put some effort into connecting to other literature as well.

It is useful to consider this manuscript in context with the other papers within the Climates of the Past PlioMIP2 special issue. Currently there are three modelling groups who has so far presented initial model descriptions; the CCSM4 study of Chandan and Peltier (2017)[1], the MRI-CGCM2.3 study of Kamae et al. (2016)[2] and the EC-EARTH study of Zheng et al. (2019)[3]. Chandan and Peltier (2017) compared globally integrated MASAT and SST against a selection of previous Pliocene simulations (mostly PlioMIP1). They also included some comparison of predicted AMOC although this was mostly with the previous CCM4 simulations within PlioMIP1. Kamae et al., 2016 compared their PlioMIP2 results with only their PlioMIP1 MRI-CGCM2.3 results (Kamae and Ueda, 2012). Zheng et al. (2019) focus on sea ice and do not compare with previous works in a way suitable for this manuscript.

Within the PlioMIP2 Climates of the Past individual group paper template[4] there is no requirement to compare results against previous Pliocene modelling. It is left to the modelling groups discretion to include comparison against existing Pliocene modelling studies. Nevertheless, I do agree that some comparison against previous work is beneficial to the reader. I have included a model-comparison of globally integrated MASAT (including CS and ESS), precipitation and AMOC.

Analysis in this paper and author's plans for future papers

The authors mention that a future paper will describe the results from P4P Tier 2 experiments that will directly lead them into discussing the nature of forcing from different boundary conditions using the factorization methodology discussed in Haywood et al. 2016. In that case why do the authors pre-empt that effort here, by discussing in a limited way, contributions from CO_2 and palaeogeography the specific and restricted differences Eoi^{400}-Eoi^{280} and Eoi^{280}-E^{280} (see also my points 2 and 3 in the scientific comments section). By the time of the second paper, the authors will have all the experiments that will be useful for them to do a more thorough discussion of the forcings by taking into account dependencies on the background state and so they will be compelled to revise the findings from this paper anyway. So, why not put all that discussion together in one related paper? Why confuse a prospective future reader by providing them a paper with some results, and then presumable soon after another paper with related and potentially revised results? I think that given their plans for future papers, I recommend the authors to focus more on the climatology of Pliocene in this paper and to focus on forcings in a future paper.

[1] Chandan, D. and Peltier, W. R.: Regional and global climate for the mid-Pliocene using the University of Toronto version of CCSM4 and PlioMIP2 boundary conditions, Clim. Past, 13, 919-942, https://doi.org/10.5194/cp-13-919-2017, 2017.

[2] Kamae, Y., Yoshida, K., and Ueda, H.: Sensitivity of Pliocene climate simulations in MRI-CGCM2.3 to respective boundary conditions, Clim. Past, 12, 1619-1634, https://doi.org/10.5194/cp-12-1619-2016, 2016.

[3] Zheng, J., Zhang, Q., Li, Q., Zhang, Q., and Cai, M.: Contribution of sea ice albedo and insulation effects to Arctic amplification in the EC-Earth Pliocene simulation, Clim. Past, 15, 291-305, https://doi.org/10.5194/cp-15-291-2019, 2019.

[4] https://geology.er.usgs.gov/egpsc/prism/data/PlioMIP2_Individual_Group_Papers_Guidance_CP_2018.pdf

To avoid reader confusion, I have removed reference to any future publication plan within the manuscript. The manuscript can now be read as a closed piece of work. Subsequent papers, such as the Pliocene4Pliocene forcing factorisation work, will compliment this initial modelling paper.

Quality of figures

1. Labels and legends on several figures are barely readable. The font sizes need to be increased.

I have increased the size of the font used in all figure labels and legends, and where appropriate increased the size of the Figures.

2. The figures in Fig 2 should have a wider aspect ratio. As it currently stands the figures will not be single column, so might as well make it as wide as the text. Its hard to read anything.

I have made this figure single column so that each subfigure can be wider. Within the Climates of the Past Latex typesetting specification, If the figures are horizontally aligned the width occupied by the entire figure [width=12cm] is less that 2 columns. If the figure is vertically aligned each figure can be wider [width=8cm].

3. Title for Figure 4 is incorrect

I have corrected this

4. Features in Figure 8 are barely visible, and the fact that the authors are using polar projections with two different outer bounding latitude lines for different plots creates a lot of confusion and difficulty in interpreting the figure. The authors are encouraged to use just one value of outer bounding latitude line and increase the size of each of the sub figures.

I have corrected this figure so that the latitudinal extent of the polar plots are equivalent. I have also increased the size of the font and increased the size of the Figure.

Scientific Comments

There is confusion about what is a Pliocene and a pre-industrial experiment. For example, why are E^{400} and E^{560}called pre-industrial? The pre-industrial was a 280 ppmv world. These two experiments are sensitivities to CO_2 and not at all pre-industrial.
This is a good point, and I agree it was sloppy writing. I have corrected the descriptions of the E^{400} and E^{560} within the manuscript by referring to these experiments as pre-industrial based sensitivity experiments.

A similar, issue arises with the authors calling all their Eoi experiments as Pliocene. Although the issue is less severe here because of the uncertainties in Pliocene CO_2, but since the word “Pliocene” is used throughout the paper in regards to their experiments with very rare reference to the specific experiment code, the authors should clarify to the reader what does the word “Pliocene” means in general in the context of the paper. When the authors say something to the effect of “the Pliocene is so and so” do they mean that the result they are discussing is robust in all of their Eoi experiments regardless of the CO_2 or do they mean a specific experiment? Their sloppy terminology here gets a little messy at some places, for example on line 3, page 9, while discussing the impacts of various boundary condition changes, the authors say they they diagnose the increase in CO_2 as $Eoi^{400} – Eoi^{280}$. So does this mean that Pliocene is 400 ppmv? Because otherwise they could have also used $Eoi^{450} – E^{280}$or $Eoi^{350} – E^{280}$

Historically, within the first PlioMIP program, the Pliocene had a single CO_2 level set at 405 ppm. Within PlioMIP2, the Pliocene CORE experiment 400 ppm CO_2 level represents our "best guess" and so I focus on Eoi^{400} in an attempt to keep the manuscript clear and concise. I have clarified this within Section 4 (Results)
"In order to keep discussion clear and concise, we principally compare the two PlioMIP2 CORE experiments which we refer to as the *control* experiments, Eoi^{400} and E^{280}. Whilst there is uncertainty in mid Piacenzian (MIS KM5c) CO_2 levels, 400 ppm represents the middle of the anticipated CO_2 range derived from marine and terrestrial based reconstructions. We therefore consider Eoi^{400} as our "best estimate" simulation."

Why is change due to paleogeography always inferred as $Eoi^{280} – E^{280}$ and not alternatively/ simultaneously as $Eoi^{400} – E^{400}$. The authors should make clear why they are favouring this difference, after all we know from other studies that there should be background dependence on CO_2
I have clarified this within the beginning of the Results Section. I have also discussed this dependency on CO2 within Section 4.1.1.
"From Table 3 it is possible to decompose the factors that contribute to Pliocene warming relative to the pre-industrial (E^{280}). Considering the CORE Pliocene experiment, Eoi^{400}, we find that the change in palaeogeography (Eoi^{280}-E^{280}) accounts for a temperature change of 1.4 ± 0.7°C, whilst the increase in CO_2 (Eoi^{400}-Eoi^{280}) accounts for a further 1.5 ± 0.7°C of warming. Considering uncertainty in Pliocene CO_2 level, we find temperature changes of 0.9 and 2.0 ± 0.7°C for Eoi^{350}-Eoi^{280} and Eoi^{450}-Eoi^{280} respectively. The PlioMIP2 experimental design provides a second pathway to examine Pliocene palaeogeographical and CO_2 forcing (e.g. Eoi^{400}-E^{400} and E^{400}-E^{280}). here the Pliocene geography (Eoi^{400}-E^{400}) accounts for 1.8 ± 0.7°C of warming and the increase in CO_2 (E^{400}-E^{280}) accounts for 1.1 ± 0.7°C of temperature increase. These differences highlight that there are non-linearities within the climate systems response to changes in boundary condition."

On page 4, the draft says "The land-sea mask is effectively 3.75 x 2.5 resolution in the top 200 m but beneath increases to 1.25 lateral resolution." I don't follow this. Didn't the previous line say that the horizontal resolution is 1.25?
The two statements are compatible. The ocean model has grid cells that are 1.25 x 1.25 degree in size. The land sea mask in the top eight ocean layers is 3.75 x 2.5 degree and beneath it is 1.25 x 1.25 degrees. I understand the confusion. I have clarified this (and removed superfluous information) by changing the sentence to "To simplify coupling with the atmosphere model, the ocean model's coastline has a resolution of 3.75 x 2.5° at the uppermost level."

Page 9 first para on precipitation says:
"Regions that have little (< 0.1 mm day^{-1}) change in precipitation are regions that receive little precipitation within E^{280}— North Africa and the East Antarctic Ice Sheet. Therefore, the models response to elevating CO_2 in the Pliocene context seems to largely follow the wet get wetter paradigm." There are two things wrong with this. Firstly, the conclusion in the second sentence does not follow from the first. In the first sentence you are saying there is no change over dry regions, which is not the same as saying wet gets wetter (or that dry regions get drier; which you haven't said directly, but is part of the same paradigm). Secondly, I don't agree that the model necessarily follows that paradigm — the anomaly over Australia for example is wet, whereas it is a desert today. There is also significant drying over the entire Amazon as implied by the anomaly, but today it is very wet. So a dry Australia has become wetter and a wet Amazon has become drier.
This was unfortunately another poorly structured paragraph, and I agree completely with what you note. With regards to the wet-get-wetter phrase I was referring to the effect of increasing Pliocene CO2. The wet Australia and dry Amazon occur due to palaeogeographic change (Eoi^{280} – E^{280}).

Nevertheless, whilst I do say that it "..*largely* follows the wet get wetter paradigm.." (emphasis mine), it is still a loose phrase. I there removed it. The paragraph now reads

"The globally integrated Mean Annual Precipitation metric (MAP; Table 4) is influenced by both Pliocene geography and CO_2 changes. Pliocene geography acts to increase globally integrated MAP although this appears sensitive to the background CO2 level (e.g. Pliocene geography increases MAP by 0.07 and 0.05 mm day^{-1} at 280 and 400 ppm respectively). The geographical distribution of MAP change can be seen within Figure 5. Northern Hemisphere land masses generally see increased precipitation within the Pliocene although this effect is minimal in the continental interiors. In the Southern Hemisphere much of South America and South Africa receives less precipitation whilst Australia and Northern Greenland see an increase in precipitation during the Pliocene. Increasing Pliocene CO_2 generally intensifies the precipitation anomaly which is most apparent in the tropics. Regions that have little (<0.1 mm day^{-1}) change in precipitation under increasing Pliocene CO_2 are regions that receive little precipitation within E^{280} e.g. North Africa and the East Antarctic Ice Sheet."

The authors should give more details about this "diffusive pipe" (page 4) that is used along the Strait of Gibraltar. An important oceanic phenomena there is the flow of extremely dense and saline waters from the Mediterranean to the Atlantic after crossing the strait and which has important implications for the Atlantic overturning circulation. How do the authors expect the lack of such transport to affect the climate in their simulations?
I have expanded upon the description of the diffusive pipe so that it now reads (The 1200m is significantly deeper than the main sill, this depth was chosen by the model developers (MOHC) as it was assumed that Mediterranean waters would sink to this depth.)
"Water mass exchange through the Strait of Gibraltar, a channel that falls subgrid-scale, is achieved with a diffusive pipe. This pipe provides transport of water properties through the 13 topmost layers of the ocean (~ 1200m) between the Eastern Atlantic with the Western Mediterranean."

I don't follow the comment "Observation derived upper-boundaries to Arctic and Antarctic sea ice concentration of 0.995 and 0.980 are used" regarding the conversation on the sea ice model on page 4.
The description within the manuscript has been expanded and clarified so that it now reads "To account for sea ice leads, upper-boundaries of 0.995 and 0.980 are imposed to Arctic and Antarctic sea ice concentrations, based upon the parameterisation of Hibler 1979."

The Persian Gulf is not really present in the PRISM4 reconstruction, but apparently it is in the author's ocean grid shown in Figure 1. Similarly, the Barents Sea is absent in PRISM4 reconstruction (there is a small negative orography depression, but that is just a resolution/ reconstruction limitation).
Firstly, regarding the Barents Sea. The PRISM4 reconstruction (Figure 3 of Dowsett et al., 2016[5]) does have the Barents Sea present as does our Pliocene model configuration (Figure 1). Svalbard is extended within PRISM4, yet within the MOHC developed pre-industrial boundary conditions, Svalbard is missing due to model development choices. It was decided when generating PRISM4 model boundary conditions to omit the extended Svalbard to keep consistent with the MOHC-developed pre-industrial boundary conditions.

[5] Dowsett, H., Dolan, A., Rowley, D., Moucha, R., Forte, A. M., Mitrovica, J. X., Pound, M., Salzmann, U., Robinson, M., Chandler, M., Foley, K., and Haywood, A.: The PRISM4 (mid-Piacenzian) paleoenvironmental reconstruction, Clim. Past, 12, 1519-1538, https://doi.org/10.5194/cp-12-1519-2016, 2016.

The PRISM4 boundary conditions specify a small inland sea in the vicinity of modern Persian Gulf. When we look at the MOHC-developed pre-industrial model boundary conditions, due to spatial resolution issues the Persian Gulf is represented by a large inland sea. A choice was made to keep the Persian Gulf constant, although it could be argued that the inland sea should have been made smaller in the Pliocene model. A sensitivity experiment has shown that this has some regional impacts but globally is minimal and doesn't alter the results of this manuscript. We will present a wide range of these additional sensitivity experiments within a future paper.

I have included the following text within Section 3.2.1 to describe the situation with the Persian Gulf.

"Similarly, we keep the Pliocene LSM in the Persian Gulf region the same as pre-industrial despite a withdrawal of the Persian Gulf within PRISM4. This choice was made as the Persian Gulf within the pre-industrial LSM is represented by an inland sea (due to inadequate spatial resolution) and so further changes would be difficult to interpret."

Technical Comments

1. Page 1, Line 6: What does a "control Pliocene" mean?
2. Page 1, Line 7: "integrated surface air temperature"
3. Page 1, Line 11: "by both geographical - and land surface changes, and the increase in CO_2 ~~increase~~"

(reviewer comment 1-3): The abstract has been rewritten so that it now reads

"We present the UK's input into the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2) using the HadCM3 climate model. The 400 ppm CO_2 Pliocene experiment has a mean annual surface air temperature that is 2.9°C warmer than the pre-industrial and a polar amplification of between 1.7 and 2.2 times the global mean warming. The PRISM4 enhanced Pliocene palaeogeography accounts for a warming of 1.4°C whilst the CO_2 increase from 280 to 400 ppm leads to a further 1.5°C of warming. The climate system's sensitivity to a doubling of CO_2 is 3.5°C for the pre-industrial and 2.9°C for the Pliocene. Precipitation change between the pre-industrial and Pliocene is complex, with geographic and land surface changes primarily modifying the geographical extent of mean annual precipitation. Sea ice extent is reduced during the Pliocene, particularly in the southern hemisphere, although it persists though Summer in both hemispheres. The Pliocene palaeogeography drives a more intense Pacific and Atlantic meridional overturning circulation (AMOC). This intensification of AMOC is coincident with more widespread sites of deep convection in the Southern Ocean and North Atlantic. We conclude by examining additional sensitivity experiments and confirm that the choice of total solar insolation (1361 vs. 1365 Wm^{-2}) and orbital configuration (modern vs. 3.205 Ma) do not to significantly influence the anomaly-type analysis in use by the Pliocene community."

4. Page 1, Line 21: "through its ~~uses a~~ potential as an analogue for the contemporary" This sentence has been replaced with "The Pliocene Model Intercomparison Project Phase 2 (hereafter PlioMIP2; Haywood et al. (2016)) has dual focus: 1) to improve understanding of Pliocene climate and 2) to evaluate climate model uncertainty for a warmer than modern climate.

5. Page 1, Line 24 “are ~~required to be~~ completed by all model groups participating in PlioMIP2, while whilst the optional” This sentence has been replaced with “The CORE components are required for all modelling groups whilst the Tier 1 and Tier 2 components are optional with Tier 1 experiments higher priority than Tier 2.”
6. Page 2, Line 2—4: Rewrite the sentences on these lines as: “Table 1 summarizes the experiments conducted within this study. These experiments include several PlioMIP2 experiments as well as non-PlioMIP2 experiments that explore additional sensitivities. From the set of proposed PlioMIP2 experiments we conduct all core and Tier 1 experiments as well as ....” This sentence has been replaced with “Table 1 details the PlioMIP2 experiments conducted within this study, along with an additional set of non-PlioMIP2 experiments that explore model sensitivities. We conduct all CORE and Tier 1 experiments as well as the Pliocene4Future Tier 2 experiments as described within Haywood et al. (2016).”
7. Page 2, Line 11: atmospheric shouldn’t be capitalized. Corrected
8. Page 2, Line 27: I don’t understand the part “or regional geographical sensitivities were explored”. I have changed this to “or regional palaeogeographical uncertainties were explored.”
9. Page 2, Line 29: atmosphere and ocean in small letters. All instances of “Atmosphere” and “Ocean” have been decapitalised where appropriate
10. Page 2, Line 33: “have been made since 2000” The sentence with this phrase is poorly worded. Please rewrite it as “Subsequent corrections and improvements to the model, as well as a thorough evaluation against observational data has been described in Valdes et al. (2017).” I agree this should have been better written. I have changed it to your recommendation.
11. Page 3, Line 6 “pressure-levels at height aloft” I have changed this to “..has 19 vertical hybrid sigma-pressure levels entending to 5 hPa”
12. Page 3, Line 8: Oasis in capital This sentence was rewritten at the suggestion of Reviewer #1.
13. Page 3, lines 13—14: The last sentence sounds weird and appears incomplete. This sentence was changed to “The radiative effects of background aerosol are represented by a simple parameterisation based on modern climatological conditions (Cusack et al., 1998).”
14. Page 4, Lines 8—9: rephrase the sentence to: “Within the modern boundary conditions, cells overlying important subgrid-scale channels, such as those along the Denmark Strait, the Iceland- Faroe and the Faroe-Shetland Channels, and straits surrounding the Indonesian archipelago, are artificially deepened to improve flow representation.” I have rephrased this sentence.
15. Page 4, Line 3: “in an attempt order to improve representation” Changed.
16. Page 4, Line 14: “Hudson Bay outflow Strait” ... “subsequently therefore unrepresented” Changed.
17. Page 5, Line 4: “setup of the Pliocene and the pre-industrial experiment experiments” Changed.
18. Page 5, Line 8: “and the letters o and o indicate inclusion of PRISM4 orography (including PRISM4 vegetation, soil and lakes) and ice-sheets., the former includes PRISM4 vegetation, soil and lakes.” Changed.
19. Page 5, Line 10 “giving yielding experiments” .... “components from the PlioMIP2 experiment design.” Sentence restructured at the request of Reviewer #1
20. Page 5, Line 11 “We use a preceding subscript in the name of an experiment to indicate” Sentence restructured to “We investigate the validity of this orbit choice by rerunning Eoi^{400} with a 3.205 Myr orbital configuration within experiment $_{orb}Eoi^{400}$.
21. Page 5, Line 15 What is the expression at the end? Presumably you want to mention something like “which we diagnose as the anomaly Eoi^{280} - E^{280}” I have moved this sentence to the first paragraph of the Results section (Section 4) and have added these words.

22. Page 5, Line 16: "Pre-industrial Control experiments description" Again, the various E experiments are not all pre-industrial. I have changed the subsection heading to "Pre-industrial and associated sensitivity experiments ($E^{280,400,560}$ and $_{1361}E^{280}$)"
23. Page 5, Line 18: "from the 'Levitus' observed" I have changed the sentence to "..had been initialised from the observed ocean state of Levitus and Boyer (1994)"
24. Page 5, Line 22: "In accordance to with the PlioMIP2" This has been changed
25. Page 5 Line 27: "PlioMIP2 enhanced and modern boundary conditions For PlioMIP2 the boundary conditions for the modern day and the 'enhanced' variant of the Pliocene reconstruction" ... "held within" I have changed this sentence to "For PlioMIP2 the boundary conditions for the modern day and the 'enhanced' variant of the Pliocene reconstruction are provided on regular 1^{o} grids …"
26. Page 6, Line 7: "despite subaerial extension within PRISM4". I don't follow what this has to do with omitting the islands. Aren't you saying the extensions of bathymetry are subaerial? At the request of Reviewer #1 I changed the phrase subaerial extension" to "subaerial exposure" so that sentence now reads "In remaining consistent with the pre-industrial boundary conditions developed by MOHC we remove Svalbard and Novaya Zemlya despite subaerial exposure within PRISM4". Within the pre-industrial experiment, the islands were removed by the MOHC to improve ocean circulation in that region. Within the PRISM 4 boundary condition these islands are larger than present day. This therefore poses a conceptual problem. I therefore omitted them in the Pliocene experiments also.
27. Page 6, Line 8: What is this diffusive pipe you are talking of? The diffusive pipe is common to the pre-industrial and Pliocene models so I have moved its description to the Section 2.2 where it is first mentioned. I have added the following sentence "This pipe provides transport through 13 topmost layers of the ocean (~1200m) between the Eastern Atlantic with the Western Mediterranean."
28. Page 7, Line 8: "First the Atmosphere atmosphere model" All instances of "..Atmosphere model.." have been changed to "..atmosphere model.."
29. Page 8, Line 2: "yet modest, disequilibrium represented departures from equilibrium and are characterized by TOA imbalances" I have changed the phrase "… ,disequilibrium represented …" with "..departures from equilibrium and are characterized …"
30. Page 8, Line 4: "occurring at depths of > 2000 of in the " At the request of Reviewer #1 I have changed this to read "..depths deeper than 2000 m in the Pacific basin."
31. Page 8, Line 5: Sentence beginning on this line is strangely worded. I have corrected this so that it now reads "The Indian and Antarctic oceans are the most equilibriated, particularly at intermediate depths and deeper."
32. Page 8, Line 6: "equilibrium states" Corrected
33. Page 8, Line 6: "Figure 2 presents the time-evolution of ocean temperature" for which simulation? You have several simulations, which one of it is on Figure 2. Even the caption on the figure doesn't say that. I have clarified this and it now reads "…Figure 2 presents the time-evolution of ocean potential temperature of the Pliocene control experiment, Eoi^{400}."
34. Page 8, Line 11: "We derive base our analysis on climatological averages" This has been changed
35. Page 8, Line 11: The range of climatology years is not applicable to the pre-industrial controls. You are correct. I have removed the text "(model years 2450 through to 2499) as it was also superfluous.
36. Page 8, Line 15: "Modelled mean annual surface air temperatures (hereafter MAT MASAT)" …. "Tables 3". NOTE: Table 3 uses MASAT, and you should use MASAT everywhere just like Table 3 as that is the more accurate term. I have corrected the manuscript (including tables and figures) so that MASAT is used throughout.
37. Page 8, Line 17: "coincide with Greenland and Antarctic regions of Pliocene ice sheet retreat (and topographical reduction) over Greenland and Antarctic. I have rephrased the

sentence so that it now reads "Differences in MASAT of up to 31.3°C coincide with Greenland and Antarctic regions where Pliocene ice sheets and the respective elevation are smaller than pre-industrial."

38. Page 8, Line 19: "This pattern of warming is in a similar in distribution to HadCM3 results within PlioMIP under using the older PRISM3". I have changed this sentence to "This pattern of warming is similar to results derived with HadCM3 within PlioMIP1 under PRISM3 boundary conditions (Exp. 2 of Bragg et al. (2012))."
39. Page 8, Line 25: "Figure 4 shows the Aannual and Sseasonal ..... and Eoi^{400}compared to the PI control" NOTE: Figure 4 does not show what you are saying it shows. It shows only annual anomalies. Figures 3 and 4 had become swapped when I had reworked the Figures prior to initial upload. I have decapitalized "Annual" and "Seasonal".
40. Page 8, Line 26: "the Hudson Bay and the Baltic Sea regions" This has been corrected
41. Page 8, Line 27: "during he the summer" This has been corrected
42. Page 9, Line 1: "From the results in Table 3 it is possible to decompose diagnose" This has been corrected
43. Page 9, Line 4: "The Climate climate system's Sensitivity sensitivity to a doubling" This has been corrected
44. Page 9, Line 7: "When we neglect geographical changes". I don't follow.... This sentence has been changed so that the paragraph ends with "When we approximate Earth System Sensitivity (ESS) using Eoi^{400} and E^{280} (with ESS = 1.88 x $\Delta T_{Eoi400\text{-}E280}$) we obtain ~5.5 ± 1.3°C. Subsequently the ESS/CS ratio is ~1.90, which lies at the higher-end of the 1.1-2.0 ensemble range of PlioMIP1 (Haywood et al., 2013a) in which HadCM3 had a ratio of 2.0. It must be noted, however, that this calculation assumes that the PlioMIP2 enhanced boundary condition represents the equilibriated Earth System under a contemporary doubling of CO_2, hence neglecting non-glacial elements of the PRISM4 retrodicted palaeogeography."
45. Page 9, Line 9: "Subsequently Consequently"
46. Page 9, Line 13: "Mean Annual Precipitation metric (MAP; Table 4)" This has been corrected
47. Page 9, Line 14: "and is relatively insensitive to Pliocene the chosen CO_2 changes in the Pliocene experiments" I have rephrased the sentence so that it now reads "The globally integrated Mean Annual Precipitation (MAP; Table 4) is influenced by both Pliocene geography and CO2 changes."
48. Page 9, Line 21: "plots of precipitation change between the 400 and 280 ppm versions of Pliocene and the PI control are shown in can be seen within Figure 6" I have changed this to "Seasonal plots of precipitation change between the Pliocene (Eoi400) and the pre-industrial (E280) control experiments are shown in Figure 6."
49. Page 9, Line 25: Capital S in South Corrected
50. Page 9, Line 26: "more eastward further east" Corrected
51. Page 9, Line 28: Last sentence is weird and incomplete I have removed the discussion on the monsoon systems.
52. Page 9, Line 30: two "the" I have removed the discussion on the monsoon systems.
53. Page 10, Line 10: "The time averaged, zonal mean, meridional" Corrected
54. Page 10, Line 11: "the indirect Ferrel" (the word is unnecessary here) I have removed the superfluous "indirect"
55. Page 10, Line 13: "Assuming Taking the maximum in of the meridional streamfunction represents as a measure of the Hadley cell strength" This sentence has been modified following your suggestion.
56. Page 10, Line 15: "than the Southern cell which is in contrast to contradiction with observational and reanalysis data (...) that show consistently show the southern cell being stronger" This sentence has been modified accordingly.

57. Page 10, Line 17: “stronger than the northern cell” also replace the “for” occurring in the parentheses with “in” This sentence has been modified accordingly.
58. Page 10, Line 22: “and Polar Jet streams (PJ)” Corrected
59. Page 11, Line 5: While Table 6 does show the MASSTs of the experiments, Figure 9 does not show that. It shows the anomalies of very specific sets of experiments. Please rephrase and rearrange this sentence. This sentence has been changed to “Modelled mean annual SST’s (MASST) are detailed within Table 6 and Pliocene anomalies are shown within Figure 9.” Figure 9 caption has also been corrected.
60. Page 11, Line 7: I think you mean Eoi^{400}– Eoi^{280} so as to be consistent with what you say on Line 3 in Page 9. This has been corrected
61. Page 11, Line 9: “Within the North Atlantic sub polar gyre where Eoi^{400}– E^{280} reaches +9.3C” That sentence does not stand on its you. You probably forgot to complete your thought here. This has been corrected to “The greatest warming occurs within the North Atlantic subpolar gyre where Eoi^{400} -E^{280} reaches 9.3°C.”
62. Page 12, Line 4: “Here we rely upon the mixed layer depth (MLD) as calculated as a diagnostic variable within HadCM3 climate model” What kind of sentence is that? Not only is there nothing in that sentence, it doesn’t sound proper either. I agree. The intention of this sentence was superfluous so I have removed it.
63. Page 12: Reference the mixed layer figure in the section on mixed layer. The first sentence now reads “The mixed layer depth (MLD) for E^{280}, Eoi^{280} and Eoi^{400} is shown within Figure 11.:
64. Page 12, Line 13: “streamfunctions” “are shown” plural.. This has been corrected.
65. Page 12, Line 14: Rewrite sentence on this line This has been rewritten as “The Atlantic Meridional Overturning Circulation (AMOC) streamfunctions for E^{280}, Eoi^{280} and Eoi^{400} are shown within Figure 12 and detailed within Table 7. The pre-industrial experiment E^{280} has a maximum AMOC strength at 26.5°N of 13.4 ± 1.2 Sv. This compares reasonably well with the estimate of 17.2 ± 4.6 Sv derived by McCarthy et al. (2015) using measurements from the RAPID array between April 2004 and October 2012. The all-latitude maximum in AMOC strength ($AMOC_{max}$) within E^{280} occurs at ∼650 m depth at 33.75°N with a strength of 15.7 ± 1.2 Sv.”
66. Page 12, Line 15: “Our AMOC... (put value here) differs to from that in Bragg et al. (2012; strength of 17.6 Sv), a difference that we ascribe to the latter’s use of” I have removed the reference to Bragg et al. (2012). The sentence is now shown in answer to your comment no/ 65
67. Page 12, Line 17: “Fluctuations of the order in the AMOC” huh??? Sincerest apologies. I have completed this sentence so that it now reads “Multidecadal to centennial fluctuations including a dominant ∼225 year oscillation are present within the Pliocene experiments but not the pre-industrial experiment.”

The HadCM3 contribution to PlioMIP Phase [..[*]]2.

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Abstract. We present the UK's input into the Pliocene Model Intercomparison Project Phase 2 (PlioMIP2) using the HadCM3 climate model. [..[2]]The 400 ppm CO_2 [..[3]]Pliocene experiment has a mean annual surface air temperature that is 2.9 °C warmer than the pre-industrial and a polar amplification of between 1.7 and 2.2 times the global mean warming. The PRISM4 enhanced Pliocene palaeogeography accounts for a warming [..[4]]of 1.4[..[5]] °C whilst the CO_2 increase from 280 to 400 ppm leads to a further 1.5[..[6]] °C of warming. Climate sensitivity is 3.5[..[7]] °C for the pre-industrial and 2.9[..[8]] °C for the Pliocene. Precipitation change between the pre-industrial and Pliocene is complex, with geographic and land surface changes primarily modifying the geographical extent [..[9]]of mean annual precipitation. Sea ice fraction and areal extent is reduced during the Pliocene particularly in the southern hemisphere, although it persists through summer in both hemispheres. The Pliocene palaeogeography drives a more intense Pacific and Atlantic Meridional Overturning Circulation (AMOC). This intensification of AMOC is coincident with more widespread deep convection in the Southern Ocean and North Atlantic. We conclude by examining additional sensitivity experiments and confirm that the [..[10]]choice of total solar insolation (1361 [..[11]]vs. 1365 [..[12]]Wm^{-2}) and orbital configuration (modern vs. 3.205 Ma) do not significantly influence the anomaly-type analysis in use by the Pliocene community.

[*]removed: 2 Part 1: Core and Tier 1 experiments.

[2]removed: We outline the process of setting up HadCM3 with the enhanced PRISM4 boundary conditions and discuss in detail the assumptions and choices made. We then present the HadCM3 spin-up process from an initial arbitrary atmosphere, zero-momentum ocean state through to a well-equilibriated climatic state. We present data from the spin-up and final climatological mean state of the Pre-industrial and Pliocene experiments. We focus on large-scale climatic and oceanic features. Comparing the control Pliocene experiment to pre-industrial the change in palaeogeography and CO

[3]removed: combined account

[4]removed: in globally integrated air temperature (sea surface temperature)

[5]removed: °C (0.8 °C) and

[6]removed: °C (1.0 °C). For the pre-industrial and Pliocene we see climate sensitivities (for 2 x CO_2) of

[7]removed: ° C

[8]removed: °C . We derive an approximation of Earth System Sensitivity of ∼5.5 ° C leading to an ESS/CS ratio ∼ 1.90. Precipitation change is more

[9]removed: , and increasing CO_2 leading to a general wet-get-wetter response. We see a reduction in summer and winter sea ice extent driven by both geographical - land surface changes and CO_2 increase. In our model, the Atlantic Meridional overturning is relatively insensitive to CO_2 but is strengthened in the Pliocene (from 15.7 to 19.6 Sv) due to the change in palaeogeography. Understanding the change in Antarctic Circumglobal Current within the Pliocene is problematic given an overly intense modern ACC and palaeogeography-driven changes in barotropic model set-up within the Pliocene. We

[10]removed: modern orbit used throughout PlioMIP2, is a satisfactory substitute for the Pliocene 3.205 Myr KM5c orbit in terms of large-scale climate and a number of important climatic indices. We also quantify the impact of the total solar irradiance choice

[11]removed: versus

[12]removed: W m^{-2}) on the Pliocene - pre-industrial anomaly and absolute climatic state and highlight climatic systems which may present non-linear responses

1 Introduction

The Pliocene Model Intercomparison Project Phase 2 (hereafter PlioMIP2; Haywood et al. (2016)) has dual focus[..[13]]: 1) to improve understanding of Pliocene climate and [..[14]]2) to evaluate climate model uncertainty [..[15]]for a warmer than modern climate. This dual focus are referred to as Pliocene4Pliocene (P4P) and Pliocene4Future (P4F). PlioMIP2 concentrates on a 'time slice' centred on an interglacial peak (Marine Isotope Stage (MIS) KM5c; 3.205 Ma) within the mid Piacenzian, for convenience we refer to this as the *Pliocene*. The overall PlioMIP2 experiment design is split up into three components - [..[16]]CORE, Tier 1 and Tier 2 experiments. The [..[17]]CORE components must be completed by all [..[18]]modelling groups, whilst the Tier 1 [..[19]]and Tier 2 components are optional with Tier 1 experiments being a higher priority than Tier [..[20]]2. The PlioMIP2 protocol specifies a standard and enhanced boundary condition dataset[..[21]]. The standard boundary conditions have a Pliocene topography constrained by the modern land sea mask [..[22]](LSM) and bathymetry, whilst the enhanced boundary conditions have full PRISM4 [..[23]]mid Piacenzian palaeogeography (Pliocene Research Interpretation and Synoptic Mapping; Dowsett et al. (2016)). Here we describe the model set-up of the enhanced boundary conditions within HadCM3 [..[24]](Hadley Centre Climate Model version 3). Table 1 details the PlioMIP2 experiments conducted within this study, [..[25]]along with an additional set of non-PlioMIP2 experiments that explore [..[26]]specific model sensitivities. We conduct all [..[27]]CORE and Tier 1 experiments as well as the Pliocene4Future Tier 2 experiments [..[28]]as described within Haywood et al. (2016).

The structure of this paper is as follows. [..[29]]Section 2 describes the model configuration[..[30]]. Section 3 describes the experiment design [..[31]]including model boundary conditions[..[32]], model initialisation and spin-up[..[33]]. Results from

[13] removed: ; to serve as a means to

[14] removed: also, through its uses a potential analogue for contemporary climate, as a means

[15] removed: . These

[16] removed: Core

[17] removed: former are

[18] removed: model groupswhilst the optional

[19] removed: (T1) experiments are

[20] removed: 2 (T2).

[21] removed: , the former has

[22] removed: and bathymetry whilst the latter has

[23] removed: palaeogeography (Dowsett et al., 2016)

[24] removed: . Table **??**

[25] removed: which include a

[26] removed: additional

[27] removed: core

[28] removed: . An additional paper will describe the Pliocene4Pliocene Tier 2 (Forcing Factorisation) experiments, and for full consistency with PlioMIP1 (Haywood et al., 2011), a second accompanying paper will describe the set-up and results from the standard boundary condition model experiments.

[29] removed: We first describe

[30] removed: and then

[31] removed: (Sections 2 and 3). The generation of

[32] removed: is then detailed (Section 3.2.1) with a focus on efforts to maintain consistency with previous work using HadCM3. This leads onto the

[33] removed: (Section 3.3) and the quantification of the equilibrium state (Section 3.4). The climatological mean state of the experiments is

the experiments are then described within [..[34]]Section 4, with a particular focus on atmospheric circulation and surface climatology (Section 4.1) and [..[35]]the oceanic responses (Section 4.2).

2 Model Description

We use the UK Meteorological Office (UKMO) HadCM3 coupled Atmosphere-Ocean [..[36]]General Circulation Model (AOGCM). A top-level description of the atmosphere and ocean models relevant to this palaeogeographic reconfiguration follows. A focus is given to the ocean model as its external geometry is changed (the atmosphere model layers drapes over the topography) and certain aspects impact upon the interpretation of model prediction. For a more comprehensive description of the fundamental model structure see Pope et al. (2000) and Gordon et al. (2000). Subsequent corrections and improvements to the model, as well as a thorough evaluation against observational data has been described in Valdes et al. (2017). The HadCM3 model used in this study is equivalent, in terms of model updates and modifications, to HadCM3B-M2.1a of Valdes et al. (2017). We keep with the name HadCM3 in reference to the UKMO (Pope et al., 2000; Gordon et al., 2000) but acknowledge the contribution made by the University of Bristol in keeping the HadCM3 model developed and updated.

The HadCM3 climate model is no longer state-of-the-art but the [..[37]]model's runtime speed, relative ease of reconfiguration, and prediction performance [..[38]]make it well suited [..[39]]for a suite of centennial scale palaeoclimate simulations as is required here. HadCM3 can be integrated for many thousands of model years and reaches a satisfactory state of equilibrium with little drift in the surface climatology. However, there are a number of model weaknesses, compared to more contemporary models, and these will be discussed where relevant.

The HadCM3 model has been used extensively for studies of the Pliocene[..[40]]. The model was used within PlioMIP1 experiments 1 (Atmosphere GCM) and 2 (Atmosphere-Ocean GCM; Bragg et al. (2012)), and amongst others has been used to successfully investigate Panama [..[41]]Seaway closure (Lunt et al., 2008), ENSO and teleconnections (Bonham et al., 2009), [..[42]]ice sheet reconstructions and orbital forcing (Dolan et al., 2011; Prescott et al., 2014), [..[43]]sea ice reconstructions (Howell et al., 2014), terrestrial and marine oxygen isotopes (Tindall and Haywood, 2015), and non-analogous aspects of

[34] removed: the results, starting with the Atmospheric

[35] removed: then the oceanic realm

[36] removed: GCM which was used for the first Pliocene model Intercomparison (PlioMIP1). This model was used by the UKMO extensively within CMIP3 (the Third Climate Model Intercomparison Project; contributing to IPCC AR4 Solomon et al. (2007)) but used only for historical and decadal experiments within CMIP5 (IPCC AR5; Flato et al. (2013)), being superseded by HadGEM1 and then HadGEM2-ES respectively. It

[37] removed: models

[38] removed: compared to similar generation models

[39] removed: to long-integration palaeoclimate studies involving the investigation of multiple forcings

[40] removed: , the

[41] removed: seaway

[42] removed: ice-sheet

[43] removed: Terrestrial

Pliocene climate (Hill, 2015). In all cases, either a modern [..[44]]LSM and bathymetry was used or [..[45]]specific regional palaeogeographical uncertainties were explored. This body of work therefore represents the first published record [..[46]]where HadCM3 has been reconfigured with a bespoke global Pliocene palaeogeography.

[..[47]]

2.1 Atmosphere model

The atmosphere component of HadCM3 has 19 vertical hybrid sigma-pressure levels [..[48]]extending to 5 hPa. Horizontal resolution is 3.75[..[49]]° longitude × 2.5[..[50]]° latitude. The model has a time-step of 30 minutes and is coupled to the ocean model (Section 2.2) [..[51]]at the end of every model day (Gordon et al., 2000). Atmospheric composition, other than CO_2 (described in Section 3.1 and 3.2) is equivalent to pre-industrial throughout (N_2O 270 ppb, CH_4 760 ppb and no CFC) consistent with both the PMIP2 protocol (Braconnot et al., 2007) [..[52]]and the previous Pliocene experiments conducted within PlioMIP1. Monthly distribution of ozone is derived from the Li and Shine (1995) climatology and ground-based troposphere measurements, corrected for the ozone hole [..[53]](Johns et al., 2003). The radiative effects of background aerosol are represented by a simple parameterisation based [..[54]]on modern climatological conditions (Cusack et al., 1998).

The solar constant (total solar irradiance; hereafter TSI) is held fixed at [..[55]]1365 Wm^{-2} within [..[56]]all PlioMIP2 protocol experiments, a value consistent with the pre-industrial experiment within PMIP2 (the 2nd Palaeoclimate Model Intercomparison Project; LSCE (2007)) and CMIP5 (the 5th Coupled model Intercomparison Project; Taylor et al. (2012)) as well as PlioMIP1. [..[57]]This value (derived in the 1990s) is used to remain consistent with previous work but acknowledge that space borne measurements of TSI have decreased from [..[58]]1371 to 1362 Wm^{-2} from 1978 to 2013 (Kopp and Lean, 2011; Meftah

[44]removed: land sea mask

[45]removed: regional geographical sensitivities

[46]removed: of

[47]removed: A top-level description of the Atmosphere and Ocean models relevant to this palaeogeographic reconfiguration follows. A focus is given to the ocean model as its external geometry is changed (the atmosphere model layers drapes over the topography) and certain aspects impact upon the interpretation of model prediction. For a more comprehensive description of the fundamental model structure see Pope et al. (2000) and Gordon et al. (2000). Valdes et al. (2017) describes corrections and improvements that have been made since 2000 as well as a thorough evaluation against observational data. The HadCM3 model used in this study is equivalent, in terms of model updates and modifications, to HadCM3B-M2.1a of Valdes et al. (2017). We keep with the name HadCM3 in reference to the UKMO (Pope et al., 2000; Gordon et al., 2000) but acknowledge the contribution made by the University of Bristol in keeping the HadCM3 developed and updated.

[48]removed: (5 terrain-following sigma-levels at the surface changing to pressure-levels at height, extending to 10 hPa)

[49]removed: x

[50]removed: ^{o} (96 longitude x 73 latitude), equivalent to 417 x 278 km and 295 x 278 km at the equator and 45^{o} latitude respectively

[51]removed: using the oasis coupler

[52]removed: . We chose PMIP2 so as to remain consistent with

[53]removed: (Hadley Centre technical Note 22; Johns et al 2001)

[54]removed: upon the modern

[55]removed: 1365.0

[56]removed: *all*

[57]removed: We use this often used canonical

[58]removed: 1,371

et al., 2014). Indeed, the CMIP6 [..[59]]pre-industrial simulation (piControl) uses a value of 1361 Wm^{-2} [..[60]](Matthes et al., 2017). We examine the impact of TSI choice within the context of both pre-industrial and Pliocene climates [..[61]]within Section 4.3.2. Recognising this source of uncertainty and the impact on climate anomalies (due to non-linear climate responses) is important as the PlioMIP2 specification (Haywood et al., 2016, Section 2.3.1) leaves the choice of TSI to individual modelling groups, whose TSI may depend upon if the group is [..[62]]a participant of CMIP6. The impact of TSI choice is minimised by the Pliocene communities use of climatological anomalies, but should be considered when comparing model-model absolute indices (summer sea ice extent, AMOC strength, etc.).

The land surface scheme is MOSES 2.1 (Met Office Surface Exchange Scheme; [..[63]]Cox et al. (1999); Essery et al. (2003)) which principally deals with the hydrology of the canopy to the subsurface and the surface energy balance (including subsurface thermodynamics). Within the scheme there are 5 plant functional types (PFTs: [..[64]]broadleaf and needleleaf trees, C_3 and C_4 grasses, and shrub) as well as soil (desert), lakes and ice. Each non-glaciated terrestrial grid cell can take fractional values of each surface type[..[65]].

The HadCM3 PlioMIP1 study of Bragg et al. (2012) used an earlier version of MOSES (MOSES1) which treats each model grid cell as a homogeneous surface and uses effective parameters to calculate the grid cell's energy and moisture flux. However, MOSES2 introduced subgrid (tiled) heterogeneity and improved representation of surface and plant processes [..[66]]such that hydrological partitioning and energy balance is computed for each subgrid tile. A comparison of MOSES1 and MOSES2.1 can be found within Valdes et al. (2017). In this study we incorporate a software update taken from the HadGEM2 climate model (Good et al., 2013) which corrects the temperature control of plant respiration and improves forest resilience to elevated temperatures (making the model MOSES2.1a in the nomenclature of Valdes et al. (2017)).

Runoff is collected in drainage basins and delivered to associated coastal outflow points (on a 3.75[..[67]]°×2.5[..[68]]° geographic grid). River transport is not modelled explicitly, instead runoff is returned to the coastal outflow point in the [..[69]]uppermost layer of ocean instantaneously [..[70]]at the atmosphere-ocean coupling step [..[71]](Gordon et al., 2000). Internally-draining basins are present but the associated water loss is not explicitly modelled within the routing scheme. Instead, the loss of freshwater in the hydrological cycle is corrected using an artificial freshwater correction field applied to the

[59] removed: *piControl* simulation

[60] removed: (Matthews et al. , 2016). We examined

[61] removed: (Section 4.3.2)

[62] removed: participating within

[63] removed: Cox et al. (1999)

[64] removed: Broadleaf and Needleleaf

[65] removed: , except if it is glaciated, which is unitary. We hold vegetation fixed through the entirety of each experiment. MOSES principally deals with the hydrology of the canopy to the subsurface, and the surface energy balance (including subsurface thermodynamics).

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[67] removed: x

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uppermost surface of the ocean (Section 2.2). This freshwater closure also acts to correct the freshwater loss due to terrestrial snowfall accumulation.

2.2 Ocean Model

The ocean component is a rigid lid model of the [..[72]]Bryan-Cox lineage (Bryan, 1969; Cox, 1984a). In the vertical there are 20 unevenly-spaced levels, concentrated near the surface [..[73]]in order to improve representation of the surface mixed layer. The [..[74]]model uses z co-ordinate vertical layers with bottom topography represented by "full" cells. [..[75]]This leads to a discontinuous representation of the bathymetry which has poorer fidelity at greater depths (where the thickness of levels is greatest). The ocean time-step is 1 hour and horizontal spatial resolution is 1.25[..[76]]°×1.25° and the grid is aligned so that there are six ocean grid cells to each atmosphere grid cell ([..[77]]3.75[..[78]]°×2.5[..[79]]°). To simplify coupling with the atmosphere model, the ocean model's coastline has a resolution of 3.75°×2.5° at the uppermost level.

Within the modern boundary conditions, cells overlying important subgrid-scale channels[..[80]], such as those along the Denmark Strait, the Iceland-Faroe and the Faroe-Shetland Channels, and straits surrounding the Indonesian archipelago[..[81]], are artificially deepened. Additionally, within the Greenland-Iceland-Scotland region, a convective adjustment scheme (Roether et al., 1994) is used to better represent down-slope mixing [..[82]]that improves the representation of dense outflows that form the North Atlantic Deep Water (NADW). [..[83]]The scheme is not [..[84]]used for Antarctic Bottom Water. Water mass exchange through the Strait of Gibraltar, a channel that falls [..[85]]subgrid-scale, is achieved with a diffusive pipe. [..[86]]This pipe provides transport of water properties through the 13 topmost layers of the ocean (∼ 1200m) between the Eastern Atlantic with the Western Mediterranean. Other subgrid-scale channels, such as the Canadian Archipelago, Hudson [..[87]]Strait outflow and the Makassar Strait, remain spatially unresolved and [..[88]]therefore unrepresented. The latter has been shown to possess most of the Indonesian throughflow [..[89]](Gordon and Fine, 1996) and so is compensated for within the model by a deepening of regional model bathymetry.

[72]removed: Bryan-Cox-Semtner lineage (Bryan, 1969; Semtner, 1974; Cox, 1984b)
[73]removed: (8 in the top 200 m) in an attempt
[74]removed: ocean time-step is 1 hour. The model uses z-type cells
[75]removed: Horizontal
[76]removed: º
[77]removed: 288 x 144 geographic grid) giving 6 grid cells per atmospheric model cell . The land-sea mask is effectively
[78]removed: x
[79]removed: º resolution in the top 200 m but beneath increases to 1.25º lateral resolution
[80]removed: are artificially deepened to improve flow representation (
[81]removed:)
[82]removed: ; important for
[83]removed: A similar
[84]removed: present
[85]removed: sub grid-scale
[86]removed: Other sub grid-scale
[87]removed: Bay
[88]removed: subsequently
[89]removed: (Gordon et al., 2000)

The fresh water budget of the ocean is balanced by [..[90]]fluxes from the river routing scheme and a [..[91]]freshwater correction applied to the uppermost ocean level. Within the pre-industrial (and associated CO_2 sensitivity experiments) the freshwater correction field is prescribed (time-invariant[..[92]]). The correction field had been derived to provided closure of the model's modern hydrological cycle and consists of a uniform background component (0.01 mm day^{-1}) correcting internal-drainage (Section 2.1) and an iceberg component (0.02 mm day^{-1}) whose geographic distribution is derived from modern observations (Gordon et al., 2000; Pardaens et al., 2003). Within the Pliocene experiments we omit the [..[93]]time-invariant correction (including the iceberg component) and instead use an [..[94]]annual model-derived geographically-invariant freshwater correction to reduce residual [..[95]]salinity drifts to zero[..[96]]. We justify this as we currently do not have *a priori* knowledge of the geographic distribution of iceberg melt consistent with the ice sheet distribution within the PlioMIP2 enhanced boundary conditions. In the [..[97]]Northern Hemisphere we do not expect significant iceberg calving given the configuration of the Greenland [..[98]]Ice Sheet and the lack of marine terminating margins specified within the PRISM4 boundary conditions.

The rigid lid streamfunction scheme imposes the need for bathymetry to be smoothed particularly in steep regions of the [..[99]]high latitudes, and for islands to be specified as line integrals for the barotropic stream function. A major consequence of the latter is that the modern Bering Strait [..[100]]throughflow is not fully resolved as it sits between two model-defined continents between which the barotropic component of flow is poorly resolved. This impacts our interpretation of the Pliocene experiments (closed Bering Strait) with respect to the pre-industrial (open Bering Strait), this is discussed within Section 3.2.2. An advantage of the rigid lid scheme on the other hand is that barotropic gravity waves are neglected, which facilitates the use of longer time-steps.

The sea ice model is a simple thermodynamic scheme based upon Semtner (1976) with parameterisations for ice drift and concentration[..[101]]. To account for sea ice leads, upper-boundaries of 0.995 and 0.980 are imposed to Arctic and Antarctic sea ice [..[102]]concentrations based upon the parameterisation of Hibler (1979). Ocean salinity is influenced by sea ice formation and melt by assuming a sea ice salinity of 0.6 psu (excess salt, in effect, is returned to the ocean). Sublimation is represented and acts to increase ocean salinity (salt blown into leads), whilst ocean-bound snowfall and precipitation reduce salinity. The effects of snow age and melt pond formation on surface albedo [..[103]]are represented with a [..[104]]linear

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[92]removed: freshwater iceberg field
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[94]removed: annually derived
[95]removed: globally-integrated
[96]removed: , and hence artificiality close the water budget
[97]removed: northern hemisphere
[98]removed: ice sheet
[99]removed: high-latitudes
[100]removed: through-flow
[101]removed: (including leads). Observation derived
[102]removed: concentration of 0.995 and 0.980 are used
[103]removed: is
[104]removed: simple parametersisation

parametrisation based upon surface temperature. Ice drifts only by the action of surface ocean current, hence within the model surface wind stress indirectly influences sea ice drift via its influence on the surface ocean current. Sea ice dynamics is represented by [..[105]]parameterisations based upon Bryan et al. (1975). Ice rheology is simply represented by preventing ice convergence above 4 m thickness. There is no representation for the interaction between floes.

3 Experiment Design

[..[106]]Here we describe the setup of the Pliocene and the pre-industrial [..[107]]experiments. The Pliocene experiments have CO_2 set to 280, 350, 400, and 450 [..[108]]ppm, each conducted with modern orbit as specified by the PlioMIP2 protocol [..[109]](Haywood et al., 2016). These experiments are labelled the *control* Pliocene experiment Eoi^{400} (PlioMIP2 [..[110]]CORE), $Eoi^{350,450}$ (Tier 1; P4F+P4P), and Eoi^{280} (Tier 2; P4F). Here we use a comma separated list in the superscript to indicate 2 or more experiments. In all cases, the superscript indicates CO_2 (in [..[111]]ppm) and the o and i indicate the inclusion of of the PRISM4 orography [..[112]](including PRISM4 vegetation, soil, and lakes[..[113]]) and ice sheets. The experiments based upon the pre-industrial geography are run with CO_2 values of 280, 400, and 560 [..[114]]ppm. These are identified as the *control* pre-industrial experiment E^{280} ([..[115]]CORE), E^{400} (Tier 2; P4F) and E^{560} (Tier 1; P4F)[..[116]].

We explore two sets of non-protocol sensitivities - [..[117]]Pliocene orbital configuration and TSI. The PlioMIP2 protocol (Haywood et al., 2016) specifies a modern orbital configuration for all Pliocene experiments. We investigate the validity of this orbit choice by rerunning Eoi^{400} with a 3.205 [..[118]]Ma orbital configuration representing the mPWP time slice of Haywood et al. (2013a) within experiment ${}_{orb}Eoi^{400}$[..[119]]. We also investigate the choice of total solar irradiance (Section 2.1) [..[120]]by rerunning the two control (CORE) experiments with a TSI of 1361 Wm^{-2} within ${}_{1361}E^{280}$ and ${}_{1361}Eoi^{400}$.

[..[121]]In total 6 Pliocene experiments were run: the CORE (Eoi^{400}), two Tier 1 (Eoi^{350} and Eoi^{450}), one Tier 2 (Eoi^{280}[..[122]]) as well as an orbital (${}_{orb}Eoi^{400}$) and TSI sensitivity experiment (${}_{1361}Eoi^{400}$). These are accompanied by 4 pre-industrial

[105] removed: parameterisation based upon Bryan (1969) and ice
[106] removed: We now
[107] removed: experiment
[108] removed: ppmv
[109] removed: , and a 3.205 Myr orbit consistent with the KM5c time slice. The modern-orbit Pliocene
[110] removed: Core experiment
[111] removed: ppmv
[112] removed: and ice-sheet, the former includes
[113] removed: . The pre-industrial experiments are run at
[114] removed: ppmv, giving
[115] removed: Core
[116] removed: components of PlioMIP2 experiment design. We use a preceding subscript to indicate a sensitivity outside the PlioMIP2 protocol. We
[117] removed: orbit and solar insolation. The
[118] removed: Myr orbit experiments(the standard is modern orbit) are distinguished by *orb*, such as
[119] removed: , and
[120] removed: , are labelled
[121] removed: For convenience when referring to climate forcing, we use the term *palaeogeography* to encompass the combined change in topography, land surface (vegetation, lakes, soils, ice sheets), land sea mask and bathymetry (
[122] removed: - E

based experiments: the CORE (E^{280}), a Tier 1 (E^{560}) and Tier 2 (E^{400}) as well as a TSI sensitivity experiment (${}_{1361}E^{280}$). These 10 simulations are detailed within Table 1.

3.1 Pre-industrial [..[123]]and associated sensitivity experiments ($E^{280,400,560}$ and ${}_{1361}E^{280}$)

The [..[124]]experiments with pre-industrial geography are 500 year continuations of a long integration ([..[125]]>2000 model years) pre-industrial experiment that had been initialised from [..[126]]the observed ocean state [..[127]]of Levitus and Boyer (1994). The experiment uses a topography and a bathymetry regridded and smoothed from ETOPO5 [..[128]](Edwards, 1989), and vegetation and soil translated from [..[129]]the land cover of Wilson and Henderson-Sellers (1985). River routing is derived by aggregating runoff in all terrestrial grid boxes within each runoff basin in a manner which is internally consistent with the model topography. All model boundary conditions were developed by the Met Office Hadley Centre (hereafter MOHC) and used within CMIP3/5. In accordance [..[130]]with the PlioMIP2 protocol (Haywood et al., 2016), levels of atmospheric CO_2 [..[131]]are set to 280, 400 and 560 [..[132]]ppm giving the pre-industrial (E^{280}) and two CO_2 sensitivity experiments (E^{400} and E^{560}). A fourth pre-industrial based experiment, ${}_{1361}E^{280}$, is run to [..[133]]investigate the model sensitivity to the choice in [..[134]]TSI value (Section 2.1 and 4.3.2).

3.2 Pliocene (PlioMIP2 enhanced) [..[135]]and sensitivity experiments ($Eoi^{280\text{-}450}$, ${}_{orb}Eoi^{280\text{-}450}$, and ${}_{1361}Eoi^{400}$)

3.2.1 Boundary condition preparation

For PlioMIP2 [..[136]]the boundary conditions for the modern day and the ‘enhanced’ variant of the Pliocene reconstruction are provided on regular 1[..[137]]° grids held within NetCDF files (USGS, 2016; Haywood et al., 2016). For convenience we shall refer to the PlioMIP2 enhanced boundary condition as PRISM4. The modern boundary condition is provided to facilitate the anomaly method of boundary condition generation. The [..[138]]LSM is first regridded by computing the anomaly of PRISM4

[123] removed: experiment description
[124] removed: pre-industrial experiments
[125] removed: >2500 model year
[126] removed: Levitus
[127] removed: (Levitus and Boyer 1994)
[128] removed: (Edwards 1989)
[129] removed: Wilson and Henderson-Sellers (1985) land cover
[130] removed: to
[131] removed: is
[132] removed: ppmv
[133] removed: allow derivation of
[134] removed: total solar irradiance
[135] removed: experiment description
[136] removed: enhanced and modern boundary conditions
[137] removed: o
[138] removed: land sea mask

[..[139]]Pliocene minus modern (at 1[..[140]]° resolution) and regridding using bilinear interpolating [..[141]]to the 3.75°×2.5° model grid, and then applying the anomaly to the models pre-industrial [..[142]]LSM. This is so that the final reconstruction is consistent with both the original [..[143]]pre-industrial model set up [..[144]]and the PRISM4 [..[145]]LSM. Finally, a number of [..[146]]manual corrections were applied to the resulting [..[147]]3.75°×2.5° PRISM4 LSM to ensure that the underlying character of the PRISM4 reconstruction is represented as best as reasonably practicable at [..[148]]the model's resolution. For consistency with the pre-industrial boundary conditions [..[149]]developed by MOHC we remove Svalbard and Novaya Zemlya[..[150]], despite their subaerial extension within PRISM4. Similarly, we keep the Pliocene LSM in the Persian Gulf region the same as pre-industrial despite a withdrawal of the Persian Gulf within PRISM4. This choice was made as the Persian Gulf within the pre-industrial LSM is represented by an inland sea (due to inadequate spatial resolution) and so further changes would be difficult to interpret. At model resolution the Pliocene Strait of Gibraltar is [..[151]]identical to the pre-industrial and so the diffusive pipe is incorporated.

The resulting PRISM4 LSM was [..[152]]used to constrain the generation of the [..[153]]Pliocene orography and bathymetry [..[154]](which was generated using area-weighted regridding, and then applied as an anomaly to the existing HadCM3 pre-industrial orography and bathymetry[..[155]]). River basins and outflow points were derived from the pre-industrial routing scheme (Section 3.1) but corrected in regions of [..[156]]LSM, topographical and ice-bedrock change using a [..[157]]model-resolution river routing model [..[158]]based on the D8 method (Tribe, 1992). This was then followed by manual correction in [..[159]]regions when model resolution fails to capture important orography[..[160]], or where the regridded Pliocene orography is flat. The [..[161]]PRISM4 vegetation scheme (represented by BIOME4 biomes) was regridded by combining a BIOME4-

[139]removed: pliocene

[140]removed: º resolution) ,

[141]removed: from 360 x 180 to the 96 x 73

[142]removed: land sea mask

[143]removed: MOHC

[144]removed: (regridding methodology and hand edits) and

[145]removed: land sea mask (LSM). Furthermore

[146]removed: hand edits were then

[147]removed: 96 x 73

[148]removed: model resolution. In particular hand edits were applied in the Eurasian Arctic, Baffin Bay, Greenland, North America, Europe and the Mediterranean, Africa, South America, Australasia and Antarctica. In remaining consistent with the MOHC developed

[149]removed: we omit

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[153]removed: model resolution

[154]removed: which were interpolated using similar methodology

[155]removed: . River routing was

[156]removed: land sea mask

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[158]removed: . This is

[159]removed: corrected regions in circumstances

[160]removed: or where new

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to-MOSES2 lookup table [..[162]]with an area-weighted survey of underlying biomes[..[163]]. A similar area-weighted regridding was conducted for the lake field. We chose not to generate the lake [..[164]]field as an anomaly from the modern lake distribution as land surface change since the pre-industrial would be imprinted on the [..[165]]model's lake distribution. [..[166]]

3.2.2 Barotropic streamfunction [..[167]]island configuration

Rigid lid Bryan-Cox type models, such as the ocean of HadCM3, require islands (and by extension, continents) to be identified so that a net non-zero barotropic flow (depth-independent) can be achieved around the line integral (streamfunction non-zero). The default pre-industrial configuration of the model has 6 islands defined and is shown within Figure 1. For consistency, aforementioned [..[168]](Section 3.2.1) manual corrections to both LSM and bathymetry have allowed islands to be specified that are consistent with the E^{280} experiment, but also reflect the key palaeogeographic changes presented by the PRISM4 palaeogeography. In particular western Iceland and East Greenland land cells were adjusted to ensure that Iceland could be defined as a streamfunction island (Figure 1), and hence we could [..[169]]fully represent the East Greenland Current. The island to the west of the Antarctic Peninsula body [..[170]]lies within the island definition of the main Antarctic continent and therefore the circulation between the two is not fully resolved (only the [..[171]]baroclinic flow is resolved fully). Figure 1 compares the pre-industrial and PRISM4 Pliocene HadCM3 island specification[..[172]], It can be seen that the 6 islands in the pre-industrial configuration has been increased to 8 islands in the Pliocene.

It is noted that within the pre-industrial HadCM3 [..[173]]model setup the Bering Strait barotropic component of throughflow is [..[174]]unresolved and both the Makassar Strait and the Canadian Archipelago are [..[175]]spatially unresolved (Section [..[176]]2.2). This poses a conceptual problem in the interpretation of the Pliocene experiments with respect to the pre-industrial, as the PRISM4 [..[177]]Pliocene geography has these throughflow regions [..[178]]closed. Therefore, [..[179]]our simulations do not resolve the full climatic response of these regional palaeogeographic changes[..[180]]. A pre-industrial experiment with a [..[181]

[162] removed: and bespoke regridding methodology relying on
[163] removed: , guided by the model resolution LSM
[164] removed: mask
[165] removed: models
[166] removed: All boundary conditions were generated within a bespoke Matlab framework using the MOHC-developed and National Centre for Atmospheric Sciences, Computing Modelling Services (NCAS-CMS) supported xancil and um2nc tools.
[167] removed: Island
[168] removed: hand edits to both land sea mask
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[171] removed: Baroclinic
[172] removed: . Within PRISM4, 8 islands have been specified
[173] removed: experiment
[174] removed: poorly resolved
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]fully-resolved Bering Strait and Canadian Archipelago would partially [..[182]]address these problems but would then force a divergence away from the previous HadCM3 descriptions and evaluations, as well as from past and current CMIP/PMIP and [..[183]]PlioMIP1 model implementations. These problems are likely to arise in all rigid [..[184]]lid streamfunction ocean models that have insufficient spatial resolution to fully-resolve these [..[185]]gateways and inherently cannot resolve line integrals around bounding land masses. Ocean models that have explicit or implicit free surface schemes with sufficiently high horizontal spatial resolution may [..[186]]reduce these issues.

3.3 Pliocene Model initialization and [..[187]]spin-up

Model spin-up is conducted in [..[188]]a series of stages in which the model and boundary conditions are increased in complexity. These stages are:

1. The atmosphere model (AGCM) was initialized in a 50 year run with PRISM4 LSM and basic surface scheme (lakes, ice, shrubs and orography)[..[189]], pre-industrial CO_2 (280 ppm) and zonal hemispheric-symmetric monthly Sea Surface Temperature (SST) and sea ice [..[190]]distribution derived from the initial 2500 model year pre-industrial HadCM3 [..[191]]simulation from Section 3.1. Model failures at this stage allow for the identification of steep topography that requires regional smoothing. [..[192]]

2. The ocean model is added (without barotropic physics) and the resulting AOGCM run is continued for 100 [..[193]]years with Pliocene bathymetry and river scheme (year 50 within Figure 2).

3. Barotropic physics is incorporated (without specifying islands) and [..[194]]the simulation is continued run for 200 years. Regional bathymetric smoothing was applied in regions which caused model failure [..[195]](Figure 2 stage a).

4. The island configuration (Section 3.2.2, Figure 1) is then derived [..[196]]using an iterative series of sensitivity tests in which each island configuration is refined. Once complete, the set of island line integrals are [..[197]]incorporated into

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[183]removed: PlioMIP
[184]removed: rid
[185]removed: channels
[186]removed: resolve
[187]removed: spin up
[188]removed: eight stages . First the Atmosphere model
[189]removed: and land sea mask
[190]removed: derived from a well spun-up
[191]removed: (AOGCM) simulation
[192]removed: This is then followed by a
[193]removed: year AOGCM run with PRISM4 bathymetry and the river scheme . Here the ocean model has barotropic physics turned off. Stage three adds the barotropic physics
[194]removed: runs
[195]removed: .
[196]removed: in stage four
[197]removed: then

the model configuration[..[198]]. At this stage we have an AOGCM incorporating full barotropic physics [..[199]](Figure 2 stage b).

5. CO_2 is [..[200]]increased from 280 ppm at 1% per year [..[201]]until 400 ppm [..[202]]is attained. CO_2 is then held fixed.

6. At model year 950 [..[203]]a problem with ancilliary file generation had been resolved allowing the vegetation boundary [..[204]]condition to be incorporated into the model. Additionally, a regional modification was made to the bathymetry and streamfunction island configuration to the west of the Antarctic Peninsula [..[205]]to resolve a persistent numerical mode within the barotrotopic solver in this region [..[206]](Figure 2 stage c).

7. The AOGCM model was then set to continue to year 2000 (CO_2 held fixed at 400 [..[207]]ppm).

8. At year 2000[..[208]], five additional experiments are spun-off [..[209]]that run alongside Eoi^{400} (Table 1), these are $Eoi^{280,350,450}$, ($_{orb}Eoi^{400}$) and $_{1361}Eoi^{400}$. All six experiments are run to year 2400. [..[210]]

9. The models are then run for the final 100 years configured with full climatological output. [..[211]]

[..[212]]

3.4 Equilibrium State

By model years 2400 to 2500, [..[213]]the Pliocene control experiment [..[214]](Eoi^{400}) has achieved a quasi-steady-state equilibrium in which the globally-integrated net top-of-the-atmosphere (TOA) radiative imbalance is [..[215]]0.047 [..[216]]Wm^{-2},

[198] removed: (1. At stage five
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[200] removed: then ramped up
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[202] removed: and
[203] removed: , stage six,
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[205] removed: following a persistent and unsatisfactory model artefact
[206] removed: . The
[207] removed: ppmv).
[208] removed: we reached stage seven at which 3 further experiments at 280, 350 and 450 ppmv
[209] removed: (as well as the four KM5c 3.205 Mya orbit experiments). All 8
[210] removed: At the final stage, stage eight, the models are
[211] removed: The final 50 years is used for climatological averages.
[212] removed: In total the ten Pliocene experiments (Core and Tier 1 detailed within Table ?? as well as $_{orb}Eoi^{400}$, $_{1361}E^{280}$, and $_{1361}Eoi^{400}$) were run for 7000 model years giving a total of 7.5Tb of data. Each instance of the model is run on 24 Intel Xeon E5-2650v4 cores of the University of Leeds Advanced Research Computing platform (ARC2) and with full physics achieve 70-90 model years per wall clock day depending upon the chosen diagnostic output suite.
[213] removed: our
[214] removed: Eoi^{400}
[215] removed: +
[216] removed: W m

surface [..[217]]1.5 m [..[218]]air temperature trend is [..[219]]0.08[..[220]]°C century^{-1} and ocean potential temperature trends within the upper 200 m and globally integrated [..[221]]are -0.026[..[222]]°C century^{-1} and [..[223]]0.041[..[224]]°C century^{-1}[..[225]]. The corresponding values for the pre-industrial control [..[226]]experiment (E^{280}) are -0.115 [..[227]]Wm^{-2}, 0.052[..[228]]°C century^{-1}, 0.008°C century^{-1} and -0.014[..[229]]°C century^{-1} respectively. High CO_2 experiments, Eoi^{450} and E^{560} present the largest, yet modest [..[230]]departures from equilibrium and are characterized by TOA imbalance >0.2 Wm^{-2}. Positive TOA imbalance is indicative of a warming of the earth system, the small heat capacity of the atmosphere [..[231]]means that residual energy is predominantly taken up by the ocean, which is reflected in the volume [..[232]]integrated ocean temperature evolution. Warming of the deep ocean is primarily occurring at depths [..[233]]deeper than 2000 m [..[234]]in the Pacific basin. The Indian and Antarctic oceans are the most equilibriated[..[235]], particularly at intermediate depths and [..[236]]deeper. Table 2 summarizes the equilibrium [..[237]]states of the seven PlioMIP2 experiments and Figure 2 presents the time-evolution of ocean [..[238]]potential temperature of the Pliocene control experiment (Eoi^{400}). All experiments are [..[239]]deemed to be in a satisfactory state of equilibrium, although the high TOA simulations Eoi^{450} and E^{560} have above average warming within the deep ocean.[..[240]]

4 Results

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[219]removed: +
[220]removed: ^{o}
[221]removed: ocean potential temperature trends
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[239]removed: satisfactory, although E^{560} has
[240]removed: Derivation of climatological trends within the surface climatology of the last 100 model years is inconsistent as the trend is small compared to the climatological standard deviation.

[..[241]] We base our analysis on climatological averages from the final 50 [..[242]]years of each simulation. The final 50 years of output is used to remain consistent with the HadCM3 PlioMIP1 submission (Exp. 2 of Bragg et al. (2012)). The PlioMIP2 protocol (Haywood et al., 2016) does not state a standardised time length for climatological means although the PlioMIP2 website (USGS, 2018) does request 100 years [..[243]]of monthly climatology. We therefore make the 50 year climatological average and 100 years of monthly climatology available on the PlioMIP2 data repository.

In order to keep discussion clear and concise, we principally compare the two [..[244]]PlioMIP2 CORE experiments which we refer to as the *control* experiments (Eoi^{400} and E^{280}). Whilst there is uncertainty in mid Piacenzian (MIS KM5c) CO_2 levels, 400 ppm represents the middle of the anticipated CO_2 range derived from marine and terrestrial based reconstructions. We therefore consider Eoi^{400} as our "best estimate" simulation. In addition, when referring to climate forcing, we use the term *palaeogeography* to encompass the combined change in topography, land surface (vegetation, lakes, soils, ice sheets), LSM and bathymetry which we diagnose from the anomaly Eoi^{280} minus E^{280}.

4.1 [..[245]]State of the atmosphere and earth surface climatology

4.1.1 Surface Air Temperature and Climate Sensitivity

Modelled mean annual 1.5 m surface air temperatures (hereafter [..[246]]MASAT) are detailed within Tables 3 and corresponding Pliocene anomalies are shown within Figure 3. Relative to the pre-industrial control (E^{280}) temperatures are generally warmer within the Pliocene experiments. Differences in [..[247]]MASAT of up to 31.3[..[248]]°C over Greenland and Antarctic regions [..[249]]coincide with Pliocene ice sheets and where their respective elevation is less than the pre-industrial. Typically, warming is greatest over land, although in ocean regions at or near Antarctic [..[250]]LSM change (pre-industrial grounded ice to Pliocene ocean) warming is significant. This pattern of warming is [..[251]]similar to results derived with HadCM3 within [..[252]]PlioMIP1 under PRISM3 boundary conditions [..[253]](Exp. 2 of Bragg et al. (2012)).

The Pliocene cooling in the Barents [..[254]]Sea is statistically significant and persistent through the model integration (Figure 3). It coincides with an increase in Pliocene winter and spring sea ice concentration driven by palaeogeographic terrestrial winter cooling in the circum-Arctic (Pliocene subaerial Barents and Baltic Sea). This cooling is potentially driven by the

[241] removed: We derive
[242] removed: yrs (model years 2450-2499)and climatic oscillations from the final
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[249] removed: of Pliocene ice sheet retreat (and topographical reduction)
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[254] removed: sea

partial suppression of northward heat transport (in the Norwegian Current) by the [..[255]]subaerial extension of Ireland and Scotland within the model.

The Eoi^{400}-E^{280} MASAT anomaly of 2.9 °C (Table 3) is lower than the 3.3 °C of HadCM3 within PlioMIP1 (Bragg et al., 2012) and lies within the PlioMIP1 model ensemble range of 1.84 - 3.60 °C (Haywood et al., 2013b). The MASAT anomaly also lies between the PlioMIP2 studies of 2.4 °C Kamae et al. (2016) and 3.8 °C (Chandan and Peltier, 2017), although note that this comparison is not exhaustive as PlioMIP2 is incomplete at the time of press. Table 3 also presents MASAT data for the equatorial (between 30 °S and 30 °N) and polar regions (latitudes greater than 60 °). The resulting polar amplification factors for the Pliocene control (Eoi^{400}) relative to the pre-industrial control (E^{280}) are 1.7 for the North Pole and 2.2 for the South Pole.

Figure 4 shows the [..[256]]annual and seasonal temperature anomalies for Eoi^{280} and Eoi^{400} (against E^{280}). Terrestrial regions that are subaerial only within the Pliocene, such as the Hudson Bay and the Baltic Sea regions [..[257]]are up to 10[..[258]] °C warmer (colder) during [..[259]]the summer (winter) seasons, due to land-ocean heat capacity contrast. It is unclear how much of this seasonal temperature response in the Baltic Sea region ([..[260]]subaerial during the Pliocene) is a driver of persistent cooling within the Barents Sea region.

From the results in Table 3 it is possible to [..[261]]diagnose the factors that contribute to Pliocene warming relative to the pre-industrial [..[262]](E^{280}). Considering the Pliocene control experiment (Eoi^{400}), we find that the change in palaeogeography [..[263]](Eoi^{280}-E^{280}) accounts for a temperature change of 1.4[..[264]] °C, whilst the increase in CO_2 (Eoi^{400}-Eoi^{280}) accounts for a further 1.5[..[265]] °C of warming. Considering uncertainty in Pliocene CO_2 level, we find temperature changes of 0.9 and 2.0 °C for Eoi^{350}-Eoi^{280} and Eoi^{450}-Eoi^{280} respectively. The PlioMIP2 experimental design provides a second pathway to examine Pliocene palaeogeographical and CO_2 forcing (e.g. Eoi^{400}-E^{400} and E^{400}-E^{280}). Within this pathway, the Pliocene geography (Eoi^{400}-E^{400}) accounts for 1.8 °C of warming and the increase in CO_2 (E^{400}-E^{280}) accounts for 1.1 °C of temperature increase. These differences highlight that there are non-linearities within the climate system's response to changes in boundary condition.

The [..[266]]climate system's sensitivity to a doubling of CO_2 ([..[267]]Climate Sensitivity; CS) is 3.5 °C for the pre-industrial [..[268]](derived from E[..[269]][..[270]]^{560} and E^{280}) and 2.9 °C for the Pliocene (derived from Eoi^{400} and Eoi^{280} and scaled by [..[271]

[255] removed: sub-aerial extension of the UK region within the model.
[256] removed: Annual and Seasonal
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[260] removed: sub-areal
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[263] removed: and land surface
[264] removed: $\pm$ 0.7^{o}
[265] removed: $\pm$ 0.7^{o}C warming.
[266] removed: Climate Sensitivity
[267] removed: CS_{2xCO_2})
[268] removed: is 3.5 $\pm$ 0.7
[271] removed: 1.88

]1.94 (=log(560/280) / log(400/280))[..[272]]. The pre-industrial CS is consistent with the 3.3[..[273]]°C for HadCM3 within CMIP3 [..[274]](Randall et al., 2007). The Pliocene CS is similar to the 3.1[..[275]]°C for HadCM3 [..[276]]and lies at the lower end of the 2.7 - 4.1°C ensemble range of PlioMIP1 Experiment 2 [..[277]](Haywood et al., 2013a). When we approximate Earth System Sensitivity (ESS) [..[278]]using Eoi^{400} and E^{280} ([..[279]]with ESS = 1.94 x $\triangle T_{Eoi^{400}}$ [..[280]]$-E^{280}$) we obtain ~[..[281]]5.6°C. Subsequently the ESS/CS ratio is ~[..[282]]1.9, which lies at the higher-end of the 1.1 - 2.0 [..[283]]range of the PlioMIP1 [..[284]]ensemble (Haywood et al., 2013a) in which HadCM3 had a ratio of 2.0. It must be noted, however, that this calculation assumes that the PlioMIP2 enhanced boundary condition [..[285]]represents the equilibriated Earth System [..[286]]under a contemporary doubling of CO_2, hence neglecting [..[287]]non-glacial elements of the PRISM4 retrodicted palaeogeography.

4.1.2 Precipitation

The globally integrated Mean Annual Precipitation [..[288]](MAP; Table 4) [..[289]]is influenced by both Pliocene geography and CO[..[290]] $_2$ changes. Pliocene geography acts to increase globally integrated MAP, although this appears sensitive to the background CO_2 level (e.g. Pliocene geography increases MAP by 0.07 and 0.05 mm day^{-1} at 280 and 400 ppm respectively). The Eoi^{400}-E^{280} MAP anomaly of 0.11 mm day^{-1} (Table 4) compares with the 0.17 mm day^{-1} from HadCM3 within PlioMIP1 (Bragg et al., 2012) and sits at the lower end of the ~ 0.09 - 0.18 mm day^{-1} of the PlioMIP1 model ensemble (Haywood et al., 2013b).

The geographical distribution of MAP change can be seen within Figure 5. Northern [..[291]]Hemisphere land masses generally see increased precipitation within the Pliocene although this effect is minimal in the continental interiors. In the [..[292]]Southern Hemisphere much of South America and South Africa receives less precipitation whilst Australia [..[293]]and Northern Greenland see an increase in precipitation during the Pliocene. Increasing Pliocene CO_2 generally intensifies the

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[278] removed: from
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[282] removed: 1.90, which again is similar to the ESS/CS ratio of
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[288] removed: metric
[289] removed: , is influenced principally by geography and land surface changesand is relatively insensitive to Pliocene
[290] removed: $_2$ changes.The change in palaeogeography (Eoi^{280} - E^{280}
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[292] removed: southern hemisphere
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precipitation anomaly which is most apparent in the tropics. Regions that [..[294]]receive little precipitation within E^{280} [..[295]]e.g. North Africa and the East Antarctic Ice Sheet [..[296]]have little (<0.1 mm day^{-1}) change in precipitation under increasing Pliocene CO_2.

Seasonal plots of precipitation change [..[297]]between the Pliocene (Eoi^{400}) and the pre-industrial (E^{280}) control experiments are shown in Figure 6. During the Pliocene we see wetter summers over much of North America and northern Europe. Regions [..[298]]experiencing reduced precipitation in western North America as well as central and western Europe are a consequence of weakened westerlies [..[299]]

[..[300]](not shown). As can be seen within Figures 6(c-f), the Pliocene geography and land surface change drive an intensification of precipitation associated with the Inter Tropical Convergence Zone (ITCZ), although changes in seasonal latitudinal distribution [..[301]]are not evident. The [..[302]]South Pacific Convergence Zone, extending from the [..[303]]Western Pacific warm pool (WPWP) southeastward to the [..[304]]South Central Pacific extends ∼15[..[305]]° further east in E^{280} than Eoi^{400} and Eoi^{280}[..[306]].

[..[307]]

[..[308]]

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[294] removed: have little (< 0.1 mm day^{-1}) change in precipitation are regions that

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[296] removed: . Therefore, the models response to elevating CO_2 in the Pliocene context seems to largely follow the wet get wetter paradigm.

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[306] removed: , Depsite this, a double-ITCZ is not otherwise present as commonly found in other GCMs (Li and Xie 2014), for example within the Western pacific.or extension into the South Atlantic is not present.

[307] removed: To understand changes in monsoon dynamics it is important to assess the underlying model performance. Here we consider the the South American and Indian monsoons. Within E^{280} the seasonal timing and geographic distribution of the South American Monsoon System (SAMS) precipitation cycle is adequately represented although the intense precipitation is too far southward, focussed too zonally at 15°S (cf. 10 - 30°S). Within E^{280} the seasonal shifts in the overlying atmosphere (e.g. the tropospheric anticyclone (250-hPa) and 925-hPa wind field) are well-represented, although the ITCZ precipitation is overly intense. During the dry season (JJA-SON) the general pattern of rainfall and dryness is captured. The change in land surface (Eoi^{280}-E^{280}) drives an intensification of the SAMS wet season over east and central Brazil as both the ITCZ and South Atlantic Convergence Zone (SACZ) intensify. Outside the SAMS region the austral winter becomes drier. As CO_2 increases a reduction in wet season precipitation in eastern Brazil coincident with increased precipitation to the west is predicted. Pliocene CO_2 has a much smaller (< 1 mm day^{-1}) influence on austral winter precipitation (SAMS dry season).

[308] removed: The Indian monsoon is represented fairly well within E^{280}, we see the seasonal switch from dry North Easterlies to wet South Westerlies. With the change in palaeogeography (Eoi^{280}-E^{280}) the mean summer (JJAS) rainfall increases by up to ∼200% in the North West and generally 60-160% over the remainder of India. With the increase in Pliocene CO_2 (from Eoi^{280} to Eoi^{400}) we see a slight reduction in precipitation of up to 7%.

4.1.3 Planetary scale atmospheric circulation.

The time averaged[..[309]], zonal mean, meridional mass stream function for the atmosphere is shown within Figure 7. Clearly distinguished are the Hadley, the [..[310]]Ferrel and the [..[311]]Polar cells. The mean meridional circulation is sensitive to equatorial asymmetries in surface temperatures as ascent in the tropical belt and subsidence in the subtropics form the Hadley cells. [..[312]]Taking the maximum of the meridional streamfunction as a measure of the Hadley cell strength, we find that the Pliocene geography acts to weaken (intensify) the Hadley cell within the [..[313]]Northern (Southern) Hemisphere. Looking at E^{280} we find the northern cell is stronger (+10.8%) than the southern cell which is in [..[314]]contradiction with observational and re-analysis data [..[315]](Stachnik and Schumacher, 2011) that consistently shows the southern cell being stronger than the northern cell. With increasing Pliocene CO_2, the southern cell intensifies and becomes stronger than the north (+19% [..[316]]in Eoi^{280} and +42% [..[317]]in Eoi^{400}). This intensification (weakening) of the Hadley cell under changed land surface and geography should be driven by steepening (shallowing) of the tropical meridional temperature gradients in the Tropics south (north) of the ITCZ. Coincident with the change in land surface and geography (Eoi^{280}-E^{280}) is a weakening of the combined annual mean overturning within the two Hadley cells (191 and 180 x10^9 [..[318]]Kg s^{-1} for E^{280} and Eoi^{280} respectively).

The wintertime Subtropical Jet (StJ; also known as the midlatitude jet) and Polar Jet [..[319]](PJ) are shown within Figure 8. We characterise the mean spatial envelope of the jet path by deriving from 50 years of daily data, the days per season in which the mean mass-weighted flow speed integrated over [..[320]]400-100 hPa (∼[..[321]]7-16 km) exceeds 30 ms^{-1}. For both E^{280} and E^{400} we obtain a seasonal jet stream configuration which is consistent with the ERA-40 and derived results of [..[322]]Archer and Caldeira (2008). The PJ and the StJ stream can be difficult to differentiate as the former is latitudinally irregular, so following [..[323]]Koch et al. (2006) we use normalised wind shear as a height differentiator. The [..[324]]StJ stream path is more persistent and stable [..[325]]and so is characterised by the mean latitude of the [..[326]]StJ core which is shown within Table 5. The change in geography (Eoi^{280}-E^{280}) drives a poleward shift of the mean [..[327]]StJ latitude of ∼1.6[..[328]]° in the Northern Hemisphere

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[322] removed: Archer and Caldeira (2008). The polar jet and the Subtropical jet
[323] removed: Koch et al., (2006)
[324] removed: Subtropical jet
[325] removed: latitudinally and so we characterise the mean response of the jets to changing boundary conditions
[326] removed: Subtropical jet core ,
[327] removed: jet
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(both seasons) and 2.2[..[329]]° in the Southern Hemisphere summer. The response to Pliocene CO_2 (Eoi^{400}-Eoi^{280}) increase is weaker with a 0.8[..[330]]° poleward shift of the mean StJ latitude in the Northern Hemisphere (both seasons). The [..[331]]Southern Hemisphere mean StJ appears only weakly poleward shifting in response to Pliocene CO_2 increase. Regionally, jet behaviour deviates from the global mean view. Within the North Atlantic, the [..[332]]PJ moves equatorward in response to the change in palaeogeography (Eoi^{280}-E^{280}) moving the jet stream mean path from northern to southern Europe [..[333]](Figure 8b vs. 8f). Synoptic storms grow and propagate along jet stream axis and so this [..[334]]equatorward shift in the PJ likely contributes to the increase in rainfall seen in southern Europe during Pliocene wintertime (Figure 6e [..[335]]vs. 6f).

4.2 [..[336]]State of the [..[337]]Ocean climatology

4.2.1 Sea [..[338]]surface temperature and [..[339]]warm pools

[..[340]]Modelled mean annual SST's (MASST) are detailed within Table 6 and Pliocene anomalies are shown within Figure 9. We see a 0.8[..[341]]°C warming due to the change in palaeogeography (Eoi^{280} [..[342]]-E^{280}) and a further 1.0[..[343]]°C of warming due to the change in Pliocene CO_2 (Eoi^{400} [..[344]]-Eoi^{280}). With increasing levels of CO_2 regional patterns of [..[345]]MASST change due to palaeogeography are overprinted by CO_2[..[346]]-induced warming. This warming is most evident in the [..[347]]mid-latitudes, particularly within the North and South Atlantic and the North Pacific. [..[348]]The greatest warming occurs within the North Atlantic subpolar gyre where Eoi^{400} [..[349]]-E^{280} reaches 9.3[..[350]]°C. In the vicinity of the modern Gulf Stream and North Atlantic Drift we find a cooling during DJF and MAM seasons (up to -4.9[..[351]]°C within Eoi^{280} [..[352]]-E^{280}). Investigation of surface ocean vectors (not shown) suggests an intensification of the North Atlantic wind-driven

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subpolar gyre and Labrador current which appears to disrupt western intensification and the path of the Gulf Stream[..[353]]. The westerlies in the region appear to intercept the remnant gulf stream and divert it from a north easterly to a more eastward path, this is seen as the warm tongue south of the extant Gulf stream (Figure 9). A similar expression of [..[354]]MASST within the North Atlantic was seen by Chandler et al. (2013) and characteristic signatures may be present within other PlioMIP1 experiments (e.g. Figure 1 of Dowsett et al. (2013)). A persistent cooling is also found within the Barents [..[355]]Sea region coincident with the surface air temperature anomalies discussed within Section 4.1.1.[..[356]]

Table 6 also details the size of the global and component equatorial warm pools within the [..[357]]pre-industrial and Pliocene experiments. We see an expansion of the globally-integrated warm pool with the change in palaeogeography (Eoi^{280} [..[358]]-E^{280}), but this effect diminishes with increased CO_2. This is evident in both the Western Hemisphere [..[359]]warm pool (WHWP) and [..[360]]Indo-Pacific warm pool (IPWP) regions. As expected, increased CO_2 drives warm pool expansion.

4.2.2 Sea Ice

A complex picture emerges in the [..[361]]sensitivity of seasonal sea ice [..[362]]distribution to geographic and CO_2 changes as shown within Figure 10. Within [..[363]]the Northern Hemisphere winter, the palaeogeography changes drive an equatorward expansion of sea ice [..[364]]in the Greenland Sea region. Increasing CO_2 from 280 to 400 ppm counteracts some of this expansion. In the [..[365]]Southern Hemisphere the palaeogeographical changes [..[366]]suppress sea ice extent significantly within the Weddell Sea and also eastward towards the Davis Sea in both summer and winter. Coincident with this suppression [..[367]]is an equatorward expansion of sea ice within the Bellinghausen Sea region. [..[368]]As we increase CO_2 [..[369]]we see a general reduction in the sea ice extent and [..[370]]concentration in both summer and winter months. Within Eoi^{400} boreal summer the Arctic is largely ice-free, the ice that is present is mostly $<50\%$ concentration. During [..[371]]austral summer the

[353]removed: , although the expression of the Gulf Stream within HadCM3 surface ocean vectors is limited
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concentration of sea ice within the Pliocene becomes more asymetric and reduced in extent[..[372]], being concentrated in the highest latitudes [..[373]]off the coast of West Antarctic.

4.2.3 Mixed [..[374]]layer depth and [..[375]]deep water formation

[..[376]]The mixed layer depth (MLD) [..[377]]for E^{280}, Eoi^{280} and Eoi^{400} is shown within Figure 11. We focus on deep convection, the principle mechanism of [..[378]]deep-water formation. Deep convection is highly localised and therefore model representation is only suggestive. Nevertheless, E^{280} represents [..[379]]reasonably well the modern open-ocean deep convection that [..[380]]occurs within the Weddell and Ross Seas ([..[381]]which form the main formation sites of Antarctic Bottom Water) and in the Labrador, Irminger and Greenland [..[382]]Seas. All Pliocene experiments exhibit [..[383]]more widespread deep convection particularly within the Labrador and Norwegian Seas, and [..[384]]near the Antarctic Peninsula island. In contrast to Burls et al. (2017) we do not model any significant increase in Pliocene North Pacific MLD, and hence no subsequent intensification of North Pacific Deep Water (NPDW) formation ([..[385]]Table 7 and Figure 11).

4.2.4 Ocean Heat and Mass Transports (Atlantic and Pacific MOC)

The Atlantic Meridional Overturning Circulation (AMOC) [..[386]]streamfunctions for E^{280}, Eoi^{280} and Eoi^{400} [..[387]]are shown within Figure 12 and detailed within Table 7. [..[388]]The pre-industrial experiment E^{280} has a maximum AMOC strength at 26.5°N of 13.4 ± 1.2 Sv. This compares reasonably well with the estimate of 17.2 ± 4.6 Sv [..[389]]derived by McCarthy et al. (2015) using measurements from the RAPID array between April 2004 [..[390]][..[391]][..[392]]and October 2012. The all-latitude maximum in AMOC strength ($AMOC_{max}$) within E^{280} occurs at ∼650 m depth at 33.75°N with a strength of 15.7 ± 1.2 Sv.

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[385] removed: see Table 7
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[388] removed: We find consistency between E^{280} and E^{400} and the observed
[389] removed: (RAPID array 26.5° N Apr
[390] removed: - Oct 2012 ;McCarthy et al., 2015)
[391] removed: 1 Sv = 10^6 m^3
[392] removed: . Our E^{280}

We find an AMOC which is more intense in the Pliocene than in the pre-industrial, which is accountable to the Pliocene palaeogeography (Table 7). The $AMOC_{max}$ [..[393]]of Eoi^{400} is 19.6 ± 1.0 Sv and occurs at ~[..[394]]650 m depth at 33.75[..[395]]°N. Multidecadal to centennial fluctuations, including a dominant ~225 year oscillation, are present within the Pliocene experiments but not the pre-industrial [..[396]]experiment. In all [..[397]]Pliocene simulations, $AMOC_{max}$ occurs within the 25 - 33.75[..[398]]°N zonal envelope and at a depth of [..[399]]~650 m. The Eoi^{400} $AMOC_{max}$ lies within the 10-24.6 Sv range of PlioMIP1 (Zhang et al., 2013), whilst the Eoi^{400}-E^{280} $AMOC_{max}$ anomaly of 4.2 Sv (Table 7) lies outside the PlioMIP1 ensemble range of -0.9–3.6 Sv.

Despite an intensification of the AMOC [..[400]]within the Pliocene experiments, we find that the overturning strength [..[401]]reduces slightly at ~40[..[402]]°N driven by the changed land surface and bathymetry (Eoi^{280}-E^{280}). This is seen within cooling evident in Gulf Stream [..[403]]MASSTs of Figure 9. Under increasing Pliocene CO_2, the mid-latitude overturning intensifies with a corresponding decrease in the Gulf Stream [..[404]]MASST cold anomaly. The overturning within the polar region is evidence of bottom water formation within the Nordic [..[405]]Seas. In E^{280} overturning extends to ~80[..[406]]°N but is weaker than in the Pliocene models (which [..[407]]extends to ~75[..[408]]°N). This is reflected within the geographic extent and intensity of deep convection shown within [..[409]]Figure 11.

The Pacific Meridional Overturning Circulation (PMOC) streamfunction is shown within Figure 13 and detailed within Table 7, in which $PMOC_{+ve}$ reflects the strength of the subtropical gyre circulation whilst $PMOC_{-ve}$ reflects the strength (and depth) of the Pacific Deep Water (PDW) and North Pacific Deep Water (NPDW). [..[410]]Pliocene palaeogeography (Eoi^{280}[..[411]]-E^{280}) drives an intensification of both the subtropical gyre and PDW overturning[..[412]], whilst increasing CO_2 acts to weaken them. [..[413]]The Pliocene subtropical gyre [..[414]]($PMOC_{+ve}$) and PDW ($PMOC_{-ve}$) overturning are stronger

[393]removed: differs to the 17.6 Sv of Bragg et al. , (2012), a difference we ascribe to the latter use of HadCM3 MOSES 1. The time-mean maximum strength within

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regardless of CO_2 level ([..[415]]e.g. within Eoi^{400} PMOC$_{+ve}$ and PMOC$_{-ve}$ are 22% and 6% stronger than E^{280}). With the change in palaeogeography ([..[416]]Eoi^{280}[..[417]]-E^{280}) the PDW shoals (from [..[418]]~4 to 3 km) and with increasing Pliocene CO_2 the NPDW overturning reduces in northward reach, [..[419]]associated with the warming of North Pacific [..[420]]MASST (Figure 9).

4.2.5 Antarctic [..[421]]Circumpolar Current

The Antarctic [..[422]]Circumpolar Current (ACC) strength is detailed within Table 8 and shown within Figure 14. We calculate the volumetric flow of the [..[423]]ACC at the Drake [..[424]]Passage across a 64.4-56.9°S, 65°W transect using the positive aspect of the U component (zonal) of the total ([..[425]]barotropic and baroclinic) velocity.

We find an overly intense ACC within E^{280} and E^{400} when [..[426]]compared against recent observations of [..[427]]134-164 Sv (Cunningham et al., 2003; Griesel et al., 2012). The overly intense ACC within HadCM3 has been identified previously. [..[428]]Meijers et al. (2012) compared CMIP5 historical experiments [..[429]]to observations and found the model's ACC flow at the Drake Passage transect of 244.5 ± 4.0 Sv [..[430]]compared unfavourably to [..[431]]observations and 155 ± 51 Sv of the CMIP5 multi-model mean. This unrealistic intensity appeared to be driven, or at least connected to, an overly strong salinity [..[432]]gradient across the ACC, particularly [..[433]]towards low-latitudes (Meijers et al., 2012). This could be a consequence of the artificial fresh water correction field used within the CMIP5 historical and piControl experiments and the E^{280} here.

Modelled ACC strength appears significantly reduced within the Pliocene experiments. Westerlies intensify in the Southern Hemisphere within the Pliocene but mostly in regions poleward of the Sub-Antarctic front (poleward of the ACC). The weakened Drake Passage throughflow is mirrored within the vertically integrated barotropic stream function. Care must be taken when [..[434]]interpreting ACC strength in situations of changed palaeogeography and island specification. The ACC is weakly stratified and vertically coherent and so is dominantly barotropic in nature. Within the Pliocene boundary conditions

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(Section 3.2.2) the island Peninsula is defined as a separate barotropic island (from the Antarctic continent), and this may be driving the Pliocene reduction in ACC strength. Also [..[435]]given a more complex line-integral configuration, the model's barotropic solver may not be converging [..[436]]fully towards a solution. The change in island specification may also be responsible for the change in ACC geographical extent shown within Table 8. Defining the streamfunction cross section by the latitudes of the centroid and upper 50% of zonal transport we see that the change in geography (from E^{280} [..[437]]to Eoi^{280}) drives a general [..[438]]latitudinal thinning of the ACC extent and [..[439]]an equatorward shift of its centroid[..[440]].

Within the Pliocene experiments, the ACC runs mostly between the surface and sea floor between 60 and 57[..[441]]°S, whilst a deeper countercurrent is present closer to the Peninsula. In the Pacific, a pronounced thinning of the ACC latitude extent is observed in which the Sub Antarctic front moves [..[442]]equatorwards (the subtropical front is mostly unchanged). [..[443]]With the Pliocene geography, there are suggestions that the Antarctic Coastal Current (the counter-current to the ACC) flows between the Peninsula island and the Antarctic land mass. [..[444]]There is uncertainty as smaller islands in this region are unrepresented within the model. Figure 14 also suggests a more continuous [..[445]]coastal current with the Pliocene palaeogeography, particularly between 180 and 90[..[446]]°E. The [..[447]]Antarctic Coastal Current plays an important role in air-sea exchange in the Weddell Sea region, leading to deep convection. This enhanced deep convection within the Pliocene is reflected within Figure 11 and would explain the strengthened AMOC within the Pliocene (Section 4.2.4)[..[448]]

[..[449]], although the limited representation of [..[450]]deep convection within the model should be noted. This intensified [..[451]]Antarctic Coastal Current is driven partially by intensified winds poleward of the Sub-Antarctic front (at latitudes >66[..[452]

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[449]removed: Figure 14 also suggests a more continuous counter current particularly between 180 and 90º E. The counter current plays an important role in air-sea exchange in the Weddell Sea region, leading to deep convection. This enhanced deep convection (DC) within the Pliocene is reflected within Figure 11 and could explain the strengthened AMOC within the Pliocene (Section 11),

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]°S) within the Pliocene. The Weddell [..[453]]Sea sub-polar gyre is weakened and restructured whilst the Ross Sea gyre is less intense and extends more [..[454]]equatorward.

4.3 Sensitivity to external boundary conditions

4.3.1 Orbital configuration

Here we examine the sensitivity of the Pliocene climate to choice of orbital configuration (e.g. modern (default) vs. KM5C at 3.205 Ma). For Eoi^{400} there is no [..[455]]meaningful difference in global means ([..[456]]Table 3 MASAT, [..[457]]Table 4 MAP, [..[458]]Table 6 MASST and warm pool areal extent).

There is a statistical [..[459]]significant difference between $_{orb}Eoi^{400}$ and Eoi^{400} $AMOC_{max}$ (t([..[460]]98)=7.20, p<<[..[461]]0.0001) and $AMOC_{max}$ 26.5°N (t([..[462]]98)=11.36, p<<[..[463]]0.0001) using a 2-sample t-test assuming unequal variance (null hypothesis being there is [..[464]]no difference in the two timeseries of annual means). With regards to $PMOC_{+ve}$, $_{orb}Eoi^{400}$ and Eoi^{400} are [..[465]]deemed equivalent (t([..[466]]98)=0.62, p=0.54) [..[467]]whilst for $PMOC_{-ve}$, the two experiments are equivalent at the 95% confidence level (t([..[468]]98)= [..[469]]1.93, p=0.06). [..[470]]Centennial-scale fluctuations in Pliocene $AMOC_{max}$ could account for statistical differences between the climatological mean [..[471]]periods of $_{orb}Eoi^{400}$ and Eoi^{400}, as $AMOC_{max}$ differences could simply reflect a lack of coherence introduced since the year 2000 fork point.

4.3.2 Total Solar Insolation[..[472]]

Section 2.1 identified the possibility of different TSI values being used within PlioMIP2 climate models. Here we determine the sensitivity of HadCM3 within E^{280} and Eoi^{400} experiments to changing the TSI parameter. Reducing total solar insolation

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[467]removed: and similarly, but less significant,
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[470]removed: Cyclical variability in the simulated AMOCwith a period of 225 years is simulated, so any statistical difference between model simulations for
[471]removed: period could simply be due to a lack of coherence between
[472]removed: (TSI)

from 1365 to 1361 [..[473]]Wm^{-2} (- 0.3%) reduces the mean incoming solar (SW) radiation averaged over the entire Earth's surface by 1 [..[474]]Wm^{-2} (from 341.25 to 340.25 [..[475]]Wm^{-2}). Table 9 accumulates climatological indices from E^{280} and Eoi^{400} under these two TSI values. Figure 15 shows the spatial pattern of climatological differences (Pliocene minus [..[476]]pre-industrial) for simulations based upon 1365 [..[477]]and 1361 [..[478]]Wm^{-2} for MASAT, MAP and MASST. Overall the patterns of climatological anomalies for the experiments using TSI of either 1361 or [..[479]]1365 Wm^{-2} are very similar. In this sense, comparison of model temperature anomalies to proxy temperature anomalies should not generally be influenced by the choice of TSI.

However, in a similar way to the [..[480]]orbital configuration, $AMOC_{max}$ does appear sensitive to TSI [..[481]]value when we compare Eoi^{400} against ${}_{1361}Eoi^{400}$ (t(98)=-13.3, p<<.0001) and [..[482]]E^{280} to ${}_{1361}E^{280}$ (t(98)=2.47, p=0.015). It is possible that this [..[483]]sensitivity to TSI could be a consequence of the previously described [..[484]]AMOC cyclicity and lack of coherence between Eoi^{400} and ${}_{1361}Eoi^{400}$.

5 Discussion

In this study we have described the incorporation of PlioMIP2 (PRISM4) mid-Piacenzian (Pliocene) enhanced boundary conditions into the HadCM3 global climate model. We conducted PlioMIP2 [..[485]]CORE and Tier 1 pre-industrial and Pliocene based experiments as well as sensitivity experiments exploring solar insolation [..[486]]and orbit choice. We then examined the large-scale features of the [..[487]]atmosphere and ocean state of these experiments.

Comparing to the pre-industrial control (E^{280}), we find Pliocene surface warming focussed within the high-latitudes in a similar distribution to HadCM3 within PlioMIP1 under PRISM3 boundary conditions [..[488]](Bragg et al., 2012). We find that the Pliocene palaeogeography and 400 ppm CO_2 account for a warming (relative to the pre-industrial) in globally integrated

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[..[489]]MASAT (and MASST) of 1.4[..[490]]℃ (0.8[..[491]]℃) and 1.5[..[492]]℃ (1.0[..[493]]℃) respectively. We derive climate sensitivities [..[494]]of 3.5[..[495]]℃ and 2.9[..[496]]℃ for the pre-industrial and Pliocene, which again are similar to [..[497]]results of PlioMIP1 of 3.3[..[498]]℃ and 3.1[..[499]]℃ respectively (Haywood et al., 2013a). We derive an approximation of Earth System Sensitivity of ∼[..[500]]5.6℃ leading to an ESS/CS ratio of ∼[..[501]]1.9, which is similar to the ESS/CS ratio of 2.0 derived within [..[502]]PlioMIP1 (Haywood et al., 2013a). This similarity between PlioMIP1 and PlioMIP2 CS and ESS/CS ratio demonstrates an insensitivity of these quantities to the degree of palaeogeographic variation between PlioMIP1 and PlioMIP2. This strongly indicates that the primary control on the ESS/CS ratio is the reconstructed ice distribution and global vegetation coverage which, with the exception to the Greenland [..[503]]Ice Sheet, is consistent between PlioMIP1 and PlioMIP2. [..[504]]The implementation of dynamic global vegetation models by PlioMIP2 participant groups will allow investigation of the sensitivity of ESS/CS to vegetation-climate feedbacks. We also recognise that CS and ESS calculations are model dependent and this will be looked at in detail in the multi-model comparison of PlioMIP2 results. Precipitation change is more complex. Pliocene geography is the primary driver of geographical distribution changes in precipitation, whilst both Pliocene geography and CO_2 increase the globally integrated MAP.

We find an AMOC which is more intense in the Pliocene than in the pre-industrial, the variation driven principally by the change in geography ([..[505]]Table 7). We determine this by comparing AMOC strength [..[506]]of E^{280} against Eoi^{400} and Eoi^{280}. In addition we have explored the sensitivity of AMOC strength to [..[507]]methodology applied for fresh water correction. The [..[508]]Eoi^{280} experiment uses a fixed fresh water correction field corresponding to pre-industrial iceberg trajectories whilst the Pliocene experiment uses an annually-derived correction (Section 2.2), in theory this could impact on simulated AMOC intensity in Eoi^{400} versus [..[509]]E^{280}. To test this we have conducted an additional E^{280} experiment using the annually-derived fresh water correction methodology of [..[510]]Eoi^{400} (results not shown). This has demonstrated for the pre-industrial that the

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fresh water correction method does not lead to [..[511]]a statistically different AMOC strength. This indicates that our intensified AMOC within Eoi^{400} is indeed a consequence of palaeogeographic changes, rather than our approach to fresh water correction. [..[512]]

Both the choice of [..[513]]TSI (1361 vs. 1365 [..[514]]Wm^{-2}) and [..[515]]PRISM4 orbital configuration (modern vs. [..[516]]3.205 Ma) have been shown not to significantly influence the anomaly-type analysis in use by the Pliocene community. For example we show that the representation of the KM5c (3.205 Ma) [..[517]]time slice with a modern orbit is an acceptable choice - leading to no statistically significant differences within MASAT ([..[518]]Table 3) or MAP ([..[519]]Table 4) which is in accordance with previous work (Haywood et al., 2013a). When considering absolute values or climatic indices the influence of TSI or orbit is minimal but should nevertheless be considered. Models with greater climate sensitivity will present more sensitivity to TSI and potential for non-linearities in climate response (e.g. relating to feedbacks at or near the sea-ice edge or climate-vegetation interactions).

Whilst the Pliocene represents an incredibly useful contemporary-climate analogue, the use of a non-modern palaeogeography (enhanced PRISM4 boundary condition dataset) does present limitations when using low to intermediate spatial resolution climate models. [..[520]]Regridding of the LSM to the 3.75°×2.5° model is imperfect due to the binary nature of the data and therefore requires manual corrections driven by an understanding of model architecture and physics (i.e. imposed by rigid-lid streamfunction, horizontal [..[521]]grid-type etc.)[..[522]]. As a pre-cursor, some *a priori* knowledge of important aspects of Pliocene ocean circulation is required to guide a series of expert-informed decisions on model configuration. Similarly, when model development teams (e.g. MOHC) create present-day boundary conditions, knowledge of circulation patterns and [..[523]]throughflow strength is often used to inform [..[524]]manual corrections (e.g artificial deepening of narrow channels) or the inclusion of parametrisations (e.g. diffusive pipes to represent otherwise unrepresented, narrow straits). This *[..[525]]*a priori knowledge is not necessarily available for the Pliocene and it is therefore difficult to assess. An example of this is in

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[512] removed: Our intensified Pliocene AMOC is in contrast to Zhang et al. (2013) which found no significant change in the AMOC strength within the PlioMIP1 Exp 2 ensemble. Unfortunately AMOC time-series data is not available from HadCM3 PlioMIP1 (Bragg et al., 2012, Exp. 2) to ascertain the statistical significance of the difference between the PlioMIP1 Pliocene (18.6 Sv) and corresponding pre-industrial (17.8 Sv). Nevertheless, looking at typical HadCM3 (MOSES2) AMOC variability within Tab 7, suggests no statistically significant increase in AMOC modelled in PlioMIP1 (the difference between Pliocene and pre-industrial in Bragg et al. being $\sim 1\sigma$). This is the first time using this model that a statistically significant increase in AMOC has been predicted for the Pliocene.

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the [..[526]]subaerial extension of Ireland and Scotland within PRISM4 and how this is represented within the model and how this may influence the [..[527]]Norwegian Current. [..[528]]Additionally, the use of [..[529]]different model architectures and models with higher spatial resolution within the PlioMIP2 framework may allow these aspects to be considered. For example, free-surface [..[530]]ocean models with higher horizontal spatial resolution may help in the interpretation of the Pliocene ACC strength and the Pliocene Arctic Ocean cold anomaly identified within this study.

Palaeogeographic induced changes in mean state, for example the path of the Antarctic [..[531]]Coastal Current around the Peninsula island (Section 4.2.5) represent non-analogous characteristics imposed by the PRISM4 Pliocene reconstruction. Other potentially non-analogous changes are associated with palaeogeographical changes to the Maritime continent and subsequent changes in Indonesian [..[532]]throughflow configuration, the closure of the Bering Strait and Canadian Archipelago, and the withdrawal of the Baltic Sea and Hudson Bay. These palaeogeographical changes should be considered alongside those described within Hill (2015) such as the suggestion of extensive uplift in the Barents Sea (e.g. Knies et al. (2014)) and the rerouting of major rivers (e.g. within North American) which may be currently unrepresented within the model. These important regional changes must be considered when considering the [..[533]]KM5c time slice as an equilibrium state analogue to contemporary climate change (i.e. a 400 ppm world).

Data availability. Climatological averages within NetCDF4 files as specified by the PlioMIP2 experiment specifications held at the University of Leeds data repository. Requests of access should be directed to A. M. Haywood. Specific data requests should be sent to the lead author (S.Hunter@leeds.ac.uk).

All PlioMIP2 boundary conditions are available on the USGS PlioMIP2 web page (http://geology.er.usgs.gov/egpsc/prism/7_pliomip2/).

Author contributions. SJH, AMH and AMD designed the study. SJH developed the software framework and conducted the model set-up, spin-up and all the data analysis. SJH and JCT developed model boundary conditions. SJH wrote the manuscript, generated figures and incorporated comments from co-authors. Correspondence and requests for materials should be addressed to SJH.

Acknowledgements. This work was undertaken on ARC3, part of the High Performance Computing facilities at the University of Leeds, UK. [..[534]]SJH, AMH, and AMD acknowledge that the work leading up to these results has received funding from the European Research Council

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under the European Union's Seventh Framework Programme (FP7/2007-2013) ERC grant agreement no. 278636. [..[535]]SJH, AMH, AMD and JCT acknowledge the Past Earth Network (EPSRC Grant No: EP/M008.363/1). We acknowledge the contribution made by the University of Bristol in keeping the HadCM3 developed and updated. All boundary conditions were generated within a bespoke Matlab framework using the MOHC-developed and National Centre for Atmospheric Sciences, Computing Modelling Services (NCAS-CMS) supported xancil and um2nc tools (NCAS, 2019). SJH is immensely grateful to two anonymous reviewers for their time and thoroughness. Their comments greatly improved this manuscript.

[535] removed: S. J. H., A. M. H., A. M. D. and J. C. T.

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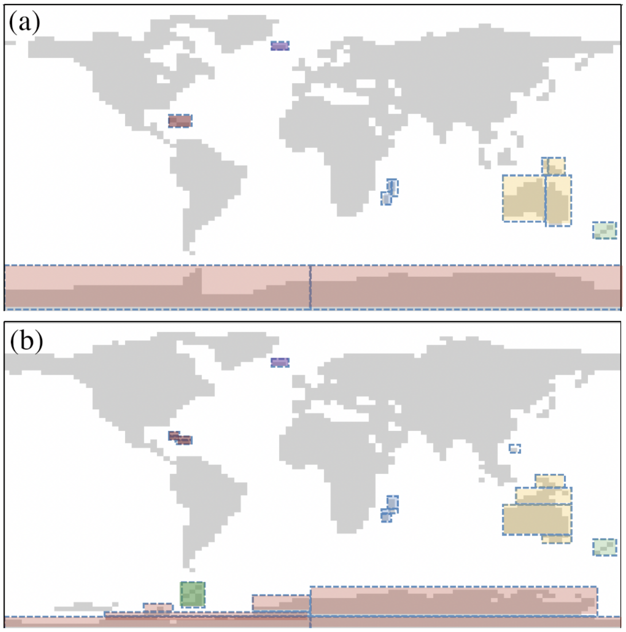

Figure 1. ~~Land Sea Mask~~ LSM and ~~Barotropic~~ barotropic streamfunction island configuration for the (a) pre-industrial and (b) Pliocene.

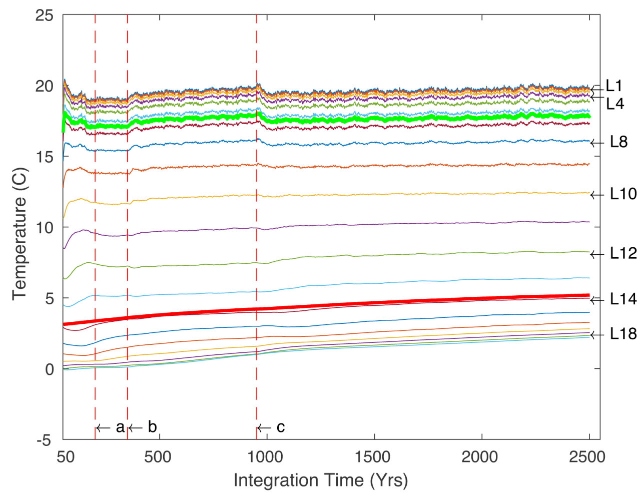

Figure 2. Time-evolution of the globally-integrated temperature for the ocean layers within the Eoi^{400} experiment. (a) All Whole ocean levels including whole ocean volume (indicated by the thick red line), and (b) Ocean layers of the top 200 m indicated by the thick green line. Vertical lines indicate key spin-up stages, ; (aIncorporation of) adding the barotropic physics into to the ocean model, (b) incorporation of barotropic streamfunction islands into the barotropic solver, and (cCorrection) correction to the barotropic streamfunction island in the souther southern high-latitudes and incorporation of full PRISM4 vegetation boundary conditions into the model. Note changes in colour scheme between aThe mid points to the ocean layers are 5 m (L1), 15 m (L2), 15 m (L3), 35 m (L4), 48 m (L5), 67 m (L6), 96 m (L7), 139 m (L8), 204 m (L9), 301 m (L10), 447 m (L11), 666 m (L12), 996 m (L13), 1501 m (L14), 2116 m (L15), 2731 m (L16), 3347 m (L17), 3962 m (L18), 4577 m (L19) and b5195 m (L20).

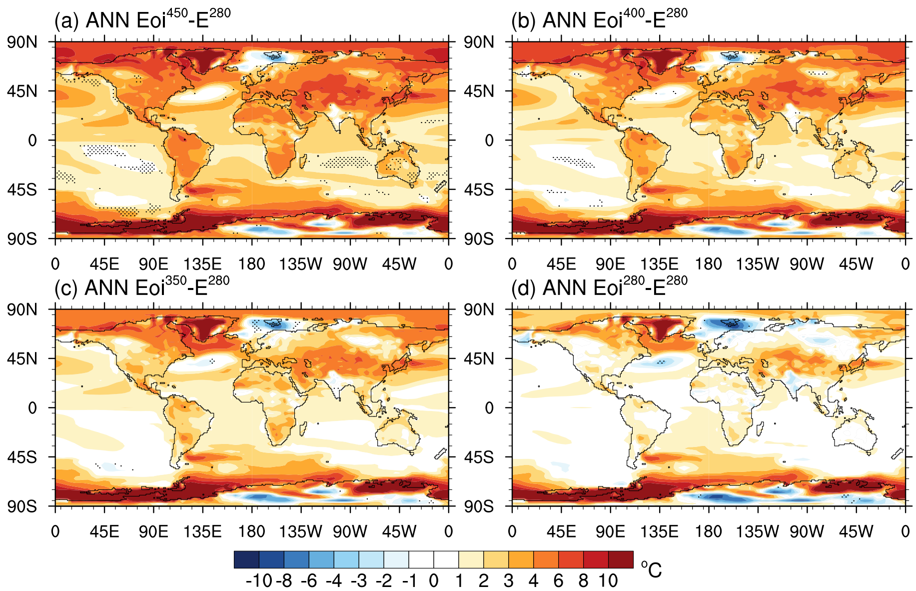

Figure 3. Pliocene ~~(Eoi) MAT~~ annual mean surface air temperature anomalies against E^{280}. (a) Eoi^{450}-E^{280}, (b) Eoi^{400}-E^{280}, (c) Eoi^{350}-E^{280} and (d) Eoi^{280}-E^{280}. Stippling indicates regions in which results are not statistically significant at a 95% confidence criteria (independent two-sample ~~student~~ Student t-test).

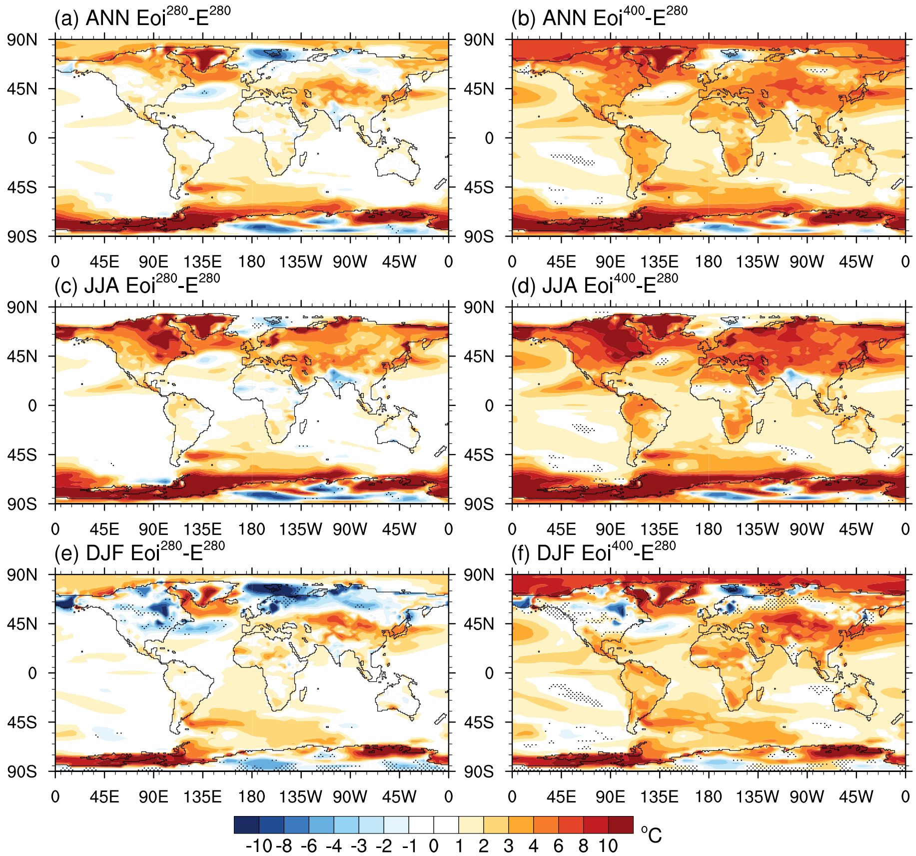

Figure 4. Mean annual and seasonal Pliocene temperature anomalies against E^{280}. (a) Annual Eoi^{280} ~~and~~ $-E^{280}$, (b) Annual Eoi^{400} ~~Seasonal~~ $-E^{280}$, (c) June-July-August (JJA) Eoi^{280}-E^{280}, (d) JJA Eoi^{400}-E^{280}, (e) December-January-February (DJF) Eoi^{280}-E^{280} and ~~MAT anomalies against E~~(f) DJF Eoi^{400}-E^{280}. Stippling indicates regions in which results are not statistically significant at a 95% confidence criteria.

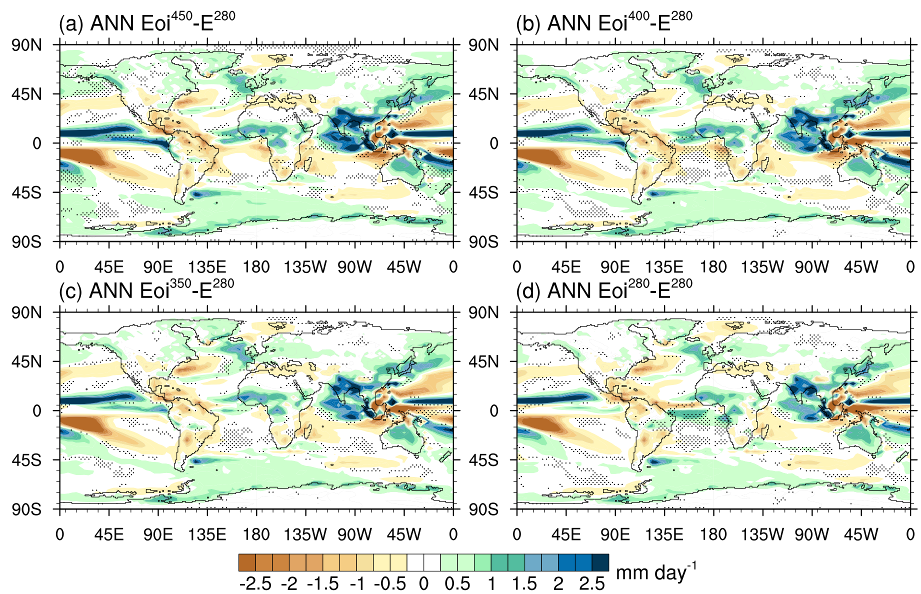

Figure 5. Pliocene ~~Mean Annual Precipitation~~ mean annual precipitation anomalies ~~(mm day^{-1})~~ against E^{280}. (a) Eoi^{450}-E^{280}, (b) Eoi^{400}-E^{280}, (c) Eoi^{350}-E^{280} and (d) Eoi^{280}-E^{280}. Stippling indicates regions in which results are not statistically significant at a 95% confidence criteria.

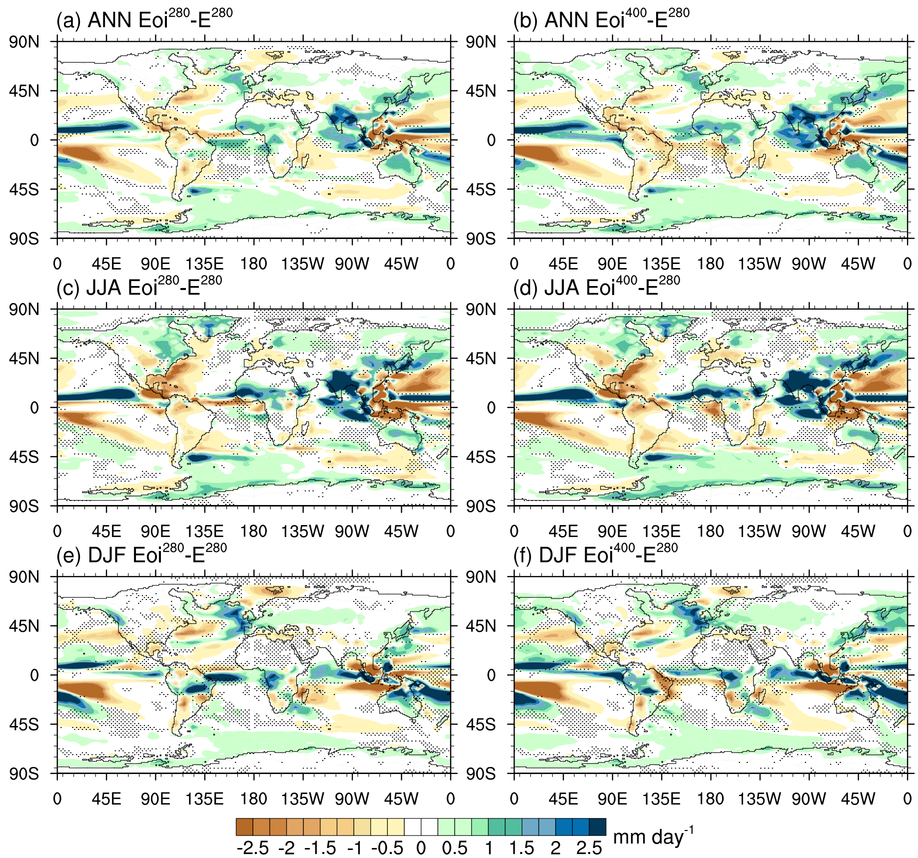

Figure 6. Mean Annual and seasonal Pliocene precipitation anomalies. (mm day^{-1} a) Annual Eoi^{280}-E^{280}, (b) Annual Eoi^{400}-E^{280}, (c) JJA Eoi^{280}-E^{280}, (d) JJA Eoi^{400}-E^{280}, (e) DJF Eoi^{280}-E^{280} and (f) DJF Eoi^{400}-E^{280}. Stippling indicates regions in which results are not statistically significant at a 95% confidence criteria.

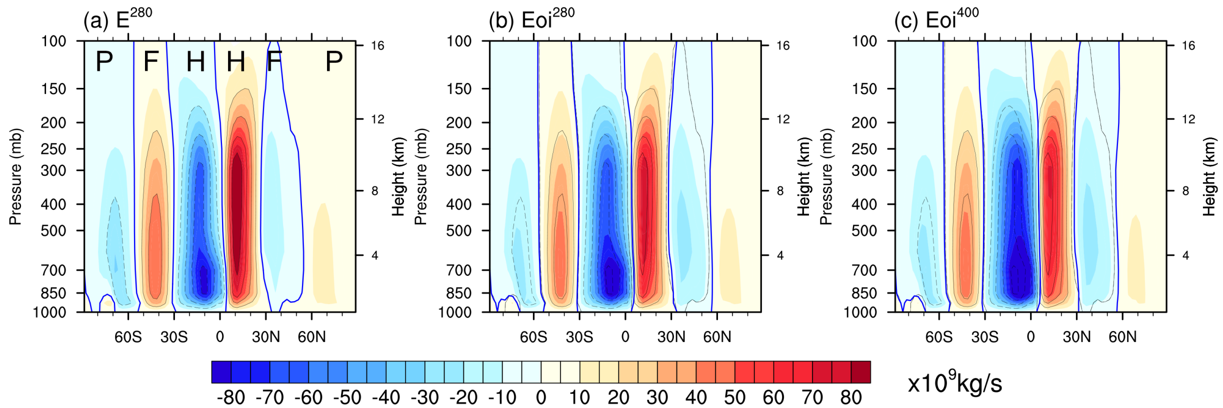

Figure 7. ~~Annual mean~~ Mean annual zonally-averaged meridional mass stream function for ~~the~~ (a) E^{280}, (b) Eoi^{280} ~~,~~ and (c) E^{400} ~~experiments~~. The contour lines are from E^{280} and are ~~every~~ shown for intervals of $2x10^{10}$ kg s^{-1} with dashed lines indicating counterclockwise (looking westward) circulation (ascending air moves southward). The solid blue contour indicates zero meridional streamfunction indicative of the boundary of circulation cells. The Hadley (H), Ferrel (F) and the Polar (P) cells are indicated within (a).

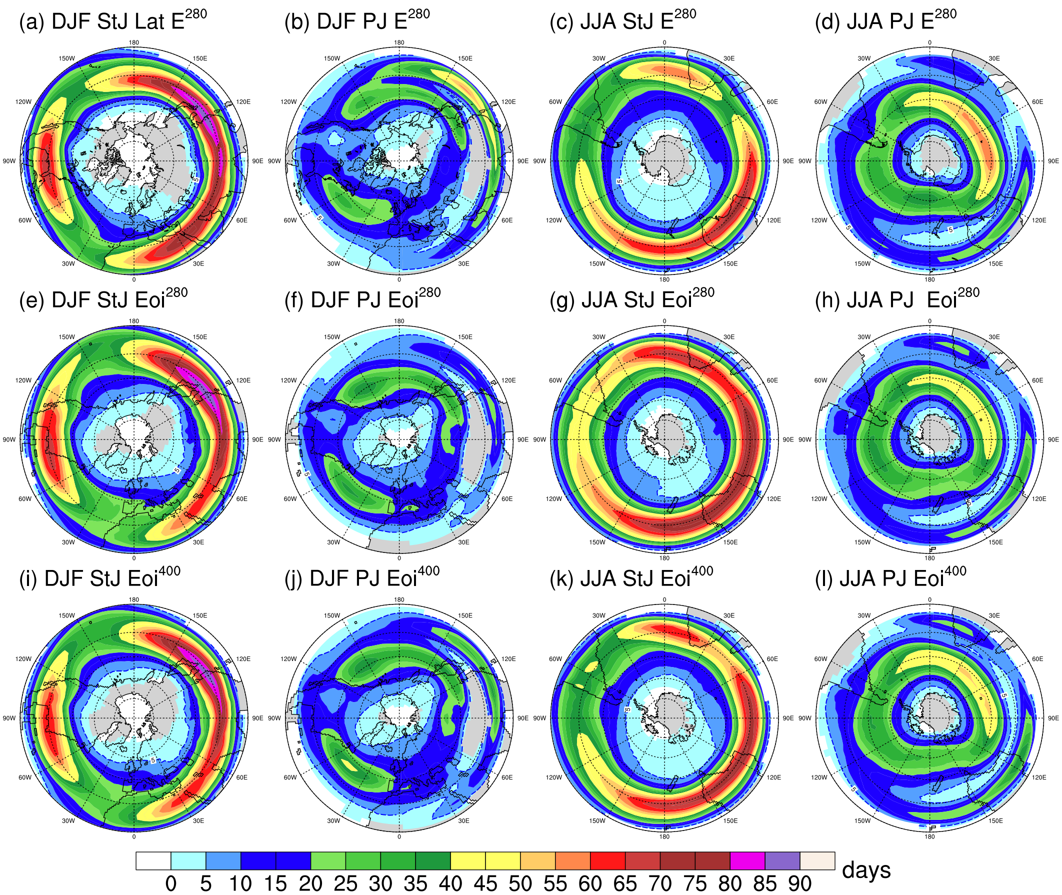

Figure 8. Seasonal (DJF and JJA) distribution of the Subtropical Jet (StJ) and Polar Jet streams (PJ) for (a-d) E^{280}, (e-h) Eoi^{280}, and (i-l) E^{400}~~experiments~~. ~~Horizontal speed computed as the mass flux-weighted horizontal speed integrated over 400 - 100 hPa.~~ Colour scale indicates mean number of days within season in which wind speed >30 ms^{-1} ~~. The Subtropical and Polar jets are differentiated by calculating upper-tropospheric wind shear normalised by the 200~~ over 400 - 100 hPa~~wind speed (following the typology Koch et al~~. ~~, 2006).~~ Note ~~difference in latitude extent between StJ (15 - 90°) and PJ (30 - 90°) plots,~~ that the wind-shear PJ classification identifies a jet ~~stream~~ downstream of the Himalayas~~in our polar jet classification.Note also that this annual-mean state is not physically realised simultaneously, instead represents a histogram of a 50 year climatology.~~

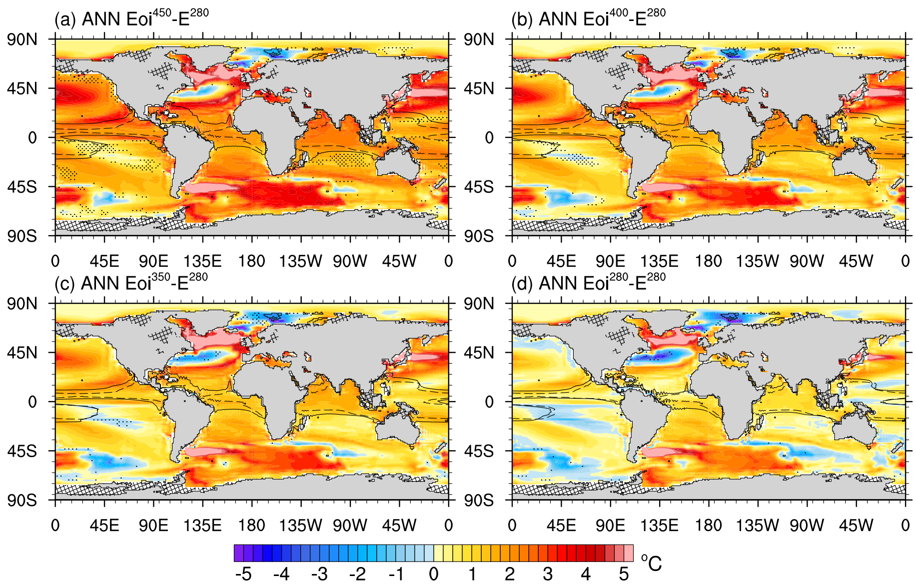

Figure 9. Pliocene mean annual sea surface temperature (~~Eoi~~MASST) ~~SST~~ anomalies against E^{280}. (a) Eoi^{450}-E^{280}, (b) Eoi^{400}-E^{280}, (c) Eoi^{350}-E^{280} and (d) Eoi^{280}-E^{280}. Dotted contour lines indicates E^{280} ~~28.5°~~ 28°C warm pool whilst the solid contour indicates the ~~Eoi~~ Pliocene 28~~°~~ °C warm pool. Cross hatching indicates regions in which either modern or ~~pliocene~~ Pliocene have contrasting land surface. Stippling indicates regions in which there is no statistical difference at a 95% confidence criteria.

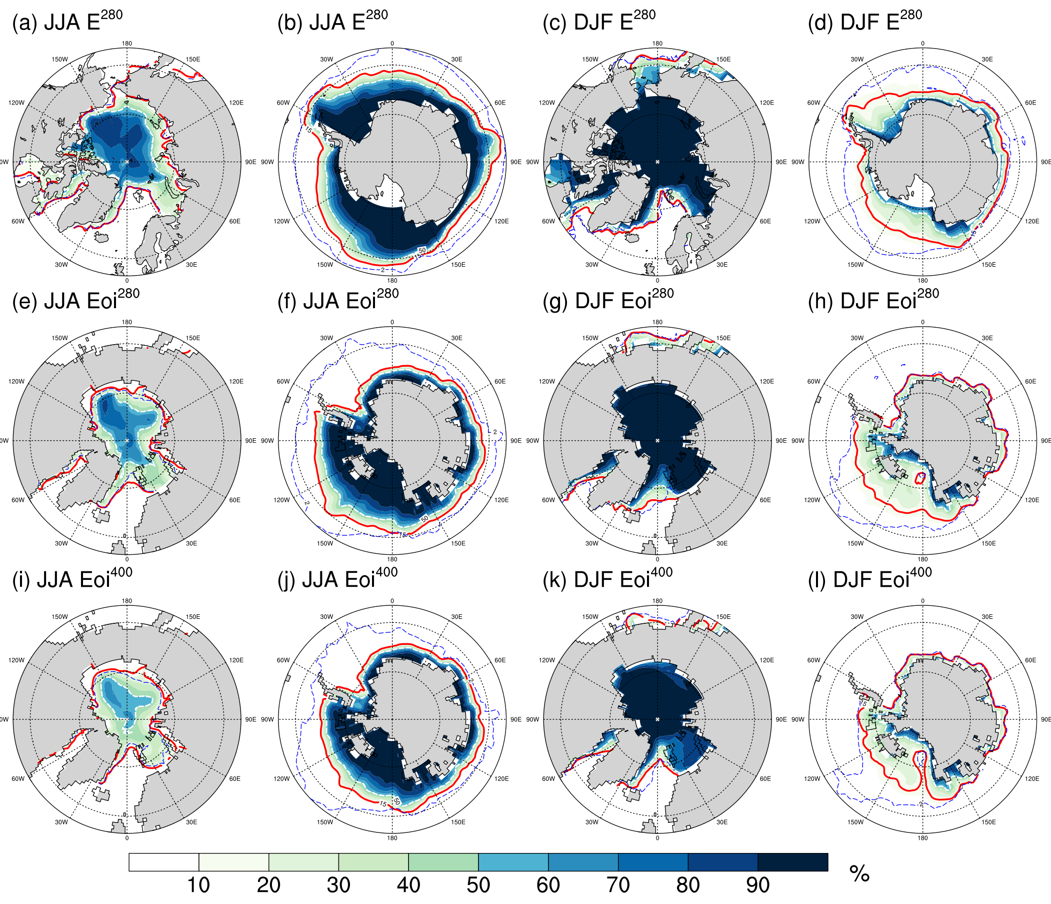

Figure 10. Sea ice concentrations (%) during JJA and DJF in the Northern and Southern hemisphere for (~~a~~a-d) E^{280}, (~~b~~e-h) Eoi^{280}, and (~~c~~i-l) Eoi^{400}. The red line indicates the sea ice edge based on a threshold of 15% whilst the dotted white line indicates the 50% threshold. The blue dotted line indicates the 2~~º~~°C isotherm, in the ~~southern ocean~~ Southern Ocean this is indicative of the Antarctic convergence zone (polar front).

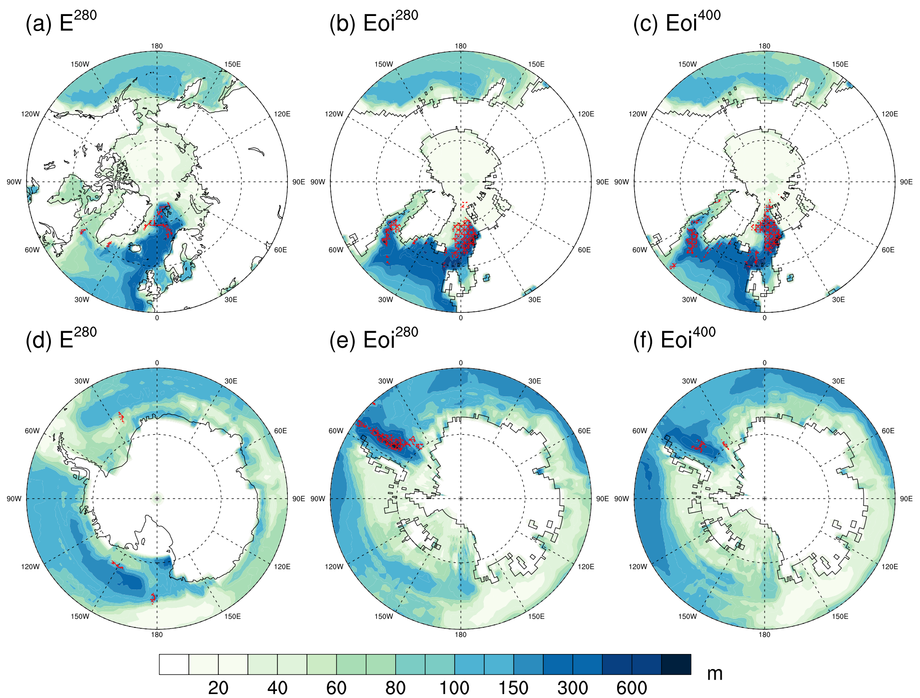

Figure 11. Mean March Northern Hemisphere and September Southern Hemisphere ~~mixed layer depth~~ Mixed Layer Depth for (a and d) E^{280}, (b and e) Eoi^{280} ~~,~~ and (c and f) Eoi^{400}. Red hashes indicate regions that exhibit deep (~~>~~ $\geq$ 1000 m) convection at least 1 month during the climatologcal meaning period, single-cell ocean regions have been expanded slightly to improve visualisation.

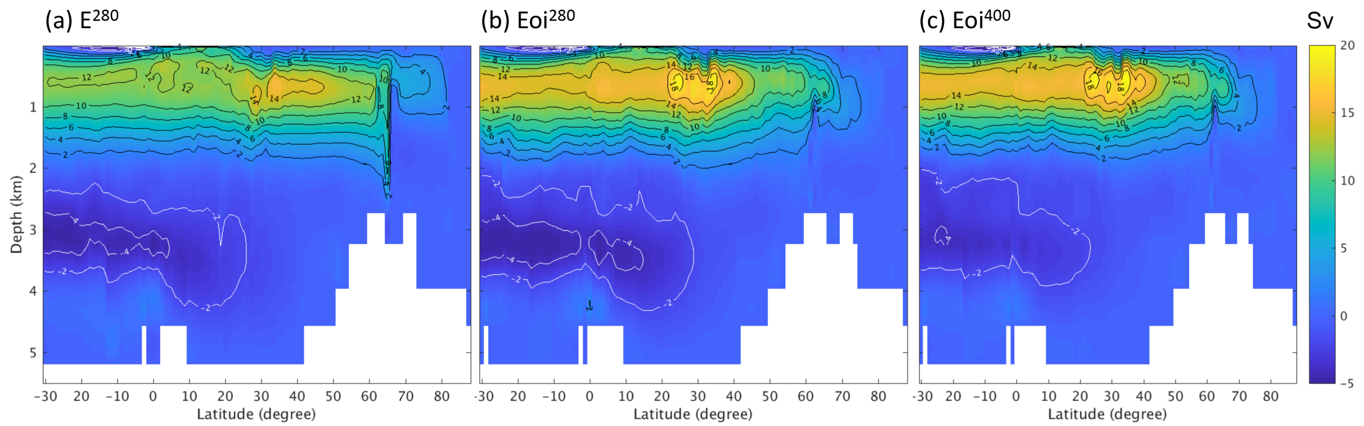

Figure 12. Time-averaged Atlantic ~~Overturning Circulation (AMOC)~~ overturning circulation for (a) E^{280}, (b) Eoi^{280} ~~,~~ and (c) Eoi^{400}. Positive values indicate clockwise circulation.

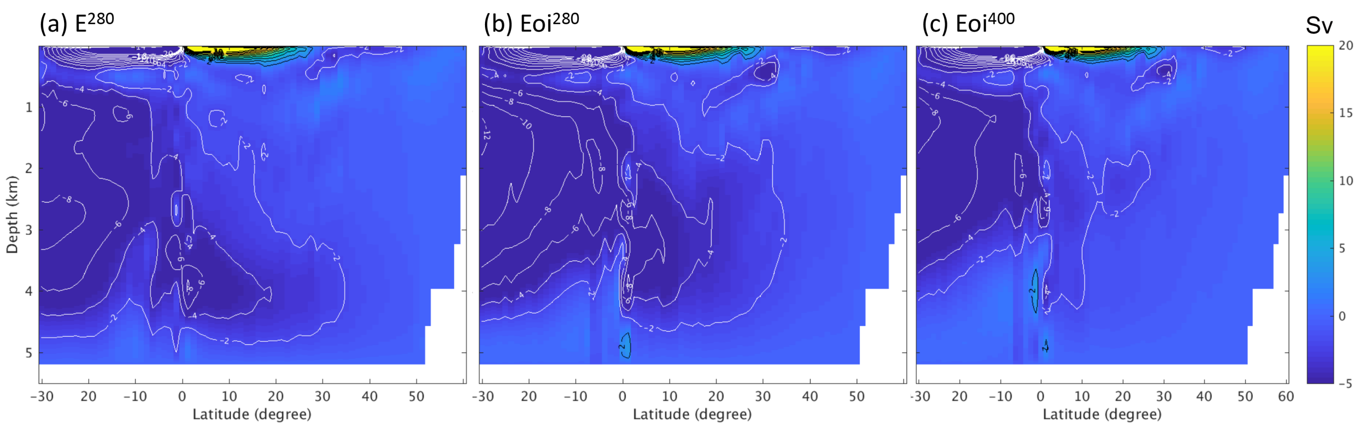

Figure 13. Time-averaged Pacific ~~Overturning Circulation (PMOC)~~overturning circulation for (a) E^{280}, (b) Eoi^{280} ~~,~~ and (c) Eoi^{400}. Positive values indicate clockwise circulation.

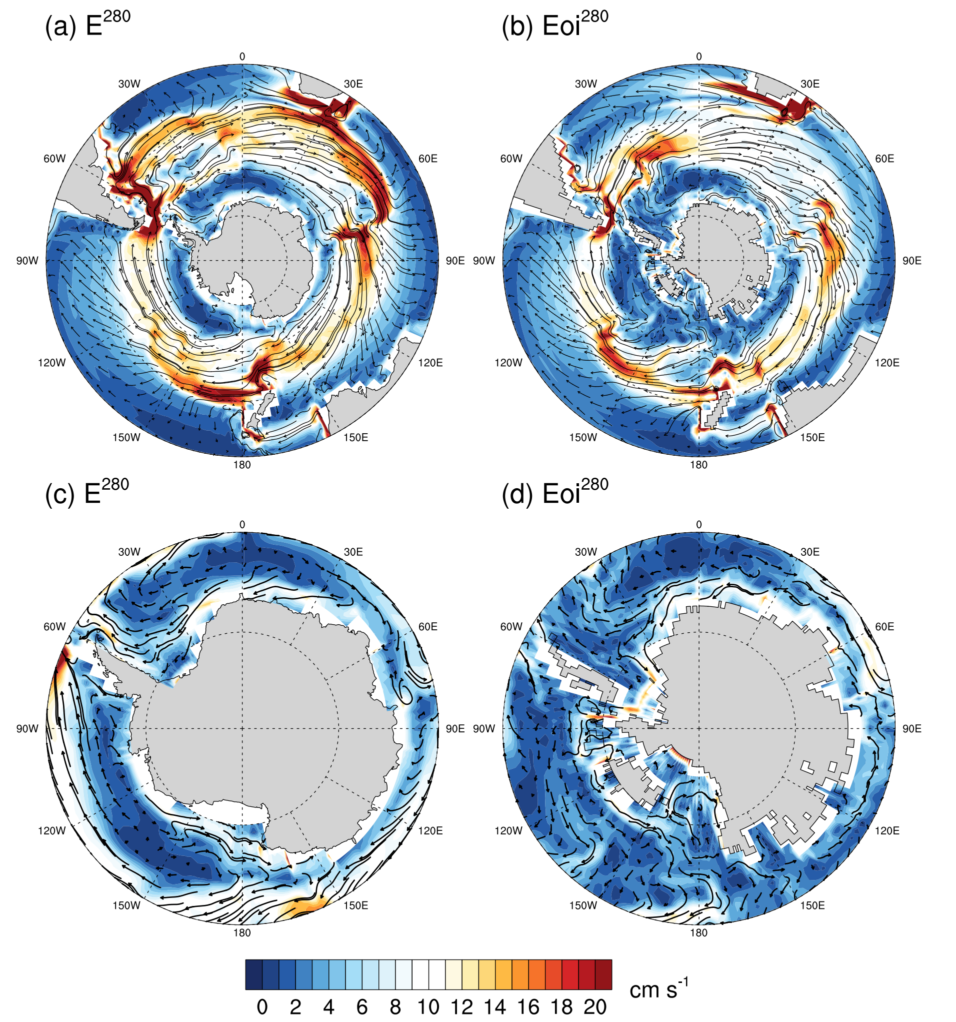

Figure 14. Surface ocean Mean Annual mean annual velocity (streamlines and vector magnitude) for E^{280} and Eoi^{280}. Antarctic Counter Current The ACC is shown clearly within (a) E^{280} and (b) Eoi^{280}, and close-ups showing whilst the counter (coastal) current for Antarctic Coastal Current is shown within the close-up plots (c) E^{280} and (d) Eoi^{280}.

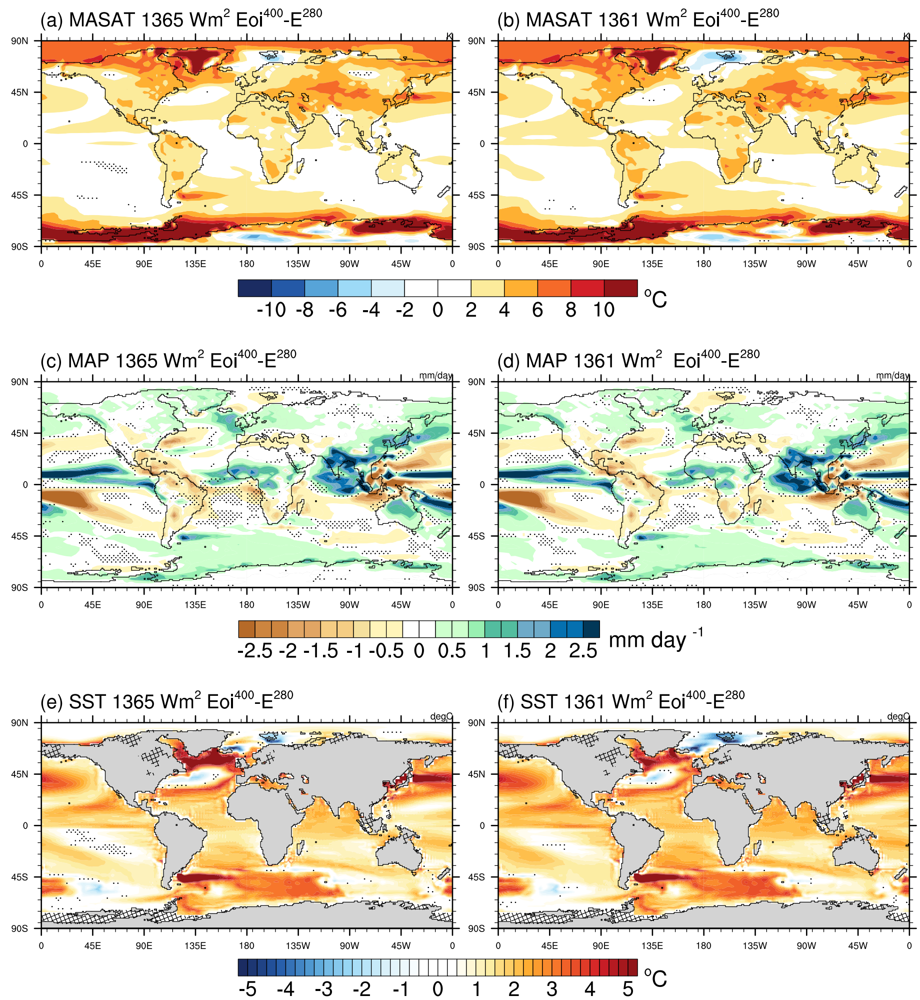

Figure 15. Sensitivity of Eoi^{400} ~~- E~~-E^{280} anomalies on TSI values for (a ~~)~~ and ~~(~~b) ~~Mean Annual Temperature~~MASAT, (c ~~)~~ and ~~(~~d) ~~Mean annual Precipitation~~MAP, and (e ~~)~~ and ~~(~~f) ~~Sea Surface Temperature~~MASST.

Table 1. Summary of simulations conducted within this study. Those in italic represent simulations beyond the PlioMIP2 experiment design.

Nº/	ID	Geography	PlioMIP2 Status: Tier 1 or 2 (T) P4F/P4P component	Descri
1	Eoi^{400}	Pliocene	CORE	Full e vegeta
2	Eoi^{450}	Pliocene	T1 P4F & P4P	As Eo
3	Eoi^{350}	Pliocene	T1 P4F & P4P	As Eo
4	Eoi^{280}	Pliocene	T2 P4F & P4P	As Eo
5	E^{280}	PI	CORE	Standa with fi
6	E^{400}	PI	T2 P4F & P4P	As E^{28}
7	E^{560}	PI	T1 P4F	As E^{28}
8	$_{orb}Eoi^{400}$	Pliocene	Additional sensitivity	As of (KM5
$_{orb}Eoi^{450}$ 9	Additional sensitivity $_{1361}Eoi^{400}$	As of Eoi^{450} but with 3.205 Myr orbit (KM5c) $_{orb}Eoi^{350}$ Pliocene	Additional sensitivity	As of $_{orb}Eoi$ but w Additi TSI=1
10	$_{1361}E^{280}$	PI	Additional sensitivity	As E^{28}

The following definitions are used: pre-industrial (PI), Tier 1 (T1), Tier 2 (T2), Pliocene for Future (P4F), Pliocene for Pliocene (P4P) and Total Solar Irradiance (TSI).

Table 2. Summary of equilibrium state parameters for the seven PlioMIP2 protocol experiments. Globally integrated ($Ocean_{all}$) and surface Ocean (top 200m; $Ocean_{surf}$) ~~Climatological~~ climatological trends and Top of the Atmosphere Energy Balance (TOA_{EB}) are derived from the last 100 model years. ~~Note that when underlying trends are small compared to the climatological standard deviation, derivation of the trend is unsatisfactory.~~

~~Model~~ ID	$Ocean_{all}$ (~~º~~°C cent^{-1})	$Ocean_{surf}$ (~~º~~°C cent^{-1})	TOA_{EB} (Wm^{-2})
Eoi^{450}	0.063	0.046	0.260
Eoi^{400}	0.041	-0.026	0.047
Eoi^{350}	0.017	0.002	-0.024
Eoi^{280}	0.017	0.002	-0.090
E^{280}	-0.014	0.008	-0.115
E^{400}	-0.048	0.010	0.098
E^{560}	0.107	0.025	0.334

Table 3. Global mean annual surface air temperature (~~1.5 M;~~ MASAT) decomposed into polar (poleward of 60°) and tropical (equaterward of 30°) regions. The Polar amplification factor ~~indicated within~~ is shown in square brackets ~~,~~ and is defined as the ~~ratio~~ *ratio* in the anomalies (against E^{280}) between the ~~pole~~ polar warming and the global mean warming.

~~Model~~ ID	MASAT (~~º~~°C)	△ T against E^{280}	North Pole MASAT (~~º~~°C)	tropical MASAT (~~º~~°C)	South Pole MASAT (~~º~~°C)
Eoi^{450}	17.4 ± ~~0.5~~ 0.1	+3.4 ~~± 0.7~~	-4.6 ± ~~1.1~~ 0.4 [1.6]	~~21.6~~ 27.6 ± ~~0.4~~ 0.1	-10.5 ± ~~0.9~~ 0.4 [2.1]
Eoi^{400}	16.9 ± ~~0.5~~ 0.1	+2.9 ~~± 0.7~~	-5.2 ± ~~1.1~~ 0.3 [1.7]	~~21.1~~ 27.2 ± ~~0.4~~ 0.1	-11.2 ± ~~0.8~~ 0.3 [2.2]
$_{orb}Eoi^{400}$	16.8 ± ~~0.5~~ 0.1	+2.8 ~~± 0.7~~	-5.2 ± ~~1.1~~ 0.4 [1.7]	~~21.1~~ 27.1± ~~0.4~~ 0.1	-11.4 ± ~~0.8~~ 0.3 [2.2]
Eoi^{350}	16.3 ± ~~0.5~~ 0.1	+2.3 ~~± 0.7~~	-6.2± ~~1.0~~ 0.3 [1.7]	~~20.6~~ 26.7 ± ~~0.4~~ 0.2	-11.8 ± ~~0.9~~ 0.4 [2.5]
Eoi^{280}	15.4 ± ~~0.5~~ 0.1	+1.4 ~~± 0.7~~	-8.1 ± ~~1.1~~ 0.4 [1.4]	~~19.6~~ 25.9 ± ~~0.4~~ 0.1	-12.6 ± ~~0.9~~ 0.3 [3.5]
E^{280}	14.0 ± ~~0.5~~ 0.1	~~-~~0	-10.0 ± ~~1.2~~ 0.3	~~18.7~~ 25.1 ± ~~0.5~~ 0.2	-17.5 ± ~~0.9~~ 0.3
E^{400}	15.8 ± ~~0.5~~ 0.1	+1.8 ~~± 0.7~~	-6.8 ± ~~1.1~~ 0.3 [1.8]	~~20.3~~ 26.5 ± ~~0.5~~ 0.2	-15.5 ± ~~0.9~~ 0.4 [1.1]
E^{560}	17.5 ± ~~0.5~~ 0.1	+3.5 ~~± 0.7~~	-3.8 ± ~~1.0~~ 0.3 [1.8]	~~21.9~~ 28.0 ± ~~0.4~~ 0.2	-13.4 ± ~~0.8~~ 0.4 [1.2]

Table 4. ~~Global~~ Globally integrated mean ~~Annual mean~~ annual precipitation (~~mm day^{-1}~~MAP).

~~Model~~ ID	MAP (mm day^{-1})
Eoi^{450}	~~3.04~~ 3.041 ± ~~0.51~~ 0.007
Eoi^{400}	~~3.02~~ 3.025 ± ~~0.51~~ 0.008
${}_{orb}$Eoi^{400}	~~3.03~~ 3.027 ± ~~0.51~~ 0.008
Eoi^{350}	~~3.01~~ 3.012 ± ~~0.51~~ 0.009
Eoi^{280}	~~2.98~~ 2.979 ± ~~0.46~~ 0.008
E^{280}	~~2.91~~ 2.912 ± ~~0.49~~ 0.008
E^{400}	~~2.97~~ 2.975 ± ~~0.53~~ 0.007
E^{560}	~~3.02~~ 3.019 ± ~~0.57~~ 0.008

Table 5. Integrated mean core latitude of the Subtropical Jet (StJ) for E^{280}, Eoi^{280} and Eoi^{400} experiments during December-January-February (DJF) and June-July-August (JJA) seasons. Note that only the ~~Subtropical Jet~~ StJ is reported as it more stable and persistent than the Polar Jet.

~~Model~~ ID	NH DJF (°N)	NH JJA (°N)	SH DJF (°S)	SH JJA (°S)
Eoi^{400}	32.8 ± 1.5	47.0 ± 2.4	~~-44.8~~44.8 ± 1.9	33.9 ± 1.3
Eoi^{280}	32.0 ± 1.1	46.2 ± 1.9	~~-44.7~~44.7 ± 1.8	33.7 ± 1.5
E^{280}	30.3 ± 1.4	44.6 ± 3.0	~~-42.5~~42.5 ± 1.3	33.5 ± 1.8

Table 6. ~~Sea~~ Global mean annual sea surface temperature (MASST) and defining ~~charactersistics~~ characteristics of the equatorial warm pool regions.

~~Model~~ ID	MASST (~~o~~ °C)	GWP ~~(x10~~ (×10^6 km^2)	WHWP$_{max}$ (~~x10~~×10^6 km^2)	IPWP$_{max}$ ~~(x10~~[year-round] (×10^6 km^2)
Eoi^{450}	20.3 ± ~~0.4~~ 0.1	~~102.3~~ 107.5 ± 2.5	25.2 ± 0.6	95.7 ± 2.8 [63.0 ± 2.8]
Eoi^{400}	19.9 ± ~~0.4~~ 0.1	~~95.7~~ 99.7 ± 2.6	24.4 ± 0.5	89.0 ± 3.3 [57.1 ± 2.1]
$_{orb}$Eoi^{400}	19.8 ± ~~0.4~~ 0.1	~~95.3~~ 98.5 ± 2.8	23.8 ± 0.5	87.4 ± 3.0 [56.2 ± 1.9]
Eoi^{350}	19.6 ± ~~0.4~~ 0.1	~~88.9~~ 92.1 ± 3.1	23.1 ± 0.5	82.4 ± 3.7 [50.9 ± 2.6]
Eoi^{280}	18.9 ± ~~0.4~~ 0.1	~~77.9~~ 78.8 ± 2.9	19.7 ± 1.2	71.7 ± 3.0 [38.6 ± 3.3]
E^{280}	18.1 ± ~~0.4~~ 0.1	~~62.6~~ 66.4 ± 4.5	15.0 ± 1.5	62.8 ± 3.9 [25.4 ± 3.1]
E^{400}	19.3 ± ~~0.5~~ 0.1	~~89.4~~ 91.5 ± 3.3	22.1 ± 1.3	85.6 ± 3.9 [50.8 ± 3.2]
E^{560}	20.4 ± ~~0.4~~ 0.1	~~112.1~~ 117.2 ± 3.3	27.2 ± 1.5	102.9 ± 2.5 [68.9 ± 2.6]

The Global Warm Pool (GWP) area defined using Mean Annual Sea Surface Temperature (MASST) and a 28°C. Western Hemisphere Warm Pool (WHWP; 130°W - 45°W), Indo-Pacific Warm Pool (IPWP; 30° E - 60°W) are defined as the max monthly mean area that is 28°C. For IPWP$_{max}$ the number in parenthesis is the area that is 28°C year-round.

Table 7. Characteristics of the Atlantic and Pacific Meridional Overturning Circulation (AMOC and PMOC).

Model ID	AMOC $_{max}$ (Sv)	$AMOC_{max}$ 26.5°N (Sv)	$PMOC_{+ve}$ (Sv)	$PMOC_{-ve}$ PDW (Sv) [Depth (m)] PDW (≥30S → °S below 500 m(Sv))
Eoi^{450}	18.6 ± 1.1	16.3 ± 1.0	39.3 ± 4.0	-9.3 ± 1.5 [1000m]
Eoi^{400}	19.6 ± 1.0	17.2 ± 0.8	40.6 ± 3.0	-9.1 ± 1.4 [1000m]
$_{orb}$Eoi^{400}	21.4 ± 1.5	19.3 ± 1.1	40.9 ± 3.3	-9.8 ± 1.9 [1000m]
Eoi^{350}	20.4 ± 1.1	18.8 ± 0.9	42.2 ± 3.9	-9.8 ± 1.8 [1000m]
Eoi^{280}	18.9 ± 0.8	17.4 ± 0.9	46.0 ± 3.4	-12.3 ± 1.6 [1500m]
E^{280}	15.7 ± 1.2	13.4 ± 1.1	33.4 ± 3.1	-8.6 ± 1.4 [2700m]
E^{400}	15.2 ± 1.2	13.6 ± 1.0	29.3± 2.5	-9.0 ± 0.9 [3960m]
E^{560}	15.9 ± 1.3	13.8 ± 0.9	25.0 ± 2.1	-7.6 7.6 ± 0.8 [3960m]

$AMOC_{max}$ is the maximum AMOC. $PMOC_{+ve}$ reflects the subtropical gyre circulation whilst $PMOC_{-ve}$ reflects the Pacific Deep Water (PDW) and North Pacific Deep Water (NPDW).

Table 8. Characteristics of the Antarctic Circumglobal Circumpolar Current for (ACC) within the Pliocene and pre-industrial experiments. From the Barotropic barotropic streamfunction we derive the Mean mean ACC latitude (the Polar front) from the centroid of the zonal transport and the core width derived from the ± 50% boundary.

Model ID	ACC at 65° °W (Sv)	Mean ACC latitude (° °S)	Mean ACC core width (° °)
Eoi^{450}	78.3 ± 2.9	58.8	11.5
Eoi^{400}	76.7 ± 2.8	58.8	11.8
$_{orb}$Eoi^{400}	77.3 ± 2.9	58.7	11.8
Eoi^{350}	73.5 ± 3.0	58.8	11.9
Eoi^{280}	51.6 ± 31.9	60.0	12.6
E^{280}	179.0 ± 11.2	66.0	33.6
E^{400}	186.6 ± 9.0	66.6	33.3

Table 9. Sensitivity of E^{280} and Eoi^{400} (and their corresponding anomalies) to TSI of 1361 and 1365 ~~W m~~Wm^{-2}. ~~Mean Annual Surface Air Temperature~~ Shown are the mean annual surface air temperature (MASAT), ~~Mean Annual Precipitation~~ mean annual precipitation (MAP), ~~Mean Annual Sea Surface Temperature~~ mean annual sea surface temperature (MASST), Atlantic and Pacific ~~Meridional Circulation~~ meridional circulation (AMOC$_{max}$ and PMOC$_{+ve,-ve}$~~) derivation as of~~; Section 4.2.4), and Antarctic Circumpolar Current (ACC~~) derivation as of~~; Section 4.2.5).

~~Model~~ ID	MASAT (°C)	MAP (mm day^{-1})	MASST (~~o~~ °C)	AMOC$_{max}$ (Sv)	PMOC$_{+ve,-ve}$ (Sv)	ACC (Sv)
E^{280}	14.0 ± ~~0.5~~ 0.1	~~2.91~~ 2.912 ± ~~0.49~~ 0.008	18.1 ± ~~0.4~~0.1	15.7 ± 1.2	33.4 ± 3.1, -8.6 ± 1.4	179.0 ± 11.1
$_{1361}E^{280}$	13.7 ± ~~0.5~~ 0.1	~~2.89~~ 2.885 ± ~~0.48~~0.008	17.9 ± ~~0.4~~0.1	16.3 ± 1.2	33.8 ± 3.9, -9.2 ± 1.5	180.0 ± 6.2
Eoi^{400}	16.9 ± ~~0.5~~ 0.1	~~3.02~~ 3.025 ± ~~0.51~~0.008	19.9 ± ~~0.4~~0.1	19.6 ± 1.0	40.6 ± 3.0, -9.1 ± 1.4	76.7 ± 2.8
$_{1361}Eoi^{400}$	16.7 ± ~~0.5~~ 0.1	~~3.01~~ 3.014 ± ~~0.50~~0.010	19.7 ± ~~0.4~~0.1	17.0 ± 0.9	37.7 ± 3.3, -8.5 ± 1.7	76.0 ± 2.5
Eoi^{400}-E^{280}	2.9 ± ~~0.7~~ 0.1	~~0.11~~ 0.113 ± ~~0.71~~0.011	1.8 ± ~~0.6~~0.1	3.9 ± 1.6	7.2 ± 4.3, -0.5 ± 2.0	-102.3 ± 11.4
$_{1361}Eoi^{400}$-$_{1361}E^{280}$	3.0 ± ~~0.7~~0.1	~~0.12~~ 0.129 ± ~~0.69~~ 0.013	1.8 ± ~~0.6~~0.1	0.7 ± 1.5	3.9 ± 5.1, 0.7 ± 1.3	-104.0 ± 6.7