15 August 2019: Cp-2018-180 Authors response

Contents

Note that within the attached Annotated manuscript the alterations made to the references are not highlighted. This is a shortcoming of latexdif.

Reply to Anonymous Referee #1 (Cp-2018-180-referee-report-2)

I have gone through your comments sequentially. I have updated the page and line numbers to correspond to **cp-2018-180-manuscript-version4.pdf.** Due to the process of marking-up the manuscript (attached to the end of this document) the page and line numbers may differ to the corrections outlined below. I would like to apologise that there was some confusion in the previous review stage. I would like to state how grateful I am for the time and thoroughness from both referees. Your comments have greatly improved this manuscript, and I cannot thank you enough.

P19L7 Regarding the Braconnot et al., 2007 reference and the misspelling of J. -Y. Peterschmitt. I obtained the original bibtex citation entry from the Climate of the Past website (https://www.clim-past.net/3/261/2007) in which the author is spelt Peterchmitt. Given your confidence I checked more recent publications of Jean-Yves Peterschmitt and I now believe that the author spelling is incorrect within the Braconnot et al., 2007 paper and the Clim. Past website. I was unsure of the correct etiquette in this circumstance, so I have followed the example of Kageyama et al., 2018 (in which Jean-Yves Peterschmitt is a co-author) who cite Braconnot et al., 2007 and have a reference containing the apparent *misspelling* ("Peterchmitt").

There is the remote possibility that either J.-L Peterchmitt and J.-L. Peterschmitt are two different people (who worked on PMIP2 to 4 at the same institute!). I do find it strange that both Braconnot et al., 2007 and the accompanying paper - Braconnot et al., 2007b have apparently misspelt the authors name. The references below are copied and pasted from Clim. Past and Geosci. Model Dev. (the emphasis is mine).

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., **Peterchmitt, J.-Y.,** Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features, Clim. Past, 3, 261-277, https://doi.org/10.5194/cp-3-261-2007, 2007.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., **Peterchmitt, J.-Y**., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C. D., Kageyama, M., Kitoh, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 2: feedbacks with emphasis on the location of the ITCZ and mid- and high latitudes heat budget, Clim. Past, 3, 279-296, https://doi.org/10.5194/cp-3-279-2007, 2007b.

Kageyama, M., Braconnot, P., Harrison, S. P., Haywood, A. M., Jungclaus, J. H., Otto-Bliesner, B. L., **Peterschmitt, J.-Y.,** Abe-Ouchi, A., Albani, S., Bartlein, P. J., Brierley, C., Crucifix, M., Dolan, A., Fernandez-Donado, L., Fischer, H., Hopcroft, P. O., Ivanovic, R. F., Lambert, F., Lunt, D. J., Mahowald, N. M., Peltier, W. R., Phipps, S. J., Roche, D. M., Schmidt, G. A., Tarasov, L., Valdes, P. J., Zhang, Q., and Zhou, T.: The PMIP4 contribution to CMIP6 – Part 1: Overview and over-arching analysis plan, Geosci. Model Dev., 11, 1033-1057, https://doi.org/10.5194/gmd-11-1033-2018, 2018.

P1L8 Capitalize “southern hemisphere”. **This has been corrected.**

P2L22-23: Should the text “(Pliocene Research Interpretation and Synoptic Mapping)” be directly following the term “PRISM4”, and the reference to Dowsett et al. (2016) follow at the end of the sentence? . **I agree. This has been corrected.**

P2L10: I think the text should read “[...] the atmosphere model layers drape [...]”. **“.. drapes ..” has been corrected to “.. drape ..”**

P2L18: Consider replacing “for a suite” by “for an ensemble”, to avoid the text “ [...] well suited for a suite [...]”. **I agree this has been changed to your suggestion. I hadn’t noticed this duplication.**

P2L23: I would consider to cite Haywood et al. (2010,2011) as references for PlioMIP1 at the end of the sentence, that is also the end of the line. **There two citations have been added, Haywood et al 2010 has been added to the bibliography.**

P3L2-3: Move the definition of the abbreviation of PMIP2 to line 9, i.e. following its first occurrence. I assume LSCE (2007) and Braconnot et al. (2007) should then both be cited in line 9? **I agree this has been changed to your suggestion.**

P3,L11: A word is missing, maybe the text should read “[...] with previous work, but we acknowledge [...]”. **“… with previous work but acknowledge …” has been corrected to “ … with previous work, but we acknowledge …”**

P3L18: Check the term “Pliocene communities”; I think it either should read “Pliocene community’s” or “Pliocene communities’”, depending on whether the authors refer to one, or more than one, community. Plus: Would it make sense to specify what exactly the authors mean when referring to “Pliocene community”? I assume that this term refers to “Pliocene modeling groups”, but I may be wrong. **I have changed “…Pliocene communities … ” to “ …Pliocene community’s …” as I was referring to the wider Pliocene community (e.g. modelling groups as well as terrestrial and marine data communities).**

P3L34 and P4L1: Consider replacing: “uppermost layer of ocean” by “uppermost ocean layer”; “Internally-draining basins” by “Internal drainage basins” or, alternatively, “endoreic basins”. **I have changed “uppermost layer of ocean” to “uppermost surface of the ocean” and I have changed “Internally-draining basins” to “Internal drainage basins”**

P4L4: I think the “a” at “Cox, 1984a” should be removed, as there is only one publication of Cox (1984) cited in this manuscript. **This was corrected.**

P4L8: Consider to clarify the structure of the sentence by changing “[...] is 1 hour and horizontal [...]” to “[...] is 1 hour, horizontal [...]”. **“.. is 1 hour and horizontal ..” has been corrected to “ … is 1 hour, horizontal …”**

P4L17: The sentence should be changed to "[...] between the Eastern Atlantic and the Western Mediterranean [...]". **" ... Eastern Atlantic and the Western Mediterranean …" has been corrected to " ... Eastern Atlantic with the Western Mediterranean …"**

P4L23: Replace "to provided" by "to provide". **I have replaced "to provided" by "to provide".**

P5L18: Consider to replace "comma separated" by "comma-separated"; furthermore, the clarification of the use of hyphens, that the authors promised to add to this sentence (see their reply to change request P5,L25 of reviewer #1) has not been added to the updated manuscript. This must be fixed to avoid continued confusion on the readers' side by the double terminology of comma-separated and hyphenated lists of model simulations, the latter of which so far is not defined in the text. **I have changed "comma separated" to "comma-separated". The description of hyphenated lists remains removed as these list forms are not used within the manuscript.**

P5L19: Replace "of of" by "of". **The duplication has been corrected**

P6L12: Based on the list of simulations in Table 1, mentioning simulations $_{orb}Eoi^{280-450}$ in subsection heading 3.2 is wrong. There is only one orbit sensitivity study for Pliocene geography, i.e. $_{orb}Eoi^{400}$, right? Please confirm and fix the text accordingly. **There is only the single orbital sensitivity experiment described within this manuscript so I have corrected the Section heading. The section heading also reflects the expansion of the hyphenated list. The section heading now reads " …($Eoi^{280,350,400,450}$, $_{orb}Eoi^{400}$, and $_{1361}Eoi^{400}$)"**

P6L16: I would rephrase the sentence to: "The modern geography is provided to facilitate the anomaly method of boundary condition generation." **I agree the sentence was not very clear. The sentence "The modern boundary condition is provided to facilitate the anomaly method of boundary condition generation." has been changed to "The modern geography is provided to facilitate the anomaly method of boundary condition generation."**

P6L17: Based on what follows in the lines of the next page I would assume that the phrase "is first regridded" is not correct here. Should this rather read: "is created"? The regridding is specified later on, and what follows in this sentence explains more than just the regridding. **I agree. This has been changed to " … is created …"**

P6L19: Add a possessive apostrophe to change "to the models" to "to the model's". **"… the models pre-industrial LSM." has been changed to "… the model's pre-industrial LSM"**

P6L32: Change "regions when" to "regions where". **I have changed " ... in regions when model …" to "… in regions where model …"**

P7L2: I think somewhere here or in the following lines the authors should give an explicit statement that highlights that vegetation is prescribed rather than simulated. Such a statement was removed further up, in response to a reviewer remark arguing that the previous location of the statement was not suitable. Yet, it seems that this important information is now completely missing from the manuscript, with the exception of Table 1. Without an explicit statement in the text, that vegetation is prescribed rather than computed, I fear that the information regarding regridding of the PRISM4 vegetation could be misinterpreted, leading to the possible assumption that PRISM4 vegetation may act as an initialization for a vegetation model, rather than as a time-invariant boundary condition in a simulation. **I have added the sentence "The vegetation scheme is then held fixed within each experiment" to clarify that the vegetation is non-dynamic. I have there also clarified this within the description of the pre-industrial based experiments (Section 3.1) with the sentence "Within all experiments the vegetation scheme is time-invariant (fixed)."** P6L5-6

P7L3: Add a comma at the end of the line after "the modern lake distribution", to clarify the meaning of the sentence in presence of many occurrences of "as". **I agree, I have added a comma.**

P7L15: I think the comma after "island specification" should be replaced by a full stop. **I have replaced the comma with a full stop.**

P7L30 – P8L2: Replace some occurrence of "and" with comma to improve readability of the rather long sentence, e.g.: "The atmosphere model (AGCM) was initialized in a 50 year run with PRISM4 LSM, basic surface scheme (lakes, ice, shrubs and orography), pre-industrial CO2 (280 ppm), as well as zonal hemispheric-symmetric monthly Sea Surface Temperature (SST) and sea ice distribution derived from the initial 2500 model year pre-industrial HadCM3 simulation from Section 3.1." **I agree, I have incorporated your sentence alterations**

P8L5: Change "is continued run" to "is continued". **I have removed the occurrence of "run".**

P8L8: Change "the set of island line integrals are" to "the set of island line integrals is", or alternatively remove "set of". **I have replaced "are" with "is"**

P8L15: I think the statement, that CO_2 is held fixed at 400 ppm, is not needed here, as this was already stated under item 5, and this fact did not change in item 6, correct? **I have removed the surplus "(CO2 held fixed at 400 ppm)" within item 6.**

P8L21: I think the height, at which surface temperature is defined, should be put into brackets: "[...] surface (1.5 m) air temperature [...]". **I agree, 1.5 m has been placed in parenthesis.**

P9L1: Is the word "imbalance" missing after "TOA"? **I agree. I have added "imbalance" after "TOA".**

P9L11-12: I would add a reference (or several) that justifies the authors claim that 400 ppm is indeed in the middle of the anticipated CO_2 range for the relevant time period. **I have added reference to Haywood et al., 2016 (and references therein) as this has a good discussion on the rationale for a 400 ppm target CO2 value.**

P9L17: Change "Tables 3" to "Table 3". **This has been corrected.**

P10L5: Order of referenced values and references could be improved. I propose to change the text to: "[...] also lies between values derived in the PlioMIP2 studies by Kamae et al. (2016) (2.4°C) and Chandan and Peltier (2017) (3.8°C), [...]". **I agree, I have placed the reported temperatures within parenthesis**

P10L3-4: I think in the context of the region chosen by the authors for analysis of polar amplification, it is more appropriate to refer here to Northern and Southern Hemisphere, rather than to North and South Pole. **I agree. I have changed North Pole and South Pole to Northern Hemisphere and Southern Hemisphere respectively**

P10L6: Add a comma after "Baltic Sea regions". **I have added a comma after "Baltic Sea regions"**

P10L15: Based on the information in Table 3, I believe the authors mixed up the values for the anomalies Eoi400-E400 (which should be 2.9-1.8=1.1°C) and E400-E280 (which should be 1.8-0=1.8°C). Please confirm and correct if necessary. **You are correct - the reported values were incorrectly switched. This has been corrected.**

P10L20 and L23: If I am not mistaken you need to refer to Haywood et al. (2013b), rather than to Haywood et al. (2013a). Please verify and fix if necessary. **I agree. Within two circumstances I have changed the reference from Haywood et al. (2013a) to Haywood et al. (2013b).**

P11L3-4 (my counting): I would add commas before and after "e.g. North Africa and the East Antarctic Ice Sheet". **I agree – I have added a comma.**

P11L11: I suggest to add a comma after "South Central Pacific". P11L13 : Remove the full stop at the end of subsection heading 4.1.3. P11L24: Remove the comma after "of daily data. **I have added a comma after "South Central Pacific". I have removed the full stop of subsection heading 4.1.3. I have also removed the comma after "of daily data".**

P12L1-2: Add a comma after "jet stream axis". Furthermore, do you talk about one axis (then add a "an" or "the" before "axis") or about multiple axes (then change "axis" to "axes") accordingly. **I have added a comma after "jet stream axis". I have changed "axis" to "axes".**

P12L4: Do not capitalize "Ocean" in the subsection heading 4.2. **I have decapitalised "Ocean" within subsection heading 4.2.**

P12L11: The cooling during DJF and MAM is not shown in any figure or table, right? Please add a respective remark to the text. **I have added a "(not shown)" to the end of the sentence in reference to DJF and MAM.**

P12L20: Could the authors please explain in the main text the meaning of their statement "but this effect diminishes with increased CO_2"? Based on the values shown in Table 6 this statement is unclear to me. According to my interpretation of the values, paleogeography indeed increases the warm pool area by about 12.4x10^6 km^2 GWP; yet, also for increased CO_2 the area further increases. The change Eoi400 vs. E400 is 8.2x10^6

km^2 GWP, right? I might be wrong, but if I consider the appreciable variability around the given mean values, then the term "diminish" appears at least to me a bit strong here. **This sentence was referring to what you interpreted, and I agree that given the error associated with the GWP error, the sentence is not a valid statement (e.g. it is not clear from the presented data if Eoi280 - E280 is notably different from Eoi400 vs. E400) I have therefore removed ",but this effect diminishes with increased CO_2".**

P14L2-4: According to Table 7 the difference in maximum AMOC between Eoi400 and E280 is rather 3.9 Sv than the mentioned 4.2 Sv. Please confirm and correct. There are some other slight inconsistencies between numerical values mentioned in the text and derived from tables, e.g. for the standard deviation for E280 AMOC maximum (1.1 in the table vs. 1.2 in the text). I would once more carefully check that values in text and tables are consistent. **I have corrected the two values within the paragraph and checked all other values- when I had originally corrected the table I had not followed through into the manuscript text. I have also incorporated the error within the sentence " … whilst the Eoi400-E280 $AMOC_{max}$ anomaly of 3.9 Sv…" so that the whole sentence now reads " … whilst the Eoi400-E280 $AMOC_{max}$ anomaly of 3.9 ± 1.6 Sv (Table 7) lies at the upper end of the PlioMIP1 ensemble range of -0.9 - 3.6 Sv."**

P14L6 : The weakening of AMOC at 40°N in Eoi280 vs. E280 is really difficult to see based on Fig. 12. By eye I would say that the strength of the AMOC at this latitude is actually stronger in Eoi280, but I may be wrong. While in general this may be a minor observation, due to the potentially causal link to sea surface temperature changes suggested by the authors, it may still be significant with respect to the conclusions drawn from the AMOC change. Could the authors kindly confirm their statement and/or provide a clarification in the text – or maybe highlight the regions of interest, for example with boxes, in Fig. 12? **My apologies for the confusion. I meant that the AMOC strength weakens *poleward* of ~40°N , rather than *at* ~40°N. The sentence has been changed from " … we find that the overturning strength reduces slightly at ~40°N, …" to " … we find that the overturning strength reduces poleward of ~40°N, … "**

P15L22: I would rephrase "[...] appear sensitive to TSI value [...]". Maybe just delete "value"? **I agree, I have therefore removed "value".**

P16L4 and 6: Again, the reference should likely be to Haywood et al. (2013b), not to Haywood et al. (2013a). **This repeated erroneous citation is particularly embarrassing, so I am grateful for your careful checking. I have corrected the two instances.**

P16L11: Consider to connect "model dependent" with a hyphen. **I have added a hyphen**

P16L17-19: I would split the long sentence in two: "[...] uses an annually-derived correction (Section 2.2). In theory, [...]". **I agree, I have split this sentence into two and added a comma.**

P17L3-4: Add a comma to the text: "[...] diffusive pipes to represent, otherwise unrepresented, narrow straits." **I have added a comma.**

P17L5-7: The text spreading over both pages could be improved, e.g.: "An example is the subaerial extension of Ireland and Scotland within PRISM4, posing the question how this region should be represented within the model, and how the model-representation may influence the simulation of the Norwegian Current." **I have followed your suggestion and improved the sentence accordingly. The sentence now reads "An example of this is in the subaerial extension of Ireland and Scotland within PRISM4, posing the question of how this region should be represented within the model and how the model-representation may influence the simulation of the Norwegian Current.**

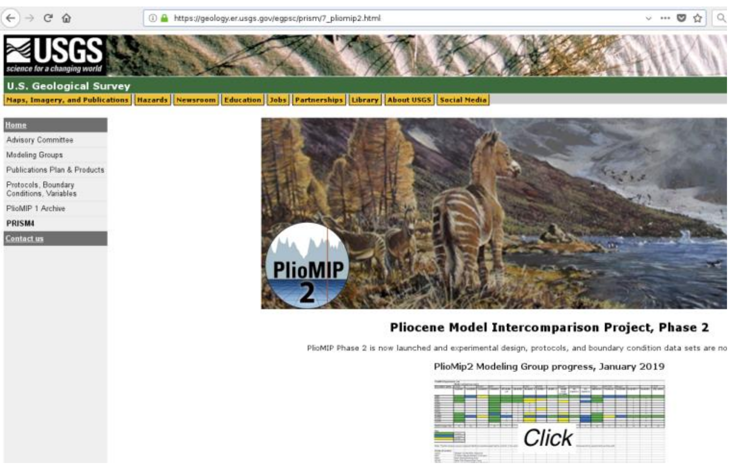
P17L11-12: Small improvements of the text could lead to the following formulation: "Paleography-induced changes in the mean state, for example the path of the Antarctic Coastal Current around the Peninsula island (Section 4.2.5), represent non-analogous [...]". **I agree. I have changed the sentence so that it now reads "Palaeogeography-induced changes in mean state, for example the path of the Antarctic Coastal Current around the Peninsula island (Section 4.2.5), represent non-analogous characteristics imposed by the PRISM4 Pliocene reconstruction.**

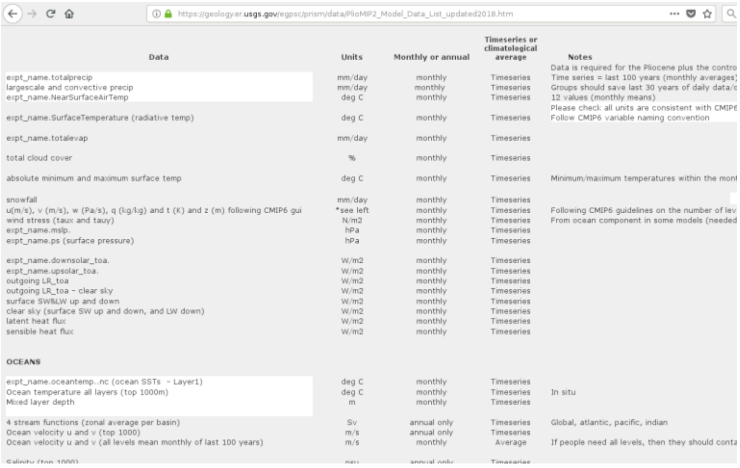
P17L16: Add a comma after "Hill (2015)". **Comma added**

P17L17: : Change "within North American" to "within North America", and add a comma after the closing bracket. **"American" changed to "America" and comma added after the closing bracket.**

P17L17-18: Avoid close proximity of the very similar words "considered" and "considering". **I have changed the sentence to " These important regional changes must be appreciated when considering the KM5c …"**

P22L26-29: Could the authors kindly check the website address to the USGS PlioMIP2 website? I have trouble accessing it via the provided link. **Both USGS links worked on two computers here with safari and firefox from the hyperlinks within the manuscript PDF file and typed by hand. (https://geology.er.usgs.gov/egpsc/prism/7_pliomip2.html and https://geology.er.usgs.gov/egpsc/prism/data/PlioMIP2_Model_Data_List_updated2018.htm**





Data	Units	Monthly or annual	Timeseries or climatological average	Notes
				Data is required for the Pliocene plus the contro
expt_name.totalprecip	mm/day	monthly	Timeseries	Time series = last 100 years (monthly averages)
largescale and convective precip	mm/day	monthly	Timeseries	Groups should save last 30 years of daily data/c
expt_name.NearSurfaceAirTemp	deg C	monthly	Timeseries	12 values (monthly means)
				Please check all units are consistent with CMIP6
expt_name.SurfaceTemperature (radiative temp)	deg C	monthly	Timeseries	Follow CMIP6 variable naming convention
expt_name.totalevap	mm/day	monthly	Timeseries	
total cloud cover	%	monthly	Timeseries	
absolute minimum and maximum surface temp	deg C	monthly	Timeseries	Minimum/maximum temperatures within the mont
snowfall	mm/day	monthly	Timeseries	
u(m/s), v (m/s), w (Pa/s), q (kg/kg) and t (K) and z (m) following CMIP6 gui	*see left	monthly	Timeseries	Following CMIP6 guidelines on the number of lev
wind stress (taux and tauy)	N/m2	monthly	Timeseries	From ocean component in some models (needed
expt_name.mslp.	hPa	monthly	Timeseries	
expt_name.ps (surface pressure)	hPa	monthly	Timeseries	
expt_name.downsolar_toa.	W/m2	monthly	Timeseries	
expt_name.upsolar_toa.	W/m2	monthly	Timeseries	
outgoing LR_toa	W/m2	monthly	Timeseries	
outgoing LR_toa - clear sky	W/m2	monthly	Timeseries	
surface SW&LW up and down	W/m2	monthly	Timeseries	
clear sky (surface SW up and down, and LW down)	W/m2	monthly	Timeseries	
latent heat flux	W/m2	monthly	Timeseries	
sensible heat flux	W/m2	monthly	Timeseries	
OCEANS				
expt_name.oceantemp..nc (ocean SSTs - Layer1)	deg C	monthly	Timeseries	
Ocean temperature all layers (top 1000m)	deg C	monthly	Timeseries	In situ
Mixed layer depth	m	monthly	Timeseries	
4 stream functions (zonal average per basin)	Sv	annual only	Timeseries	Global, atlantic, pacific, indian
Ocean velocity u and v (top 1000)	m/s	annual only	Timeseries	
Ocean velocity u and v (all levels mean monthly of last 100 years)	m/s	monthly	Average	If people need all levels, then they should conta
Salinity (top 1000)	psu	annual only	Timeseries	

P19L33-37 and P20L1-3: Maybe the order of references Dowsett et al. (2016) and Dowsett et al. (2013) should be swapped? **I was initially unsure why this was happening as this is Latex->Bibtex and reference ordering should be automatic. The Dowsett et al., 2016 is from Scientific Reports which lists authors using middle initial, whilst the Dowsett et al., 2013 is from Climates of the Past which didn't include middle initial. I think this is the reason Dowsett et al., 2016 appears before Dowsett et al., 2013. I have corrected the reference ordering by adding a middle initial to Harry Dowsett within Dowsett et al., 2013, so that bibtex recognises that they are the same person and so orders the two references correctly.**

Looking fully at the bibtex logfile I've also corrected the Randall et al., 2007 reference ("journal" was replaced with "booktitle" to correctly incorporate the book title), Roether et al., 1994 (changed from "misc" to "incollection" to correctly incorporate the editor). I have also corrected the ETOPO5 reference (from "incollection" to "misc" so that the author is now correctly National Geophysical Data Center in accordance with https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ngdc.mgg.dem:3141). I have also corrected the Levitus reference so that it conforms with https://repository.library.noaa.gov/view/noaa/1381

Note: After the references section, ending on page P36, there is an offset in page numbering. Page numbers provided by the authors are not unique across the manuscript. I have recounted the pages from P37 on (which is P28 according to the authors page numbers) and give my page numbers for the comments below.

P25: Consider to not capitalize the "Y" in the time unit. **I have changed the x-axis label within Figure 2 so that it now reads "Integration Time (yrs)"**

P26,27,28,29,32 and 38 : if you consider to mention the confidence criterion is also there, like done for other relevant figure captions, but not yet on page 51 (my counting): Consider to replace all occurrences of "criteria" by "criterion", which to my knowledge is the correct singular form of this word. Maybe also consider to replace the formulation "at a" by "based on a". **Within the captions of Figures 3,4,5,6, and 9 I have changed "criteria" to "criterion" I have also added "Stippling indicates regions in which results are not statistically significant at a 95% confidence criterion" to Figure 15**

P30, Fig. 7: I have to admit that the color scale of the color bar, where intervals of $10x10^9$kg/s intervals are split into two subintervals, albeit having same color, is causing difficulty kg/s intervals are split into two subintervals, albeit having same color, is causing difficulty when trying to interpret the statements by the authors with regard to strength of Hadley Cells in the model vs. observational and reanalysis data. If there is no good reason for having subdivisions of same color, I would just merge them. Furthermore, remove the superfluous space in E ^{280}. There is an inconsistency between simulations as listed in the overall figure caption and the subfigure caption (E400 vs. Eoi400) – this needs to be fixed. **I have removed the superfluous space in E^{280}. Within the Figure caption I have changed "E^{400}" to "Eoi^{400}". I have changed the colour scale of Figure 7 from NCL:BlueDarkRed18 to NCL:ncl_default. This colour scheme has a more continuous colour palette so that each subdivision is a different colour**

P31 Figure 8: Remove the superfluous space in E ^{280}. Furthermore, there is an apparent inconsistency between the captions of subfigures, that state that data for simulations E280, Eoi280, and Eoi400 is shown, while the caption of the whole figure states that rather values for E280, Eoi280, and E400 are shown. This inconsistency needs to be fixed, also with regard to references to the figure in the text (P19/P20). As in the light of this inconsistency it is difficult to impossible for me to follow the conclusions drawn by the authors on said text pages, the authors may want to carefully check their statements on the behavior of StJ and PJ once more. Furthermore, I would add an "a" after "within", and an "is" after "speed". Due to the chosen color for the minimum and maximum of the index, it is often difficult to differentiate between extremes of the data and the land sea mask. Maybe the authors find colors that provide a better contrast between data extremes and land sea mask. **I have removed the superfluous space in E^{280} and within the Figure caption I have changed "E^{400}" to "Eoi^{400}" Within the manuscript I do refer to E^{400} experiment but do not show the data – I have added a "(not shown)" after reference to E^{400}** (P11L26)**. For clarification, I have added followed E^{280} with "(Figure 8 a-d)"** (P11L25)**. . I have added an "a" after "within" in the Figure caption, and an "is" after "speed". I have added a "(not shown)" to "For both E280 (Figure 8(a-d)) and E400 (not shown) we obtain a seasonal jet stream configuration which is consistent with the ERA-40 and derived results of Archer and Caldeira (2008)." which should now resolve the confusion. Within the caption of Figure 8, I have added an "is" after "speed", and "a" after "within".**

P31 (continued) **I have changed the colour scale within the Figure from NCL:prcp_1 to NCL: BlAqGrYeOrReVi200 so that the end colours are more distinguishable and non white/grey.**

P33, Figure 10: Consider to capitalize "hemisphere". **This has been capitalized**

P34, Figure 11: Fix multiple typos in "climatologcal meaning", where I assume rather "climatological averaging" is meant. **The spelling has been corrected and "meaning" changed to "averaging"**

P38, Figure 15: Resolve the inconsistent terminology (MASST vs. SST) in figure caption vs. subfigure caption. **The figure captions have been corrected with "MASST"**

P39 Table 1, (P38 in the typeset version); simulation no. 5: Fix the typo in “vegegation”; simulation no. 8: consider to remove the “of”. **I have corrected the misspelling of “vegetation” and removed the “as”**

P40, Table 5: Add an “is” in the caption after “reported as it”. **I have inserted an “is” to the caption**

P41, Table 6: See reviewer #1’s comments regarding Page 37, Table 6 for the first review. There are some suggested reformulations for the text below the table that have not yet been implemented. Yet, doing so would make lots of sense in my humble opinion. **Wrt the other Reviewers initial review comments to Table 6 sub-caption. There is no discrepancy between the 28C isotherm of SST Figure 9 and the sub-caption – as Table 6 was recomputed to ensure that all Warm Pool diagnostics were defined by the 28C isotherm. (Note in my original submission I had used a 28.5C definition of one of the warm pools which caused confusion). I have added “criterion” so that the first sentence of the sub caption now ends “…and a 28C criterion. I have corrected two latex errors within the sub caption that mean that the “>” had not been incorporated into the pdf file. The final two sentences of the sub caption now read “ … max monthly mean area that is >=28°C. For $IPWP_{max}$ the number in parenthesis is the area that is >=28°C year-round.”**

P42, Table 8: I suggest the following reformulation: “From the barotropic streamfunction we derive the mean ACC latitude (the Polar front) from the centroid of the zonal transport, and the core width from the ± 50% boundary.” **I agree. I have rephrased the caption sentences as you suggest.**

Reply to Anonymous Referee #2 (Cp-2018-180-referee-report-1)

I have gone through your comments sequentially. I have updated the page and line numbers to correspond to **cp-2018-180-manuscript-version4.pdf.** Due to the process of marking-up the manuscript (attached to the end of this document) the page and line numbers may differ to the corrections outlined below. I would like to apologise that there was some confusion in the previous review stage. I would like to state how grateful I am for the time and thoroughness from both referees. Your comments have greatly improved this manuscript, and I cannot thank you enough.

Page 2, line 10: "the atmosphere mode layers drapes drape over the topography" **".. drapes .." has been corrected to ".. drape .."**

Page 2, Line 27: ".... was used or only specific regional ....." **I have added "only"**

Page 3, Lines 3 and 9: remove "the 2nd" and "the 5th" prefixes for the project names in favour of the suffixes "Phase 2" and "Phase 5" **I have changed "the 2nd … " to "the second phase of the …", and "the 5th " with "the fifth phase of the" as these were more commonly used.**

Page 2, Line 30: Change the section header to "Atmosphere and land models" since you are discussing both those components in the section. **Good point, I have corrected this**

Page 3, Line 11: "... with previous work but and the authors acknowledge that space borne measurements indicate that of TSI have has decreased from 1371 Wm2 in 1978 to 1362 Wm2 from 1978 to in 2013" **These suggestions greatly improve the readability of the sentence. I have changed the sentence so that it now reads "This value (derived in the 1990s) is used to remain consistent with previous work and the authors acknowledge that space borne measurements indicate that TSI has decreased from 1371 Wm-2 in 1978 to 1362 Wm-2 in 2013 (Kopp and Lean, 2011; Meftah et al., 2014)."**

Page 3, Line 13: "We therefore examine" **I have added a "therefore".**

Page 3, Line 16-17: "TSI may depend upon if whether or not the group is a participant of CMIP6" **I agree, I have I have replaced "if" with "whether or not" so that the sentence now reads "…whose TSI may depend upon whether or not the group is a participant of CMIP6."**

Page 3, Line 30-31: I didn't understand the context in which the word "resilience" is used here with regards to the forests. I think that the vegetation is static so you are not using it to mean that the forest fractional area can change in response to temperature. I agree, this is confusing given that I am not using a dynamic vegetaion model. **I have removed " .. and improves forest resilience to elevated temperatures" so that the sentence now reads "… which corrects the temperature control of plant respiration (making the model MOSES2.1a in the nomenclature of …"**

Page 4, Line 3: Change the section header to "Ocean and sea ice models". **Good point, I have changed this**

Page 5, Line 23: "We also explore two sets of non-protocol sensitivities — experiments to assess sensitivities to the Pliocene orbital configuration and the TSI" **These changes improve the readability of the sentence so I have made the changes and it now reads "We also explore two**

sets of non-protocol experiments to assess sensitivities to Pliocene orbital configuration and the TSI."

Page 6, Line 12: There should only be $!_{orb}Eoi^{400}$ in the list in the section header **This has been corrected**

Page 6, Line 17: "anomaly if PRISM4 Pliocene minus PRISM4 modern" **This is a good point. I have added the second "PRISM4"**

Page 7, Lines12-13: Figure 1 does not show the island as part of the Antarctic stream function configuration. **My apologies for the confusion. The unmarked island is correct within Figure 1, as this island integral was removed within Stage 6 of the Pliocene model spin-up procedure described within Section 3.3. I hadn't updated the text to reflect this. I have therefore changed the "within" to "outside" so that the sentence now reads (emphasise mine) "The island to the west of the Antarctic Peninsula body lies outside the island definition of the main Antarctic continent and therefore the circulation between the two is not fully resolved (only the baroclinic flow is resolved fully). " The rest of the sentence remains factually correct with this alteration. I have also removed the reference "Figure 1" within Section 3.3 Stage 4, and added "The final island configuration is shown within Figure 1." to the end of Section 3.3 stage 6.**

Page 9, Line 19-20: "Very high differences in MASAT differences of up to 31.3C are reached over regions of Greenland and Antarctica where the elevation of Pliocene ice sheets have been changed with respect to the present." **I have taken up your suggestion and restructured the sentence accordingly so that it now reads "Very high differences in MASAT of up to 31.3C are reached over regions of Greenland and Antarctica where the elevation of Pliocene ice sheets have been changed with respect to the present**

Page 9, Line 31: (Kamae et al. 2016) **At the request of Anonymous reviewer 1 this was changed to " … between the PlioMIP2 studies of Kamae et al. (2016) (2.4°C) and Chandan and Peltier (2017) (3.8°C)"**

Page 10, Line 6: "regions that are subaerial exposed" **I have changed "subaerial" to "exposed"**

Page 10, Line 8: "subaerial exposed" Both Baltic Sea and Hudson Bay are exposed in Pliocene, not subaerial. **I have changed "subaerial" to "exposed"**

Page 10, Line 15: The values 1.8C and 1.1C are reversed **This has been corrected**

Page 10, Lines 23-—26: "It must be noted, however, that this calculation such a comparison of CS to ESS is only meaningful and revealing when one assumes that the PlioMIP2 enhanced boundary condition represents approximates the ...., which is a reasonable position since the hence neglecting non-glacial elements of the PRISM4 retroacted paleogeography are relatively small (Dowsett et al. 2016)."

I have changed the sentence from "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. " to

"It must be noted, however, that such a comparison of CS and ESS is only meaningful when one assumes that the PlioMIP2 enhanced boundary condition approximates the equilibriated Earth System under a contemporary doubling of CO_2 which is a reasonable position since the

changes in non-glacial elements of the PRISM4 retrodicted palaeogeography are relatively small."

Page 11, Line 13: "meridional mass transport stream function" **I have inserted "transport"**

Page 11, Line 14. The meaning of the sentence spanning these lines is unclear to me. **The sentence "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." was superfluous so it was removed.**

Page 12, Line 8: "levels of !CO_2, regional" **I have added a comma so that it now reads "… CO2, regional …"**

Page 12, Line 8-9: What does 'This warming' refer to? **I was referring the CO-induced warming in the close of the preceding sentence. I have clarified this by joining the two sentences and so that it now reads "…overprinted by CO_2 induced warming which is most evident in the mid-latitudes."**

Page 12, Line 11: "we find a cooling during DJF and MAM (not shown)" Note: although I'd recommend the authors to put this in supplement. **I have inserted a "(not shown)"**

Page 12, Line 10-11: Can the authors re-check the text in the parentheses? **The text and numerical value that were within the parentheses was correct. The sentence has now be rephrased so that it now reads "In the vicinity of the modern Gulf Stream and North Atlantic Drift we find a cooling during DJF and MAM seasons of up to -4.9°C within Eoi280 -E280 (not shown)."**

Page 12, Line 11-13: Gulf Stream should be capitalized. Also I don't follow the sentence and it's substance as it is currently written. **"Gulf Stream" capitalized. The sentence "Investigation of surface ocean vectors (not shown) suggests an intensification of the North Atlantic wind-driven subpolar gyre and Labrador current which appears to disrupt western intensification and the path of the Gulf Stream.", I have changed the sentence, removing superfluous elements and being more specific. The sentence now reads (emphasis mine) "Investigation of surface ocean velocity vectors (not shown) suggests an intensification of the North Atlantic wind-driven subpolar gyre which appears to disrupt western intensification and the path of the Gulf Stream.**

Page 12, Line 20: "but this effect diminishes with increased CO_2" I don't follow, the GWP area in all Eoi configurations are larger than in E^{280}, and that area grows larger with CO_2. **Sorry for the confusion, the end of sentence had now been removed.**

Page 12, Line 22: "As expected, increased CO_2 drives warm pool expansion under both modern and Pliocene geographic conditions." **This has been added.**

Page 12, Line 31-32: "becomes more asymmetric" in what way? I don't see what is becoming asymmetric. **I was referring to how the summer sea ice is now focussed within the South West. The phrase is redundant anyway as I finish the sentence with "… being concentrated in the highest latitudes on the coast of West Antarctica.". I have rephrased the sentence so that it now reads "During austral summer the concentration of sea ice within the Pliocene is reduced in extent and more zonally asymmetric, concentrated within the Amundsen and Ross Seas"**

Page 13, Line 16-17: It would be good to show the AMOC time series in supplement. **Currently it is unclear how much of the centennial variability in AMOC is associated with model spin-up (e.g. a non physical transient phenomenon). This initial PlioMIP2 paper is focussed on the climatological averaging period rather than a "catch all" paper and so I am leaving it to a subsequent paper to investigate this further. I have changed the text of "Multidecadal to centennial fluctuations, including a dominant ~225 year oscillation within parts of the spin-up phase, are present within the Pliocene experiments but not the pre-industrial experiment." to "Multidecadal to centennial fluctuations within the spin-up phase are present within the Pliocene experiments but not within the pre-industrial experiment.". I have also added a "potentially" within Page X Line Y so that the sentence now reads "Centennial-scale fluctuations in Pliocene $AMOC_{max}$ could potentially account for statistical differences …". I hope to expand upon decadal to multi-centential variability within the spin-up phase in a subsequent paper in which I can put this into context with other Pliocene and pre-industrial climate modelling.**

Page 14, Lines 31: Here, in reference to the deep convection around Antarctica the authors say that the increased deep convection here "would explain the strengthened AMOC within the Pliocene", but this is not correct. The measure of Pliocene MOC in the preceding section is based on the max of the NADW which originates from the North Atlantic, whereas the deep waters from Antarctica constitute the AABW. It's a different cell from the NADW, so it doesn't directly contribute to the top cell. Additionally, various studies have shown a compensation between the two cells such that a stronger NADW reduces AABW and vice versa. So a larger deep water formation around Antarctica would reduce the strength of the top cell, not strengthen it. Furthermore, this compensation is exactly seen in Fig 12. In Eoi400 with a stronger top cell, the bottom cell constituting waters from Antarctica is reduced in strength and northward penetration. **My knowledge of the role of AABW within AMOC was lacking here. I have discussed the role of North Atlantic deep convective mixing within Section 4.2.4 in relation to AMOC strength.**

Within Section 4.2.5 (ACC) which you are referring to, I had initially corrected the sentence and made it more specific so that it read "This enhanced deep convection within Eoi^{280} is reflected within Figure 11 and would explain the strengthened AABW (Figure 12b), although the limited representation of deep convection within the model should be noted."

On reflection, I have decided to remove the closing sentences all together because E280 has little modelled deep convection in the Southern Ocean yet it still has a large AABW. It is a more complex story which I think is beyond the scope of this paper, particularly given the fidelity in which deep convection is represented within the model – I feel that it requires a more thorough evaluation and an investigation into the mechanistic drivers of AABW (and NADW) formation within E280, Eoi280 and Eoi400.

I have now appropriately defined AABW at its first use within Section 2.2. Page 4 Line 15

I have also removed mention of the Southern Ocean within the abstract so that the sentence now reads " 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 North Atlantic." Page 1 Line 10

Page 15, Line 6: "statistically significant" **I have changed "statistical" to "statistically"**

Page 15, Line 6: "and $AMOC_{max}$ at 26.5N" **This has been corrected**

Page 15, Line 30: "Comparing Compared ..... surface warming ... high-latitudes in a similar and whose spatial distribution is similar to that obtained with HadCM3 within for PlioMIP1 under ..." **This is a good way to improve the sentence – changes have been made so that the sentence now reads "Compared to the pre-industrial control (E^{280}), we find Pliocene surface warming focussed within the high-latitudes and whose spatial distribution is similar to that obtained with HadCM3 for PlioMIP1 under …"**

Page 16, Line 3: "... 3.5C and 2.9C per doubling of CO_2" **This has been corrected**

Page 16, Line 2-4: "which again are also similar to results of from PlioMIP1 wherein they were estimated to be of 3.3C and 3.1C respectively" **This has been changed so that the entire sentence now reads "We derive climate sensitivities of 3.5°C and 2.9°C per doubling of CO2 for the pre-industrial and Pliocene, which are also similar to results from PlioMIP1 wherein they were estimated to be 3.3°C and 3.1°C respectively (Haywood et al., 2013b)."**

Page 16, Line 4-5: "We derive an approximation of estimate the Earth System Sensitivity of at ~5.6C leading to implying an ESS/CS ...." **This changes have been incorporated**

Page 16, Line 10: "... vegetation models by other PlioMIP2 participating groups ..." **I have left out the "other" as our group is aiming to run with a vegetation model too**

Page 16, Lines 12-13: The sentence about precipitation change is too short and ends abruptly. **I feel that it leads onto the next sentence well, so I have left it as it stands.**

Page 17, Line 11—15: Why do the authors say that the geographic changes along the Antarctic Peninsula in the Pliocene are not analogous to those that can be expected in the future? The West Antarctic Ice Sheet is marine grounded and the disintegration of that ice sheet under warmer conditions would lead to geographic conditions that are entirely like the Pliocene. One would have the main large islands that are seen in the PRISM4 version along with several smaller (and below climate model resolution) islands. This is well established from ice modelling studies and from GIA modelling following the removal of the ice load. And these changes are not something that one would have to wait very long for — ice sheet modelling studies (Pollard and DeConto, Nature 2016) show that the WAIS can completely collapse in as little as a few hundred years.

This is a good point. Figure 4h of Pollard and Deconto 2016 (PD16) show that the Peninsula becomes an "island" at the earliest between 2100-2150 under worst case business as usual RCP 8.5 scenario. Under RCP8.5 CO_2 is ~1200 ppm at yr 2100 – this is beyond the range of the Pliocene CO_2 values within the manuscript. I acknowledge that this is a transient response and it is unclear at what equilibrium CO_2 this would occur at. Within PD16 it can be seen within RCP4.5 (which stabilises at ~550 ppm at 2100) that by 2500 that the Antarctic Peninsula is an "island". I would still say that these aspects of the Pliocene Palaeogeography are potentially non-analogous in the sense of near-term climate (e.g. a 400 ppm world). I have rephrased this by adding "potential" so that it now reads " for example the path of the Antarctic Coastal Current around the Pensinula island (Section 4.2.5) represent potentially non-analogous characteristics imposed by the PRISM4 Pliocene reconstruction (in the sense of a fixed 400 ppm CO2 forcing). Other non-analogous …" (Page 17, Line 11—15)

Figure 30: "meridional mass transport stream function" **I have added "transport" to the caption sentence.**

Table 2: "Summary of equilibrium parameters metrics for seven ..." **I have changed "parameters" to "metrics"**

Table 3: "Global mean annual surface air temperature (MASAT) decomposed into and the mean surface air temperatures in polar ...." **I have changed the Table 3 caption so that it now reads "Global mean annual surface air temperature (MASAT) and the mean annual surface air temperatures of the polar …"**

Table 3: "North Pole" and "South Pole" make it look at first glance that you are talking about exactly at the pole. Maybe change these to something like "NH polar" or something else? **As requested I have changed the Table 3 column titles to "..NH polar MASAT.." and "..SH polar MASAT.."**

Table 5: "Integrated mean Climatological zonal mean" **Within Table 5 caption I have changed "Integrated" to "Climatological zonal"**

Table 6: "... and defining characteristics various metrics for the spatial extent of the equatorial..." **I have replaced "defining characteristics" with "various metrics for the spatial extent"**

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. 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. Climate sensitivity 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 fraction and areal extent is reduced during the Pliocene particularly in the ~~southern hemisphere~~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 choice of total solar insolation (1361 vs. 1365 Wm^{-2}) and orbital configuration (modern vs. 3.205 Ma) do not significantly influence the anomaly-type analysis in use by the Pliocene community.

1 Introduction

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. 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 - CORE, Tier 1 and Tier 2 experiments. The CORE components must be completed by all modelling groups, whilst the Tier 1 and Tier 2 components are optional with Tier 1 experiments being a higher priority than Tier 2. The PlioMIP2 protocol specifies a standard and enhanced boundary condition dataset. The standard boundary conditions have a Pliocene topography constrained by the modern land sea mask (LSM) and bathymetry, whilst the enhanced boundary conditions have full PRISM4 ~~mid Piacenzian palaeogeography~~ (Pliocene Research Interpretation and Synoptic Mapping~~; Dowsett et al. (2016))~~) mid Piacenzian palaeogeography (Dowsett et al., 2016) . Here we describe the model set-up of the enhanced boundary conditions within HadCM3 (Hadley Centre Climate Model version 3). Table 1 details the PlioMIP2 experiments conducted within this study, along with an additional set of non-PlioMIP2 experiments that explore specific 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).

The structure of this paper is as follows. Section 2 describes the model configuration. Section 3 describes the experiment design including model boundary conditions, model initialisation and spin-up. Results from the experiments are then described within Section 4, with a particular focus on atmospheric circulation and surface climatology (Section 4.1) and the oceanic responses (Section 4.2).

2 Model Description

We use the UK Meteorological Office (UKMO) HadCM3 coupled Atmosphere-Ocean 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~~ drape 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 model's runtime speed, relative ease of reconfiguration, and prediction performance make it well suited for ~~a suite~~ an ensemble 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. The model was used within PlioMIP1 experiments 1 (Atmosphere GCM) and 2 (Atmosphere-Ocean GCM~~; Bragg et al. (2012))~~) (Haywood et al., 2010, 2011; Bragg et al., 2012) , and amongst others has been used to successfully investigate Panama Seaway closure (Lunt et al., 2008), ENSO and teleconnections (Bonham et al., 2009), ice sheet reconstructions and orbital forcing (Dolan et al., 2011; Prescott et al., 2014), sea ice reconstructions (Howell et al., 2014), terrestrial and marine oxygen isotopes (Tindall and Haywood, 2015), and non-analogous aspects of Pliocene climate (Hill, 2015). In all cases, either a modern LSM and bathymetry was used or specific regional palaeogeographical uncertainties were explored. This body of work therefore represents the first published record where HadCM3 has been reconfigured with a bespoke global Pliocene palaeogeography.

2.1 Atmosphere ~~model~~and land models

The atmosphere component of HadCM3 has 19 vertical hybrid sigma-pressure levels extending to 5 hPa. Horizontal resolution is 3.75° longitude × 2.5° latitude. 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 (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) (the second phase of the Palaeoclimate Model Intercomparison Project; LSCE (2007); Braconnot et al. (2007)) 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 (Johns et al., 2003). The radiative effects of background aerosol are represented by a simple parameterisation based on modern climatological conditions (Cusack et al., 1998).

The solar constant (total solar irradiance; hereafter TSI) is held fixed at 1365 Wm^{-2} within all PlioMIP2 protocol experiments, a value consistent with the pre-industrial experiment within PMIP2 (the 2nd Palaeoclimate Model Intercomparison Project; LSCE (2007)) (LSCE, 2007; Braconnot et al., 2007) and CMIP5 (the 5th fifth phase of the Coupled model Intercomparison Project; Taylor et al. (2012)) as well as PlioMIP1. This value (derived in the 1990s) is used to remain consistent with previous work but and the authors acknowledge that space borne measurements of TSI have indicate that TSI has decreased from 1371 to 1362 Wm^{-2} from Wm^{-2} in 1978 to 1362 Wm^{-2} in 2013 (Kopp and Lean, 2011; Meftah et al., 2014). Indeed, the CMIP6 pre-industrial simulation (piControl) uses a value of 1361 Wm^{-2} (Matthes et al., 2017). We therefore examine the impact of TSI choice within the context of both pre-industrial and Pliocene climates 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 whether or not the group is a participant of CMIP6. The impact of TSI choice is minimised by the Pliocene communities community's 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; 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, 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.

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)).

Runoff is collected in drainage basins and delivered to associated coastal outflow points (on a 3.75°×2.5° geographic grid). River transport is not modelled explicitly, instead runoff is returned to the coastal outflow point in the uppermost layer of ocean ocean layer instantaneously at the atmosphere-ocean coupling step (Gordon et al., 2000). Internally-draining Internal drainage 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.

2.2 Ocean ~~Model~~and sea ice models

The ocean component is a rigid lid model of the Bryan-Cox lineage (Bryan, 1969; Cox, 1984). In the vertical there are 20 unevenly-spaced levels, concentrated near the surface in order to improve representation of the surface mixed layer. 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). The ocean time-step is 1 hour~~and~~, horizontal spatial resolution is 1.25°×1.25° and the grid is aligned so that there are six ocean grid cells to each atmosphere grid cell (3.75°×2.5°). 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, such as those along the Denmark Strait, the Iceland-Faroe and the Faroe-Shetland Channels, and straits surrounding the Indonesian archipelago, 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 that improves the representation of dense outflows that form the North Atlantic Deep Water (NADW). The scheme is not used for Antarctic Bottom Water (AABW). 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 ($\sim$ 1200m) between the Eastern Atlantic ~~with~~ and the Western Mediterranean. Other subgrid-scale channels, such as the Canadian Archipelago, Hudson Strait outflow and the Makassar Strait, remain spatially unresolved and therefore unrepresented. The latter has been shown to possess most of the Indonesian throughflow (Gordon and Fine, 1996) and so is compensated for within the model by a deepening of regional model bathymetry.

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~~ provide 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 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.

The rigid lid streamfunction scheme imposes the need for bathymetry to be smoothed particularly in steep regions of the 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 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. 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). 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 are represented with a linear 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 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

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

We also explore two sets of non-protocol ~~sensitivities -~~ experiments to assess sensitivities to Pliocene orbital configuration and the 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 Ma orbital configuration representing the mPWP time slice of Haywood et al. (2013a) within experiment $_{orb}Eoi^{400}$. We also investigate the choice of total solar irradiance (Section 2.1) by rerunning the two control (CORE) experiments with a TSI of 1361 Wm^{-2} within $_{1361}E^{280}$ and $_{1361}Eoi^{400}$.

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 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 and associated sensitivity experiments ($E^{280,400,560}$ and $_{1361}E^{280}$)

The experiments with pre-industrial geography are 500 year continuations of a long integration (>2000 model years) pre-industrial experiment that had been initialised from the observed ocean state of Levitus and Boyer (1994). The experiment uses a topography and a bathymetry regridded and smoothed from ETOPO5 (National Geophysical Data Center, 1993), and vegetation and soil translated from the land cover of Wilson and Henderson-Sellers (1985). Within all experiments the vegetation scheme is time-invariant (fixed). 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 with the PlioMIP2 protocol (Haywood et al., 2016), levels of atmospheric CO_2 are set to 280, 400 and 560 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 investigate the model sensitivity to the choice in TSI value (Section 2.1 and 4.3.2).

3.2 Pliocene (PlioMIP2 enhanced) and sensitivity experiments ($Eoi^{~~280-450~~\,280,350,400,450}$, $_{orb}Eoi^{~~280-450~~\,400}$, and $_{1361}Eoi^{400}$)

3.2.1 Boundary condition preparation

For PlioMIP2 the boundary conditions for the modern day and the 'enhanced' variant of the Pliocene reconstruction are provided on regular 1° 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~~ geography is provided to facilitate the anomaly method of boundary condition generation. The LSM is ~~first regridded~~ created by computing the anomaly of PRISM4 Pliocene minus PRISM4 modern (at 1° resolution) and regridding using bilinear interpolating to the 3.75°×2.5° model grid, and then applying the anomaly to the ~~models~~ model's pre-industrial LSM. This is so that the final reconstruction is consistent with both the original pre-industrial model set up and the PRISM4 LSM. Finally, a number of manual corrections were applied to the resulting 3.75°×2.5° PRISM4 LSM to ensure that the underlying character of the PRISM4 reconstruction is represented as best as reasonably practicable at the model's resolution. For consistency with the pre-industrial boundary conditions developed by MOHC we remove Svalbard and Novaya Zemlya, 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 identical to the pre-industrial and so the diffusive pipe is incorporated.

The resulting PRISM4 LSM was used to constrain the generation of the Pliocene orography and bathymetry (which was generated using area-weighted regridding, and then applied as an anomaly to the existing HadCM3 pre-industrial orography and bathymetry). 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 where model resolution fails to capture important orography, or where the regridded Pliocene orography is flat. The PRISM4 vegetation scheme (represented by BIOME4 biomes) was regridded by combining a BIOME4-to-MOSES2 lookup table with an area-weighted survey of underlying biomes. The vegetation scheme is then held fixed within each experiment. A similar area-weighted regridding was conducted for the lake field. We chose not to generate the lake field as an anomaly from the modern lake distribution, as land surface change since the pre-industrial would be imprinted on the model's lake distribution.

3.2.2 Barotropic streamfunction 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 (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 fully represent the East Greenland Current. The island to the west of the Antarctic Peninsula body lies within the island definition of the main Antarctic continent and therefore the circulation between the two is not fully resolved (only the baroclinic flow is resolved fully). Figure 1 compares the pre-industrial and PRISM4 Pliocene HadCM3 island specification, . 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 model setup the Bering Strait barotropic component of throughflow is unresolved and both the Makassar Strait and the Canadian Archipelago are spatially unresolved (Section 2.2). This poses a conceptual problem in the interpretation of the Pliocene experiments with respect to the pre-industrial, as the PRISM4 Pliocene geography has these throughflow regions closed. Therefore, our simulations do not resolve the full climatic response of these regional palaeogeographic changes. A pre-industrial experiment with a fully-resolved Bering Strait and Canadian Archipelago would partially 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 PlioMIP1 model implementations. These problems are likely to arise in all rigid lid streamfunction ocean models that have insufficient spatial resolution to fully-resolve these 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 reduce these issues.

3.3 Pliocene Model initialization and spin-up

Model spin-up is conducted in 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), pre-industrial CO_2 (280 ppm)~~and~~, as well as zonal hemispheric-symmetric monthly Sea Surface Temperature (SST) and sea ice distribution derived from the initial 2500 model year pre-industrial HadCM3 simulation from Section 3.1. Model failures at this stage allow for the identification of steep topography that requires regional smoothing.

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

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

4. The island configuration (Section 3.2.2, Figure 1) is then derived using an iterative series of sensitivity tests in which each island configuration is refined. Once complete, the set of island line integrals ~~are~~ is incorporated into the model configuration. At this stage we have an AOGCM incorporating full barotropic physics (Figure 2 stage b).

5. CO_2 is increased from 280 ppm at 1% per year until 400 ppm is attained. CO_2 is then held fixed.

6. At model year 950 a problem with ancilliary file generation had been resolved allowing the vegetation boundary 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 to resolve a persistent numerical mode within the barotrotopic solver in this region (Figure 2 stage c). The final island configuration is shown within Figure 1.

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

8. At year 2000, five additional experiments are spun-off 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.

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

3.4 Equilibrium State

By model years 2400 to 2500, the Pliocene control experiment (Eoi^{400}) has achieved a quasi-steady-state equilibrium in which the globally-integrated net top-of-the-atmosphere (TOA) radiative imbalance is 0.047 Wm^{-2}, surface (1.5 m) air temperature trend is 0.08°C $century^{-1}$ and ocean potential temperature trends within the upper 200 m and globally integrated are -0.026°C $century^{-1}$ and 0.041°C $century^{-1}$. The corresponding values for the pre-industrial control experiment (E^{280}) are -0.115 Wm^{-2}, 0.052°C $century^{-1}$, 0.008°C $century^{-1}$ and -0.014°C $century^{-1}$ respectively. High CO_2 experiments, Eoi^{450} and E^{560} present the largest, yet modest 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 means that residual energy is predominantly taken up by the ocean, which is reflected in the volume integrated ocean temperature evolution. Warming of the deep ocean is primarily occurring at depths deeper than 2000 m in the Pacific basin. The Indian and Antarctic oceans are the most equilibriated, particularly at intermediate depths and deeper. Table 2 summarizes the equilibrium states of the seven PlioMIP2 experiments and Figure 2 presents the time-evolution of ocean potential temperature of the Pliocene control experiment (Eoi^{400}). All experiments are deemed to be in a satisfactory state of equilibrium, although the high TOA imbalance simulations Eoi^{450} and E^{560} have above average warming within the deep ocean.

4 Results

We base our analysis on climatological averages from the final 50 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 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 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 (Haywood et al., 2016, and references therein) . 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 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 MASAT) are detailed within ~~Tables~~ Table 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~~ Very high differences in MASAT of up to 31.3°C ~~over Greenland and Antarctic regions coincide with~~ are reached over regions of Greenland and Antarctica where the elevation of Pliocene ice sheets ~~and where their respective elevation is less than the pre-industrial~~have been changed with respect to the present. Typically, warming is greatest over land, although in ocean regions at or near Antarctic LSM change (pre-industrial grounded ice to Pliocene ocean) warming is significant. This pattern of warming is similar to results derived with HadCM3 within PlioMIP1 under PRISM3 boundary conditions (Exp. 2 of Bragg et al. (2012)).

The Pliocene cooling in the Barents 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 partial suppression of northward heat transport (in the Norwegian Current) by the 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 Kamae et al. (2016) (2.4°C~~Kamae et al. (2016) and~~) and Chandan and Peltier (2017) (3.8°C~~(Chandan~~ 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~~ Northern Hemisphere and 2.2 for the ~~South Pole~~Southern Hemisphere.

Figure 4 shows the annual and seasonal temperature anomalies for Eoi^{280} and Eoi^{400} (against E^{280}). Terrestrial regions that are ~~subaerial~~ exposed only within the Pliocene, such as the Hudson Bay and the Baltic Sea regions, are up to 10°C warmer (colder) during 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 (~~subaerial~~ exposed during the Pliocene) is a driver of persistent cooling within the Barents Sea region.

From the results in Table 3 it is possible to diagnose the factors that contribute to Pliocene warming relative to the pre-industrial (E^{280}). Considering the Pliocene control experiment (Eoi^{400}), we find that the change in palaeogeography (Eoi^{280}-E^{280}) accounts for a temperature change of 1.4°C, whilst the increase in CO_2 (Eoi^{400}-Eoi^{280}) accounts for a further 1.5°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~~1.1°C of warming and the increase in CO_2 (E^{400}-E^{280}) accounts for ~~1.1~~1.8°C of temperature increase. These differences highlight that there are non-linearities within the climate system's response to changes in boundary condition.

The climate system's sensitivity to a doubling of CO_2 (Climate Sensitivity; CS) is 3.5°C for the pre-industrial (derived from E^{560} and E^{280}) and 2.9°C for the Pliocene (derived from Eoi^{400} and Eoi^{280} and scaled by 1.94 (=log(560/280) / log(400/280)). The pre-industrial CS is consistent with the 3.3°C for HadCM3 within CMIP3 (Randall et al., 2007). The Pliocene CS is similar to the 3.1°C for HadCM3 and lies at the lower end of the 2.7 - 4.1°C ensemble range of PlioMIP1 Experiment 2 ~~(Haywood et al., 2013a)~~ (Haywood et al., 2013b) . When we approximate Earth System Sensitivity (ESS) using Eoi^{400} and E^{280} (with ESS = 1.94 x $\triangle T_{Eoi^{400}-E^{280}}$) we obtain ∼5.6°C. Subsequently the ESS/CS ratio is ∼1.9, which lies at the higher-end of the 1.1 - 2.0 range of the PlioMIP1 ensemble ~~(Haywood et al., 2013a)~~ (Haywood et al., 2013b) in which HadCM3 had a ratio of 2.0. It must be noted, however, that ~~this calculation~~ such a comparison of CS and ESS is only meaningful when one assumes that the PlioMIP2 enhanced boundary condition ~~*represents*~~ approximates the equilibriated Earth System under a contemporary doubling of CO_2, ~~hence neglecting~~ which is a reasonable position since the changes in non-glacial elements of the PRISM4 retrodicted palaeogeography are relatively small.

4.1.2 Precipitation

The globally integrated Mean Annual Precipitation (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 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 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 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.

Seasonal plots of precipitation change 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 experiencing reduced precipitation in western North America as well as central and western Europe are a consequence of weakened westerlies (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 are not evident. The South Pacific Convergence Zone, extending from the Western Pacific warm pool (WPWP) southeastward to the South Central Pacific, extends ∼15° further east in E^{280} than Eoi^{400} and Eoi^{280}.

4.1.3 Planetary scale atmospheric circulation.

The time averaged, zonal mean, meridional mass transport stream function for the atmosphere is shown within Figure 7. Clearly distinguished are the Hadley, the Ferrel and the 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.~~ 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 Northern (Southern) Hemisphere. Looking at E^{280} we find the northern cell is stronger (+10.8%) than the southern cell which is in contradiction with observational and re-analysis data (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% in Eoi^{280} and +42% 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 Kg s^{-1} for E^{280} and Eoi^{280} respectively).

The wintertime Subtropical Jet (StJ; also known as the midlatitude jet) and Polar Jet (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 400-100 hPa (∼7-16 km) exceeds 30 ms^{-1}. For both E^{280} (Figure 8(a-d)) and E^{400} (not shown) we obtain a seasonal jet stream configuration which is consistent with the ERA-40 and derived results of Archer and Caldeira (2008). The PJ and the StJ stream can be difficult to differentiate as the former is latitudinally irregular, so following Koch et al. (2006) we use normalised wind shear as a height differentiator. The StJ stream path is more persistent and stable and so is characterised by the mean latitude of the StJ core which is shown within Table 5. The change in geography (Eoi^{280}-E^{280}) drives a poleward shift of the mean StJ latitude of ∼1.6° in the Northern Hemisphere (both seasons) and 2.2° in the Southern Hemisphere summer. The response to Pliocene CO_2 (Eoi^{400}-Eoi^{280}) increase is weaker with a 0.8° poleward shift of the mean StJ latitude in the Northern Hemisphere (both seasons). The 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 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 (Figure 8b vs. 8f). Synoptic storms grow and propagate along jet stream ~~axis~~ axes and so this equatorward shift in the PJ likely contributes to the increase in rainfall seen in southern Europe during Pliocene wintertime (Figure 6e vs. 6f).

4.2 State of the ~~Ocean~~ ocean climatology

4.2.1 Sea surface temperature and warm pools

Modelled mean annual SST's (MASST) are detailed within Table 6 and Pliocene anomalies are shown within Figure 9. We see a 0.8°C warming due to the change in palaeogeography (Eoi^{280} -E^{280}) and a further 1.0°C of warming due to the change in Pliocene CO_2 (Eoi^{400} -Eoi^{280}). With increasing levels of CO_2, regional patterns of MASST change due to palaeogeography are overprinted by CO_2-induced warming ~~. This warming~~ which is most evident in the mid-latitudes~~, particularly within the North and South Atlantic and the North Pacific~~. The greatest warming occurs within the North Atlantic subpolar gyre where Eoi^{400} -E^{280} reaches 9.3°C. In the vicinity of the modern Gulf Stream and North Atlantic Drift we find a cooling during DJF and MAM seasons ~~(~~of up to -4.9°C within Eoi^{280} -E^{280} (not shown). Investigation of surface ocean vectors (not shown) suggests an intensification of the North Atlantic wind-driven subpolar gyre and Labrador current which appears to disrupt western intensification and the path of the Gulf Stream. 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~~ Stream (Figure 9). A similar expression of 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 Sea region coincident with the surface air temperature anomalies discussed within Section 4.1.1.

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

Pacific warm pool (IPWP) regions. As expected, increased CO_2 drives warm pool expansion under both modern and Pliocene geographic conditions.

4.2.2 Sea Ice

A complex picture emerges in the sensitivity of seasonal sea ice distribution to geographic and CO_2 changes as shown within Figure 10. Within the Northern Hemisphere winter, the palaeogeography changes drive an equatorward expansion of sea ice in the Greenland Sea region. Increasing CO_2 from 280 to 400 ppm counteracts some of this expansion. In the Southern Hemisphere the palaeogeographical changes 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 is an equatorward expansion of sea ice within the Bellinghausen Sea region. As we increase CO_2 we see a general reduction in the sea ice extent and 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 austral summer the concentration of sea ice within the Pliocene ~~becomes more asymetric and~~ is reduced in extent ~~, being concentrated in the highest latitudes off the coast of West Antarctic~~and more zonally asymmetric, concentrated within the Amundsen and Ross Seas.

4.2.3 Mixed layer depth and deep water formation

The mixed layer depth (MLD) for E^{280}, Eoi^{280} and Eoi^{400} is shown within Figure 11. We focus on deep convection, the principle mechanism of deep-water formation. Deep convection is highly localised and therefore model representation is only suggestive. Nevertheless, E^{280} represents reasonably well the modern open-ocean deep convection that occurs within the Weddell and Ross Seas (which form the main formation sites of ~~Antarctic Bottom Water~~AABW) and in the Labrador, Irminger and Greenland Seas. All Pliocene experiments exhibit more widespread deep convection particularly within the Labrador and Norwegian Seas, and 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 (Table 7 and Figure 11).

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

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~~ 1.1 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.

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 $AMOC_{max}$ of Eoi^{400} is 19.6 ± 1.0 Sv and occurs at ∼650 m depth at 33.75°N. Multidecadal to centennial fluctuations ~~, including a dominant ∼225 year oscillation,~~ within the spin-up phase are present within the Pliocene experiments but not the pre-industrial experiment. In all Pliocene simulations, $AMOC_{max}$ occurs within the 25 - 33.75°N zonal envelope and at a depth of ~650 m. The Eoi^{400} $AMOC_{max}$ lies within the ~~10-24.6~~ 10 - 24.6 Sv range of PlioMIP1 (Zhang et al., 2013), whilst the Eoi^{400}-E^{280} $AMOC_{max}$ anomaly of ~~4.2~~ 3.9 ± 1.6 Sv (Table 7) lies ~~outside the~~ at the upper end of the PlioMIP1 ensemble range of -0.9 ~~-3.6~~ - 3.6 Sv.

Despite an intensification of the AMOC within the Pliocene experiments, we find that the overturning strength reduces ~~slightly at~~ poleward of ~40°N driven by the changed land surface and bathymetry (Eoi^{280}-E^{280}). This is seen within cooling evident in Gulf Stream MASSTs of Figure 9. Under increasing Pliocene CO_2, the mid-latitude overturning intensifies with a corresponding decrease in the Gulf Stream MASST cold anomaly. The overturning within the polar region is evidence of bottom water formation within the Nordic Seas. In E^{280} overturning extends to ~80°N but is weaker than in the Pliocene models (which extends to ~75°N). This is reflected within the geographic extent and intensity of deep convection shown within 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). Pliocene palaeogeography (Eoi^{280}-E^{280}) drives an intensification of both the subtropical gyre and PDW overturning, whilst increasing CO_2 acts to weaken them. The Pliocene subtropical gyre ($PMOC_{+ve}$) and PDW ($PMOC_{-ve}$) overturning are stronger regardless of CO_2 level (e.g. within Eoi^{400} $PMOC_{+ve}$ and $PMOC_{-ve}$ are 22% and 6% stronger than E^{280}). With the change in palaeogeography (Eoi^{280}-E^{280}) the PDW shoals (from ~4 to 3 km) and with increasing Pliocene CO_2 the NPDW overturning reduces in northward reach, associated with the warming of North Pacific MASST (Figure 9).

4.2.5 Antarctic Circumpolar Current

The Antarctic Circumpolar Current (ACC) strength is detailed within Table 8 and shown within Figure 14. We calculate the volumetric flow of the ACC at the Drake Passage across a 64.4-56.9°S, 65°W transect using the positive aspect of the U component (zonal) of the total (barotropic and baroclinic) velocity. We find an overly intense ACC within E^{280} and E^{400} when compared against recent observations of 134-164 Sv (Cunningham et al., 2003; Griesel et al., 2012). The overly intense ACC within HadCM3 has been identified previously. Meijers et al. (2012) compared CMIP5 historical experiments to observations and found the model's ACC flow at the Drake Passage transect of 244.5 ± 4.0 Sv compared unfavourably to 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 gradient across the ACC, particularly 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 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 (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 given a more complex line-integral configuration, the model's barotropic solver may not be converging 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} to Eoi^{280}) drives a general latitudinal thinning of the ACC extent and an equatorward shift of its centroid.

Within the Pliocene experiments, the ACC runs mostly between the surface and sea floor between 60 and 57°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 equatorwards (the subtropical front is mostly unchanged). 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. There is uncertainty as smaller islands in this region are unrepresented within the model. Figure 14 also suggests a more continuous coastal current with the Pliocene palaeogeography, particularly between 180 and 90°E. ~~The 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), although the limited representation of deep convection within the model should be noted. This intensified Antarctic Coastal Current is driven partially by intensified winds poleward of the Sub-Antarctic front (at latitudes >66°S) within the Pliocene. The Weddell Sea sub-polar gyre is weakened and restructured whilst the Ross Sea gyre is less intense and extends more 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 meaningful difference in global means (Table 3 MASAT, Table 4 MAP, Table 6 MASST and warm pool areal extent).

There is a ~~statistical~~ statistically significant difference between ${}_{orb}Eoi^{400}$ and Eoi^{400} $AMOC_{max}$ (t(98)=7.20, p<<0.0001) and AMOC ~~$_{max}$~~ at 26.5°N (t(98)=11.36, p<<0.0001) using a 2-sample t-test assuming unequal variance (null hypothesis being there is no difference in the two timeseries of annual means). With regards to $PMOC_{+ve}$, ${}_{orb}Eoi^{400}$ and Eoi^{400} are deemed equivalent (t(98)=0.62, p=0.54) whilst for $PMOC_{-ve}$, the two experiments are equivalent at the 95% confidence level (t(98)= 1.93, p=0.06). Centennial-scale fluctuations in Pliocene $AMOC_{max}$ could account for statistical differences between the climatological mean 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

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 from 1365 to 1361 Wm^{-2} (- 0.3%) reduces the mean incoming solar (SW) radiation averaged over the entire Earth's surface by 1 Wm^{-2} (from 341.25 to 340.25 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 pre-industrial) for simulations based upon 1365 and 1361 Wm^{-2} for MASAT, MAP and MASST. Overall the patterns of climatological anomalies for the experiments using TSI of either 1361 or 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 orbital configuration, $AMOC_{max}$ does appear sensitive to TSI ~~value~~ when we compare Eoi^{400} against $_{1361}Eoi^{400}$ ($t(98)=-13.3$, $p<<.0001$) and E^{280} to $_{1361}E^{280}$ ($t(98)=2.47$, $p=0.015$). It is possible that this sensitivity to TSI could be a consequence of the previously described 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 CORE and Tier 1 pre-industrial and Pliocene based experiments as well as sensitivity experiments exploring solar insolation and orbit choice. We then examined the large-scale features of the atmosphere and ocean state of these experiments.

~~Comparing~~ Compared to the pre-industrial control (E^{280}), we find Pliocene surface warming focussed within the high-latitudes ~~in a similar distribution to~~ and whose spatial distribution is similar to that obtained with HadCM3 ~~within~~ for PlioMIP1 under PRISM3 boundary conditions (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 MASAT (and MASST) of 1.4°C (0.8°C) and 1.5°C (1.0°C) respectively. We derive climate sensitivities of 3.5°C and 2.9°C per doubling of CO_2 for the pre-industrial and Pliocene, which ~~again are~~ are also similar to results ~~of~~ from PlioMIP1 ~~of~~ wherein they were estimated to be 3.3°C and 3.1°C respectively ~~(Haywood et al., 2013a) . We derive an approximation of~~ (Haywood et al., 2013b) . We estimate the Earth System Sensitivity ~~of~~ at ∼5.6°C ~~leading to~~ implying an ESS/CS ratio of ∼1.9, which is similar to the ESS/CS ratio of 2.0 derived within PlioMIP1 ~~(Haywood et al., 2013a)~~ (Haywood et al., 2013b) . 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 Ice Sheet, is consistent between PlioMIP1 and PlioMIP2. 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~~ 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 (Table 7). We determine this by comparing AMOC strength of E^{280} against Eoi^{400} and Eoi^{280}. In addition we have explored the sensitivity of AMOC strength to methodology applied for fresh water correction. The 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~~. In theory, this could impact on simulated AMOC intensity in Eoi^{400} versus E^{280}. To test this we have conducted an additional E^{280} experiment using the annually-derived fresh water correction methodology of Eoi^{400} (results not shown). This has demonstrated for the pre-industrial that the fresh water correction method does not lead to 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.

Both the choice of TSI (1361 vs. 1365 Wm^{-2}) and PRISM4 orbital configuration (modern vs. 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) time slice with a modern orbit is an acceptable choice - leading to no statistically significant differences within MASAT (Table 3) or MAP (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. 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 grid-type etc.). 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 throughflow strength is often used to inform 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 *a priori* knowledge is not necessarily available for the Pliocene and it is therefore difficult to assess. An example of this is in the subaerial extension of Ireland and Scotland within PRISM4~~and how this is~~ , posing the question of how this region should be represented within the model and how ~~this~~ the model-representation may influence the simulation of the Norwegian Current. Additionally, the use of different model architectures and models with higher spatial resolution within the PlioMIP2 framework may allow these aspects to be considered. For example, free-surface 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~~ Palaeogeography-induced changes in mean state, for example the path of the Antarctic 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 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)~~America), which may be currently unrepresented within the model. These important regional changes must be ~~considered~~ appreciated when considering the 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.

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References

Archer, C. L. and Caldeira, K.: Historical trends in the jet streams, Geophysical Research Letters, 35, https://doi.org/10.1029/2008GL033614, 2008.

Bonham, S. G., Haywood, A. M., Lunt, D. J., Collins, M., and Salzmann, U.: El Niño Southern Oscillation, Pliocene climate and equifinality, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 367, 127–156, https://doi.org/10.1098/rsta.2008.0212, 2009.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, T., Hewitt, C. D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S. L., Yu, Y., and Zhao, Y.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum - Part 1: experiments and large-scale features, Climate of the Past, 3, 261–277, https://doi.org/10.5194/cp-3-261-2007, https://www.clim-past.net/3/261/2007/, 2007.

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, Geoscientific Model Development, 5, 1109–1125, https://doi.org/10.5194/gmd-5-1109-2012, 2012.

Bryan, K.: Climate and the Ocean Circulation, Monthly Weather Review, 97, 806–827, 1969.

Bryan, K., Manabe, S., and Packanowski, R. C.: A global ocean-atmosphere climate model. II the oceanic circulation, Journal of Physical Oceanography, 5, 30–46, https://doi.org/10.1175/1520-0485(1975)005<0030:AGOACM>2.0.CO;2, 1975.

Burls, N. J., Fedorov, A. V., Sigman, D. M., Jaccard, S. L., Tiedemann, R., and Haug, G. H.: Active Pacific meridional overturning circulation (PMOC) during the warm Pliocene, Science Advances, 3, https://doi.org/10.1126/sciadv.1700156, 2017.

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, Climate of the Past, 13, 919–942, https://doi.org/10.5194/cp-13-919-2017, https://www.clim-past.net/13/919/2017/, 2017.

Chandler, M. A., Sohl, L. E., Jonas, J. A., Dowsett, H. J., and Kelley, M.: Simulations of the mid-Pliocene Warm Period using two versions of the NASA/GISS ModelE2-R Coupled Model, Geosci. Model Dev., 6, 517–531, https://doi.org/10.5194/gmd-6-517-2013, 2013.

Cox, M.: A Primitive Equation, 3-dimensional Model of the Ocean, GFDL Ocean Group technical report, Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, 1984.

Cox, P. M., Betts, R. A., Bunton, C. B., Essery, R. L. H., Rowntree, P. R., and Smith, J.: The impact of new land surface physics on the GCM simulation of climate and climate sensitivity, Climate Dynamics, 15, 183–203, https://doi.org/10.1007/s003820050276, 1999.

Cunningham, S. A., Alderson, S. G., King, B. A., and Brandon, M. A.: Transport and variability of the Antarctic Circumpolar Current in Drake Passage, Journal of Geophysical Research: Oceans, 108, https://doi.org/10.1029/2001JC001147, 2003.

Cusack, S., Slingo, A., Edwards, J. M., and Wild, M.: The radiative impact of a simple aerosol climatology on the Hadley Centre atmospheric GCM, Quarterly Journal of the Royal Meteorological Society, 124, 2517–2526, https://doi.org/10.1002/qj.49712455117, 1998.

Dolan, A. M., Haywood, A. M., Hill, D. J., Dowsett, H. J., Hunter, S. J., Lunt, D. J., and Pickering, S. J.: Sensitivity of Pliocene ice sheets to orbital forcing, Palaeogeography, Palaeoclimatology, Palaeoecology, 309, 98–110, https://doi.org/10.1016/j.palaeo.2011.03.030, 2011.

Dowsett, H. J., Foley, K. M., Stoll, D. K., Chandler, M. A., Sohl, L. E., Bentsen, M., Otto-Bliesner, B. L., Bragg, F. J., Chan, W.-L., Contoux, C., Dolan, A. M., Haywood, A. M., Jonas, J. A., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Nisancioglu, K. H., Abe-Ouchi, A., Ramstein, G., Riesselman, C. R., Robinson, M. M., Rosenbloom, N. A., Salzmann, U., Stepanek, C., Strother, S. L., Ueda, H., Yan, Q., and Zhang, Z.: Sea Surface Temperature of the mid-Piacenzian Ocean: A Data-Model Comparison, Scientific Reports, 3, 1–8, https://doi.org/10.1038/srep02013, 2013.

Dowsett, H. J., 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, Climate of the Past, 12, 1519–1538, https://doi.org/10.5194/cp-12-1519-2016, 2016.

Essery, R. L. H., Best, M. J., Best, R. A., Cox, P. M., and Taylor, C. M.: Explicit Representation of Subgrid Heterogeneity in a GCM Land Surface Scheme, Journal of Hydrometeorology, pp. 530–543, https://doi.org/10.1175/1525- 7541(2003)004<0530:EROSHI>2.0.CO;2, 2003.

Good, P., Jones, C., Lowe, J., Betts, R., and Gedney, N.: Comparing Tropical Forest Projections from Two Generations of Hadley Centre Earth System Models, HadGEM2-ES and HadCM3LC, Journal of Climate, 26, 495–511, https://doi.org/10.1175/JCLI-D-11-00366.1, 2013.

Gordon, A. L. and Fine, R. A.: Pathways of water between the Pacific and Indian oceans in the Indonesian seas, Nature, 379, 146–149, https://doi.org/10.1038/379146a0, 1996.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., and Wood, R. A.: The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, Climate Dynamics, 16, 147–168, https://doi.org/10.1007/s003820050010, 2000.

Griesel, A., Mazloff, M. R., and Gille, S. T.: Mean dynamic topography in the Southern Ocean: Evaluating Antarctic Circumpolar Current transport, Journal of Geophysical Research: Oceans, 117, https://doi.org/10.1029/2011JC007573, 2012.

Haywood, A. M., Dowsett, H. J., Otto-Bliesner, B., Chandler, M. A., Dolan, A. M., Hill, D. J., Lunt, D. J., Robinson, M. M., Rosenbloom, N., Salzmann, U., and Sohl, L. E.: Pliocene Model Intercomparison Project (PlioMIP): experimental design and boundary conditions (Experiment 1), Geoscientific Model Development, 3, 227–242, https://doi.org/10.5194/gmd-3-227-2010, 2010.

Haywood, A. M., Dowsett, H. J., Robinson, M. M., Stoll, D. K., Dolan, A. M., Lunt, D. J., Otto-Bliesner, B., and Chandler, M. A.: Pliocene Model Intercomparison Project (PlioMIP): experimental design and boundary conditions (Experiment 2), Geoscientific Model Development, 4, 571–577, https://doi.org/10.5194/gmd-4-571-2011, 2011.

Haywood, A. M., Dolan, A. M., Pickering, S. J., Dowsett, H. J., McClymont, E. L., Prescott, C. L., Salzmann, U., Hill, D. J., Hunter, S. J., Lunt, D. J., Pope, J. O., and Valdes, P. J.: On the identification of a Pliocene time slice for data-model comparison, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 371, https://doi.org/10.1098/rsta.2012.0515, 2013a.

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, Climate of the Past, 9, 191–209, https://doi.org/10.5194/cp-9-191-2013, https://www.clim-past.net/9/191/2013/, 2013b.

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, Climate of the Past, 12, 663–675, https://doi.org/10.5194/cp-12-663-2016, 2016.

Hibler, W. D.: A Dynamic Thermodynamic Sea Ice Model, Journal of Physical Oceanography, 9, 815–846, https://doi.org/10.1175/1520-0485(1979)009<0815:ADTSIM>2.0.CO;2, 1979.

Hill, D. J.: The non-analogue nature of Pliocene temperature gradients, Earth and Planetary Science Letters, 425, 232–241, https://doi.org/https://doi.org/10.1016/j.epsl.2015.05.044, 2015.

Howell, F. W., Haywood, A. M., Dolan, A. M., Dowsett, H. J., Francis, J. E., Hill, D. J., Pickering, S. J., Pope, J. O., Salzmann, U., and Wade, B. S.: Can uncertainties in sea ice albedo reconcile patterns of data-model discord for the Pliocene and 20th/21st centuries?, Geophysical Research Letters, 41, 2011–2018, https://doi.org/10.1002/2013GL058872, 2014.

Johns, T. C., Gregory, J. M., Ingram, W. J., Johnson, C. E., Jones, A., Lowe, J. A., Mitchell, J. F. B., Roberts, D. L., Sexton, D. M. H., Stevenson, D. S., Tett, S. F. B., and Woodage, M. J.: Anthropogenic climate change for 1860 to 2100 simulated with the HadCM3 model under updated emissions scenarios., Climate Dynamics, 20, 583–612, https://doi.org/10.1007/s00382-002-0296-y, 2003.

Kamae, Y., Yoshida, K., and Ueda, H.: Sensitivity of Pliocene climate simulations in MRI-CGCM2.3 to respective boundary conditions, Climate of the Past, 12, 1619–1634, https://doi.org/10.5194/cp-12-1619-2016, https://www.clim-past.net/12/1619/2016/, 2016.

Knies, J., Mattingsdal, R., Fabian, K., Grøsfjeld, K., Baranwal, S., Husum, K., Schepper, S. D., Vogt, C., Andersen, N., Matthiessen, J., Andreassen, K., Jokat, W., Nam, S.-I., and Gaina, C.: Effect of early Pliocene uplift on late Pliocene cooling in the Arctic-Atlantic gateway, Earth and Planetary Science Letters, 387, 132–144, https://doi.org/https://doi.org/10.1016/j.epsl.2013.11.007, 2014.

Koch, P., Wernli, H., and Davies, H. C.: An event-based jet-stream climatology and typology, International Journal of Climatology, 26, 283–301, https://doi.org/10.1002/joc.1255, 2006.

Kopp, G. and Lean, J. L.: A new, lower value of total solar irradiance: Evidence and climate significance, Geophysical Research Letters, 38, 5–48, https://doi.org/10.1029/2010GL045777, 2011.

Levitus, S. and Boyer, T. P.: World ocean atlas 1994. Vol. 4, Temperature, NOAA atlas NESDIS ; 4, 1994.

Li, D. and Shine, K. P.: A 4-Dimensional Ozone Climatology for UGAMP Models, UGAMP Internal Report No. 35, http://catalogue.ceda.ac.uk/uuid/bff84b935ce5aa9f04624777b0eea507, 1995.

LSCE: PMIP2 Boundary Conditions, https://pmip2.lsce.ipsl.fr/design/boundary.shtml, accessed: 14-04-2019, 2007.

Lunt, D. J., Valdes, P. J., Haywood, A., and Rutt, I. C.: Closure of the Panama Seaway during the Pliocene: implications for climate and Northern Hemisphere glaciation, Climate Dynamics, 30, 1–18, https://doi.org/10.1007/s00382-007-0265-6, 2008.

Matthes, K., Funke, B., Andersson, M. E., Barnard, L., Beer, J., Charbonneau, P., Clilverd, M. A., Dudok de Wit, T., Haberreiter, M., Hendry, A., Jackman, C. H., Kretzschmar, M., Kruschke, T., Kunze, M., Langematz, U., Marsh, D. R., Maycock, A. C., Misios, S., Rodger, C. J., Scaife, A. A., Seppälä, A., Shangguan, M., Sinnhuber, M., Tourpali, K., Usoskin, I., van de Kamp, M., Verronen, P. T., and Versick, S.: Solar forcing for CMIP6 (v3.2), Geoscientific Model Development, 10, 2247–2302, https://doi.org/10.5194/gmd-10-2247-2017, 2017.

McCarthy, G. D., Smeed, D. A., Johns, W. E., Frajka-Williams, E., Moat, B. I., Rayner, D., Baringer, M. O., Meinen, C. S., Collins, J., and Bryden, H. L.: Measuring the Atlantic Meridional Overturning Circulation at 26°N, Progress in Oceanography, 130, 91–111, https://doi.org/10.1016/j.pocean.2014.10.006, 2015.

Meftah, M., Dewitte, S., Irbah, A., Chevalier, A., Conscience, C., Crommelynck, D., Janssen, E., and Mekaoui, S.: SOVAP/Picard, a Space-borne Radiometer to Measure the Total Solar Irradiance, Solar Physics, 289, 1885–1899, https://doi.org/10.1007/s11207-013-0443-0, 2014.

Meijers, A. J. S., Shuckburgh, E., Bruneau, N., Sallee, J.-B., Bracegirdle, T. J., and Wang, Z.: Representation of the Antarctic Circumpolar Current in the CMIP5 climate models and future changes under warming scenarios, Journal of Geophysical Research: Oceans, 117, https://doi.org/10.1029/2012JC008412, 2012.

National Geophysical Data Center: 5-minute Gridded Global Relief Data (ETOPO5)., National Geophysical Data Center, NOAA, https://doi.org/10.7289/V5D798BF, 1993.

NCAS: Computational Modelling Services. Tools and Utilities, http://cms.ncas.ac.uk/wiki/ToolsAndUtilities, accessed: 14-04-2019, 2019.

Pardaens, A. K., Banks, H. T., Gregory, J. M., and Rowntree, P. R.: Freshwater transports in HadCM3, Climate Dynamics, 21, 177–195, https://doi.org/10.1007/s00382-003-0324-6, 2003.

Pope, V. D., Gallani, M. L., Rowntree, P. R., and Stratton, R. A.: The impact of new physical parametrizations in the Hadley Centre climate model: HadAM3, Climate Dynamics, 16, 123–146, https://doi.org/10.1007/s003820050009, 2000.

Prescott, C. L., Haywood, A. M., Dolan, A. M., Hunter, S. J., Pope, J. O., and Pickering, S. J.: Assessing orbitally-forced interglacial climate variability during the mid-Pliocene Warm Period, Earth and Planetary Science Letters, 400, 261–271, https://doi.org/https://doi.org/10.1016/j.epsl.2014.05.030, 2014.

Randall, D., Wood, R., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Ronald, S., Sumi, A., and Taylor, K.: Climate Models and Their Evaluation, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Solomon, S., Qin, M., Manning, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H., pp. 589–662, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Roether, W., Roussenov, V. M., and Well, R.: A Tracer Study of the Thermohaline Circulation of the Eastern Mediterranean, in: Ocean Processes in Climate Dynamics: Global and Mediterranean Examples, edited by Malanotte-Rizzoli, P. and Robinson, A. R., pp. 371–394, Springer Netherlands, Dordrecht, https://doi.org/10.1007/978-94-011-0870-6_16, 1994.

Semtner, A. J.: A model for the thermodynamic growth of sea ice in numerical investigations of climate, Journal of Physical Oceanography, 6, 379–389, https://doi.org/10.1175/1520-0485(1976)006<0379:AMFTTG>2.0.CO;2, 1976.

Stachnik, J. P. and Schumacher, C.: A comparison of the Hadley circulation in modern reanalyses, Journal of Geophysical Research: Atmospheres, 116, https://doi.org/10.1029/2011JD016677, 2011.

Taylor, K. E., Stouffer, R. J., and Meehl, G. A.: An Overview of CMIP5 and the Experiment Design, Bulletin of the American Meteorological Society, 93, 485–498, https://doi.org/10.1175/BAMS-D-11-00094.1, 2012.

Tindall, J. C. and Haywood, A. M.: Modeling oxygen isotopes in the Pliocene: Large-scale features over the land and ocean, Paleoceanography, 30, 1183–1201, https://doi.org/10.1002/2014PA002774, 2015.

Tribe, A.: Automated recognition of valley lines and drainage networks from grid digital elevation models: a review and a new method, Journal of Hydrology, pp. 263–293, https://doi.org/10.1016/0022-1694(92)90206-B, 1992.

USGS: Pliocene Model Intercomparison Project, Phase 2, https://geology.er.usgs.gov/egpsc/prism/7_pliomip2.html, accessed: 14-04-2019, 2016.

USGS: PMIP2 Model Data List, https://geology.er.usgs.gov/egpsc/prism/data/PlioMIP2_Model_Data_List_updated2018.htm, accessed: 14-04-2019, 2018.

Valdes, P. J., Armstrong, E., Badger, M. P. S., Bradshaw, C. D., Bragg, F., Crucifix, M., Davies-Barnard, T., Day, J. J., Farnsworth, A., Gordon, C., Hopcroft, P. O., Kennedy, A. T., Lord, N. S., Lunt, D. J., Marzocchi, A., Parry, L. M., Pope, V., Roberts, W. H. G., Stone, E. J., Tourte, G. J. L., and Williams, J. H. T.: The BRIDGE HadCM3 family of climate models: HadCM3@Bristol v1.0, Geoscientific Model Development, 10, 3715–3743, https://doi.org/10.5194/gmd-10-3715-2017, 2017.

Wilson, M. and Henderson-Sellers, A.: A global archive of land cover and soils data for use in General Circulation Climate Models, Journal of Climatology, 5, 119–143, https://doi.org/10.1002/joc.3370050202, 1985.

Zhang, Z.-S., Nisancioglu, K. H., Chandler, M. A., Haywood, A. M., Otto-Bliesner, B. L., Ramstein, G., Stepanek, C., Abe-Ouchi, A., Chan, W.-L., Bragg, F. J., Contoux, C., Dolan, A. M., Hill, D. J., Jost, A., Kamae, Y., Lohmann, G., Lunt, D. J., Rosenbloom, N. A., Sohl,

L. E., and Ueda, H.: Mid-pliocene Atlantic Meridional Overturning Circulation not unlike modern, Climate of the Past, 9, 1495–1504, https://doi.org/10.5194/cp-9-1495-2013, 2013.

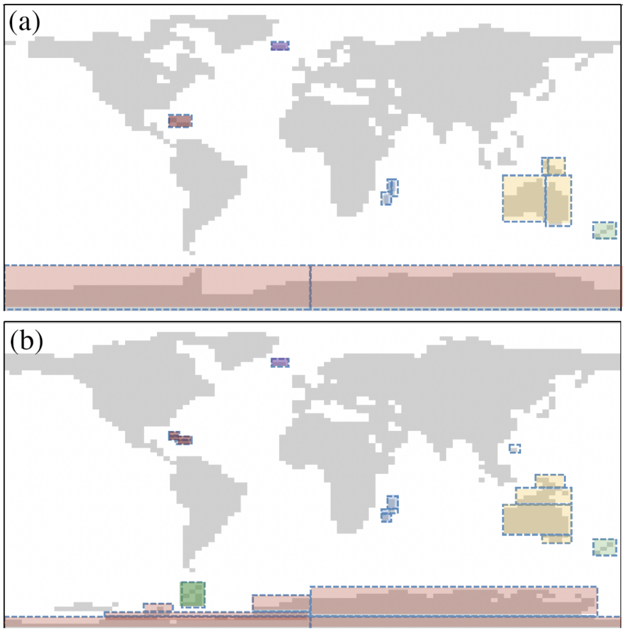

Figure 1. LSM and barotropic streamfunction island configuration for the (a) pre-industrial and (b) Pliocene.

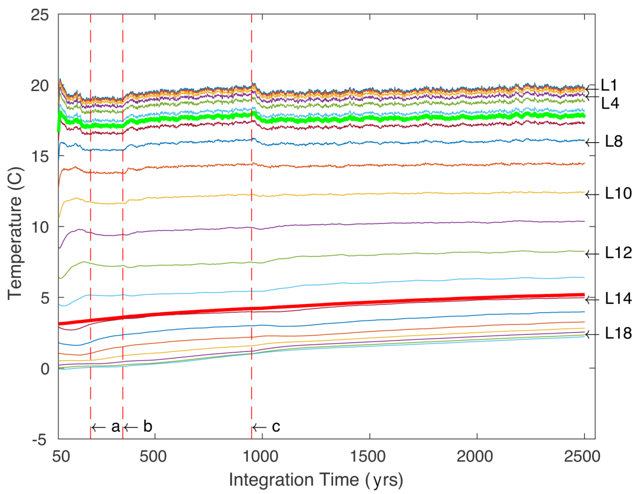

Figure 2. Time-evolution of the globally-integrated temperature for the ocean layers within the Eoi^{400} experiment. Whole ocean volume indicated by the thick red line and the top 200 m indicated by the thick green line. Vertical lines indicate key spin-up stages; (a) adding the barotropic physics to 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), 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).

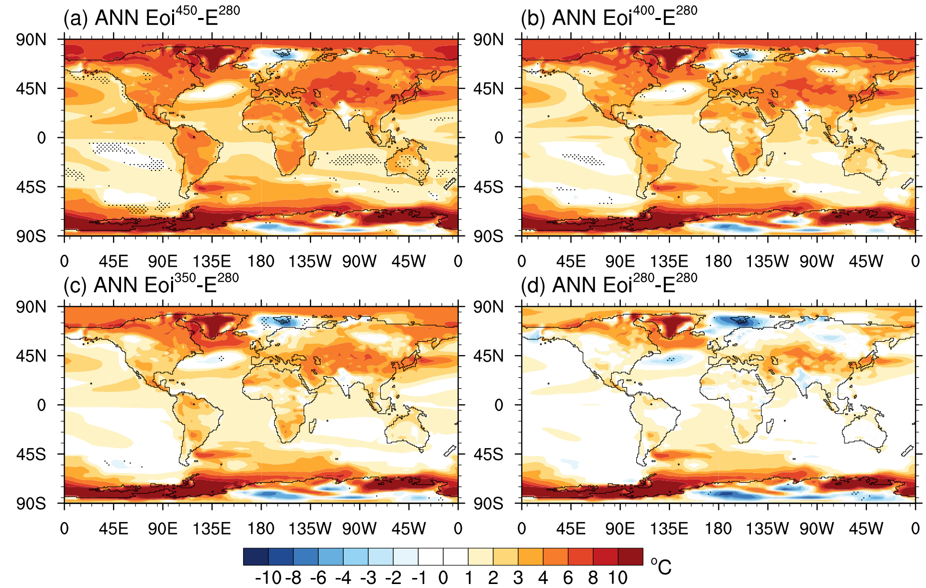

Figure 3. Pliocene annual mean surface air temperature anomalies against E^{280}. (a) Eoi^{450}-E^{280}, (b) Eoi^{400}-E^{280}, (c) Eoi^{350}-E^{280} and (d) Eoi^{280}-E^{280}. Stippling indicates regions in which results are not statistically significant at a 95% confidence ~~criteria~~ criterion (independent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

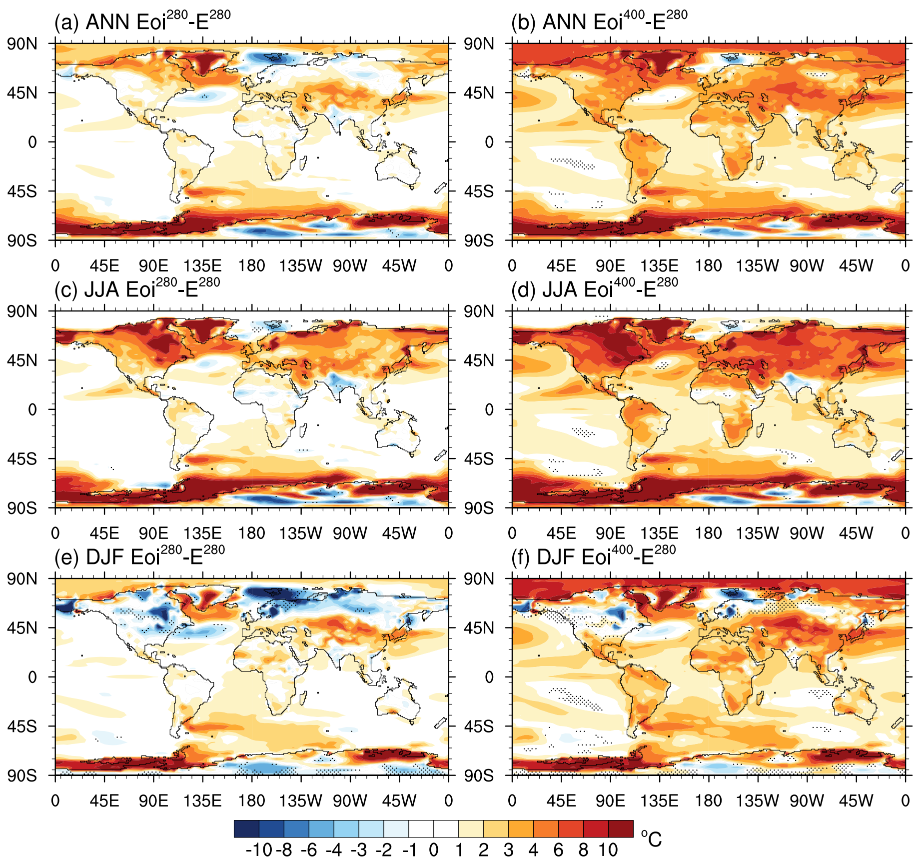

Figure 4. Mean annual and seasonal Pliocene temperature anomalies against E^{280}. (a) Annual Eoi^{280}-E^{280}, (b) Annual Eoi^{400}-E^{280}, (c) June-July-August (JJA) Eoi^{280}-E^{280}, (d) JJA Eoi^{400}-E^{280}, (e) December-January-February (DJF) Eoi^{280}-E^{280} and (f) DJF Eoi^{400}-E^{280}.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

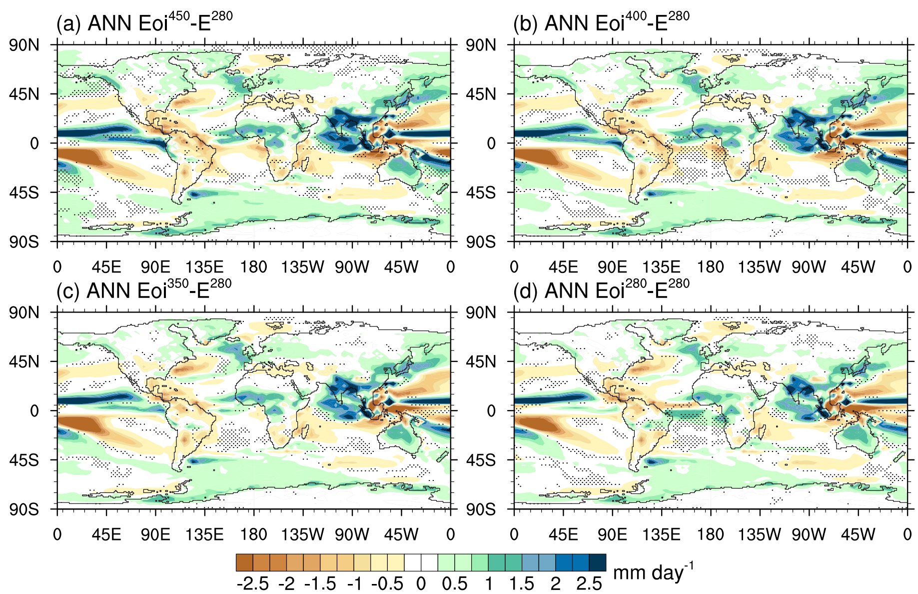

Figure 5. Pliocene mean annual precipitation anomalies against E^{280}. (a) Eoi^{450}-E^{280}, (b) Eoi^{400}-E^{280}, (c) Eoi^{350}-E^{280} and (d) Eoi^{280}-E^{280}. Stippling indicates regions in which results are not statistically significant at a 95% confidence ~~criteria~~criterion.

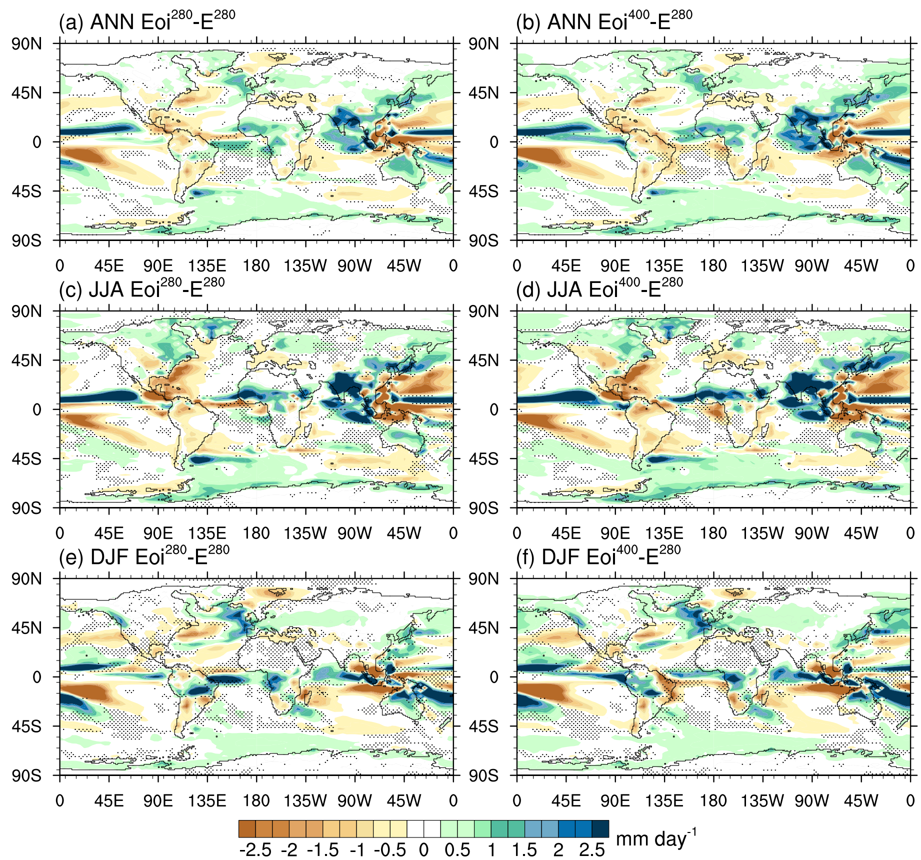

Figure 6. Mean Annual and seasonal Pliocene precipitation anomalies. (a) Annual Eoi^{280}-E^{280}, (b) Annual Eoi^{400}-E^{280}, (c) JJA Eoi^{280}-E^{280}, (d) JJA Eoi^{400}-E^{280}, (e) DJF Eoi^{280}-E^{280} and (f) DJF Eoi^{400}-E^{280}. Stippling indicates regions in which results are not statistically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

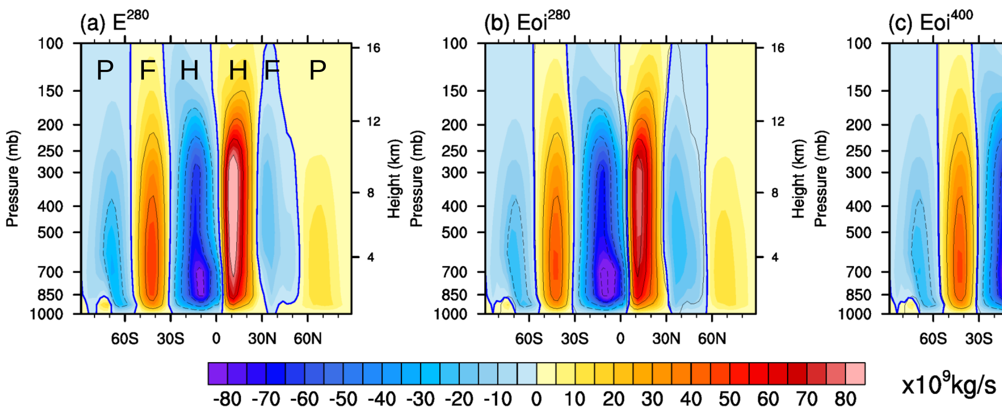

Figure 7. Mean annual zonally-averaged meridional mass transport stream function for (a) E^{280}, (b) Eoi^{280} and (c) EEoi^{400}. The contour lines are from E^{280} and are shown for intervals of $2x10^{10}$ kg s^{-1} with dashed lines indicating counterclockwise (looking westward) circulation (ascending 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).

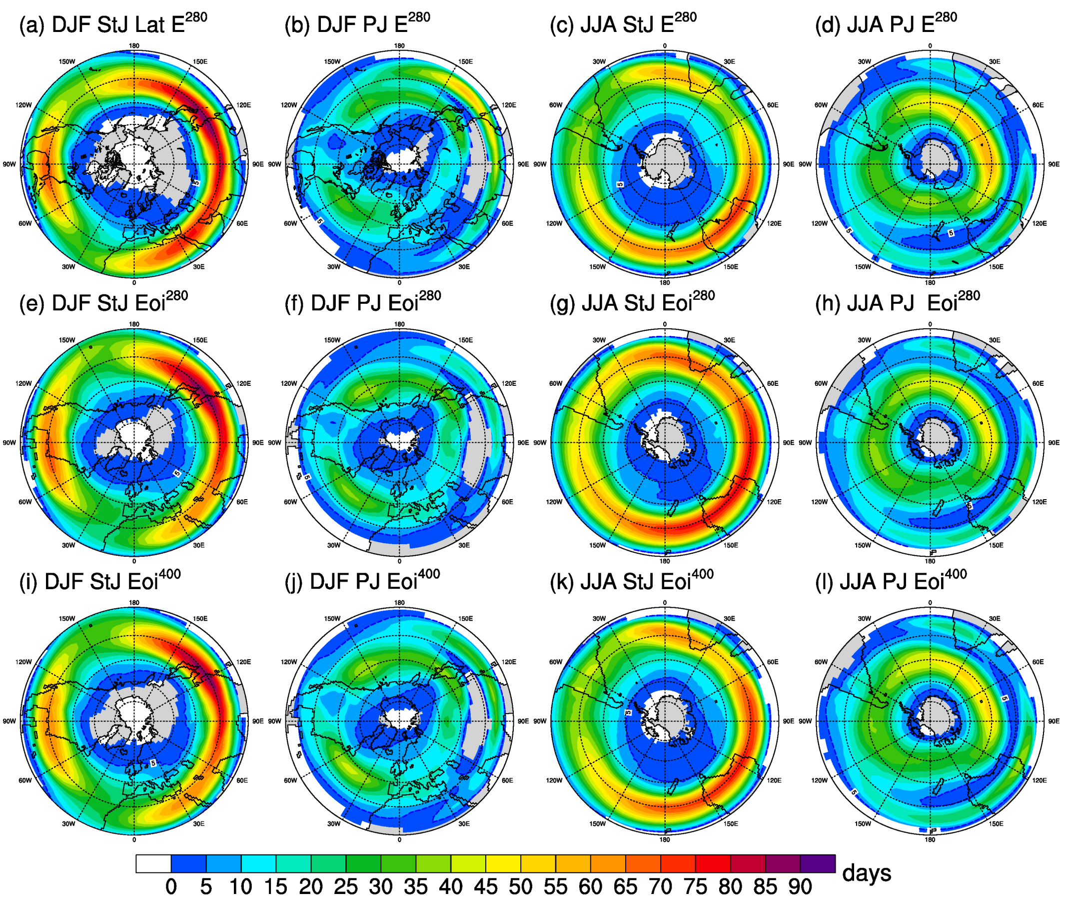

Figure 8. Seasonal (DJF and JJA) distribution of the Subtropical Jet (StJ) and Polar Jet streams (PJ) for (a-d) E^{280}, (e-h) Eoi^{280}, and (i-l) ~~E~~Eoi^{400}. Colour scale indicates mean number of days within a season in which wind speed is >30 ms^{-1} over 400 - 100 hPa. Note that the wind-shear PJ classification identifies a jet downstream of the Himalayas.

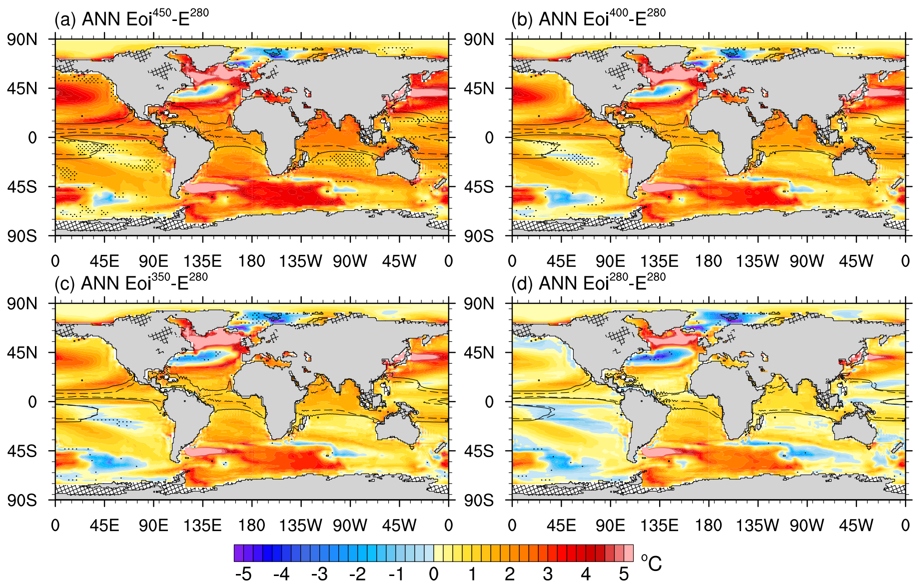

Figure 9. Pliocene mean annual sea surface temperature (MASST) anomalies against E^{280}. (a) Eoi^{450}-E^{280}, (b) Eoi^{400}-E^{280}, (c) Eoi^{350}-E^{280} and (d) Eoi^{280}-E^{280}. Dotted contour lines indicates E^{280} 28°C warm pool whilst the solid contour indicates the Pliocene 28°C warm pool.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

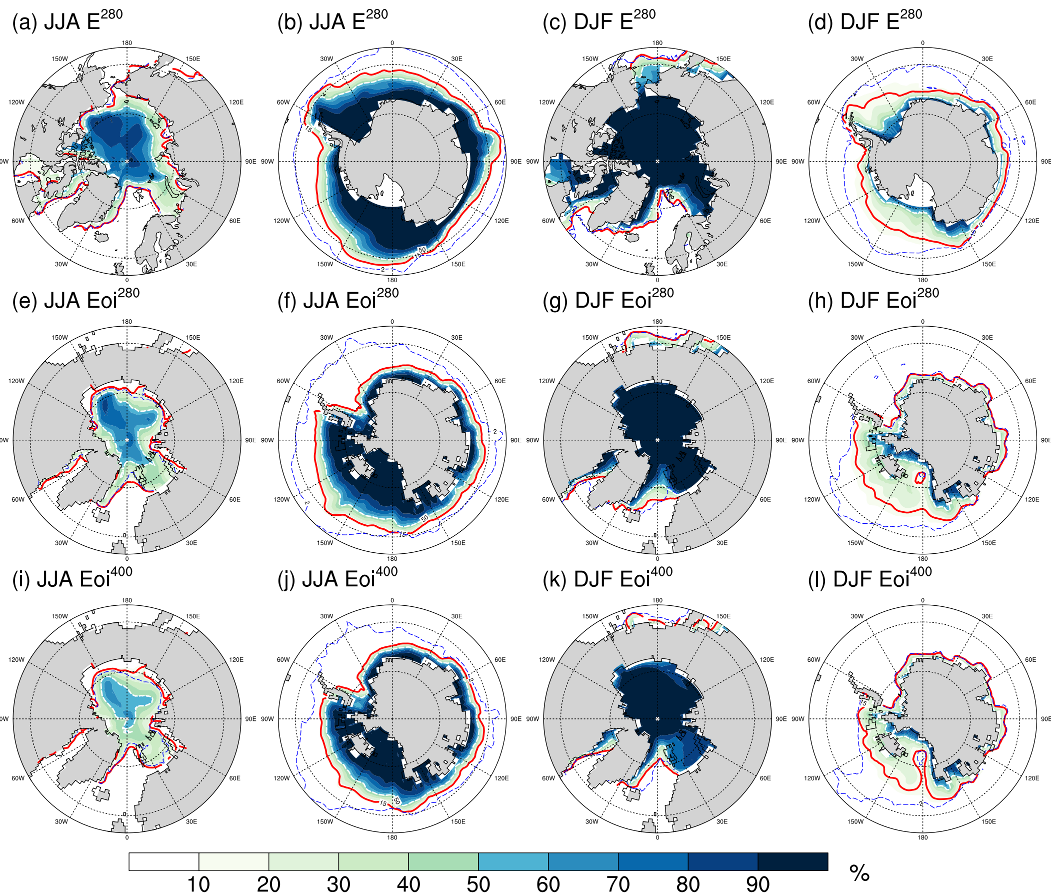

Figure 10. Sea ice concentrations (%) during JJA and DJF in the Northern and Southern ~~hemisphere~~ Hemisphere for (a-d) E^{280}, (e-h) Eoi^{280}, and (i-l) Eoi^{400}. The red line indicates the sea ice edge based on a threshold of 15% whilst the dotted white line indicates the 50% threshold. The blue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

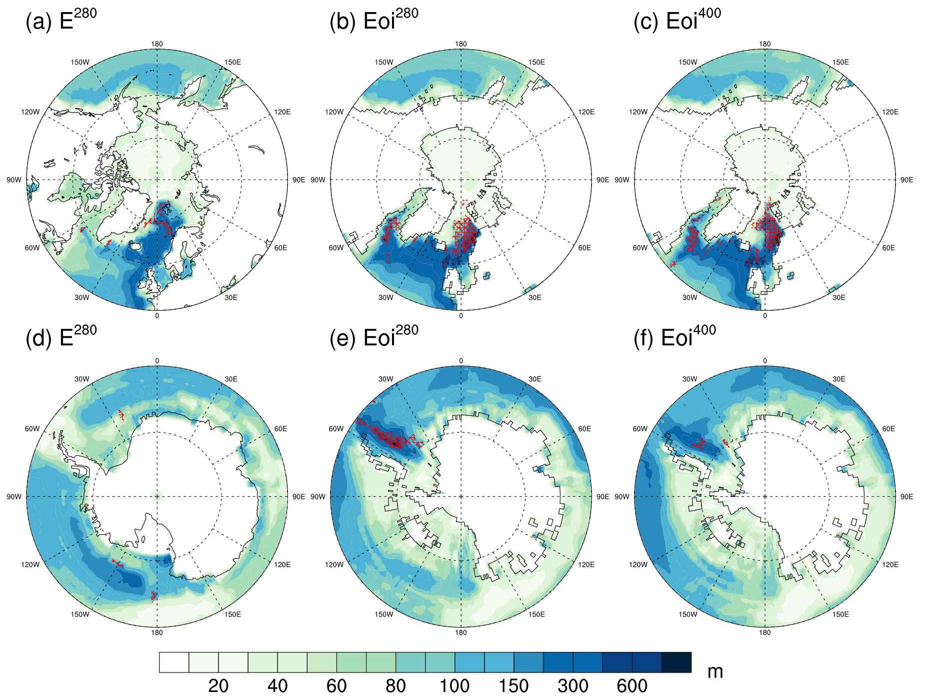

Figure 11. Mean March Northern Hemisphere and September Southern Hemisphere Mixed Layer Depth for (a and d) E^{280}, (b and e) Eoi^{280} and (c and f) Eoi^{400}. Red hashes indicate regions that exhibit deep (>1000 m) convection at least 1 month during the ~~climatologeal meaning~~ climatological averaging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

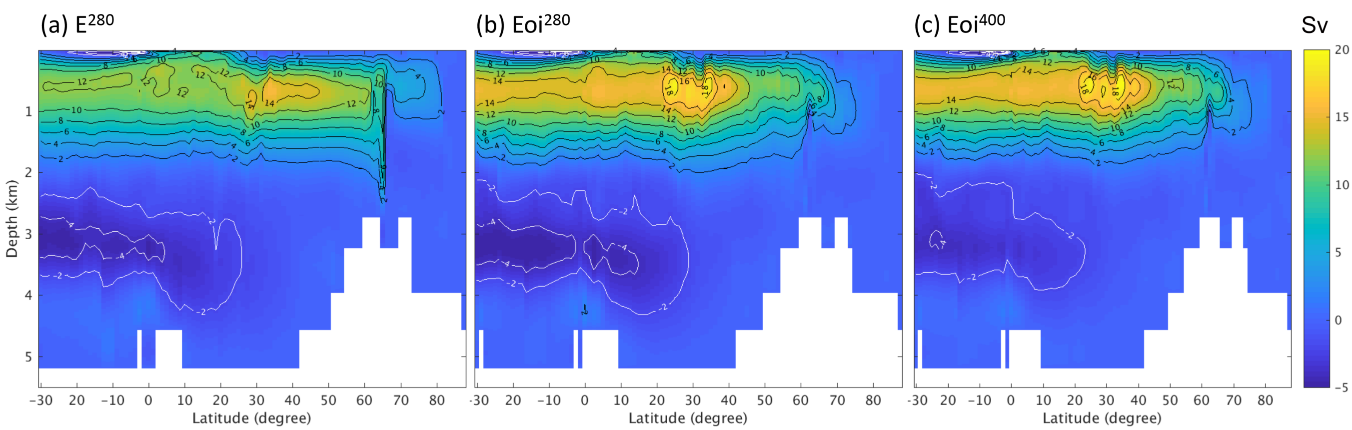

Figure 12. Time-averaged Atlantic overturning circulation for (a) E^{280}, (b) Eoi^{280} and (c) Eoi^{400}. Positive values indicate clockwise circulation.

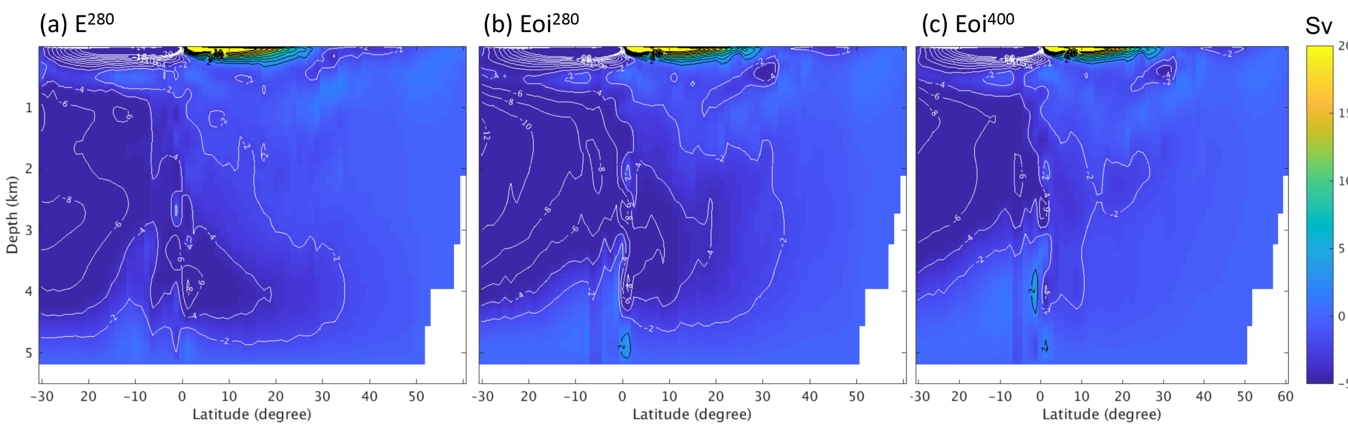

Figure 13. Time-averaged Pacific overturning circulation for (a) E^{280}, (b) Eoi^{280} and (c) Eoi^{400}. Positive values indicate clockwise circulation.

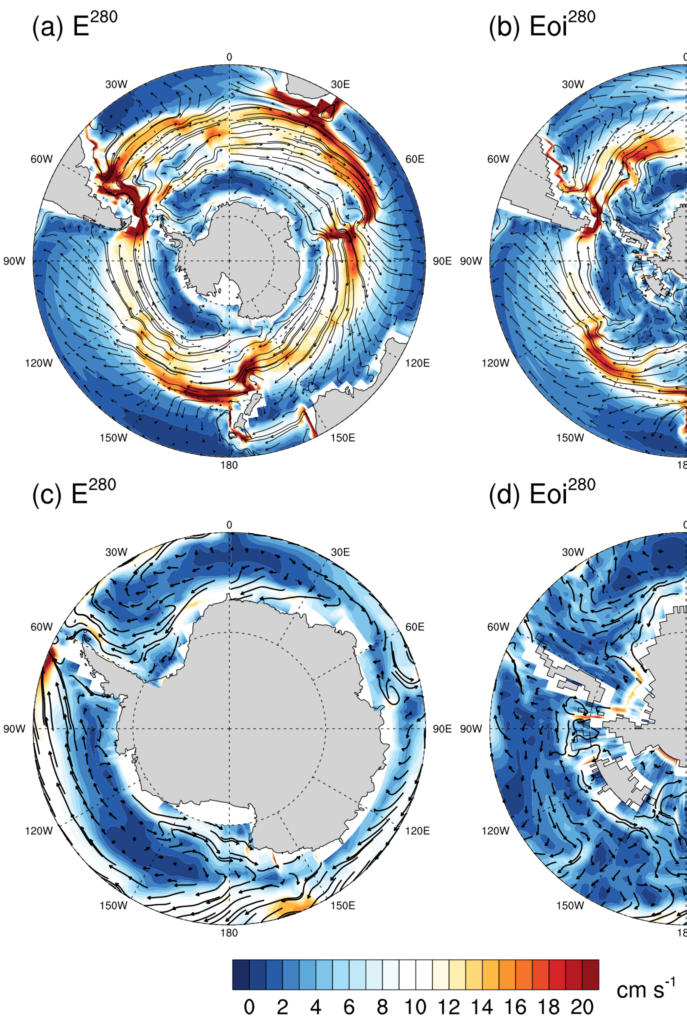

Figure 14. Surface ocean mean annual velocity (streamlines and vector magnitude) for E^{280} and Eoi^{280}. The ACC is shown clearly within (a) E^{280} and (b) Eoi^{280}, whilst the Antarctic Coastal Current is shown within the close-up plots (c) E^{280} and (d) Eoi^{280}.

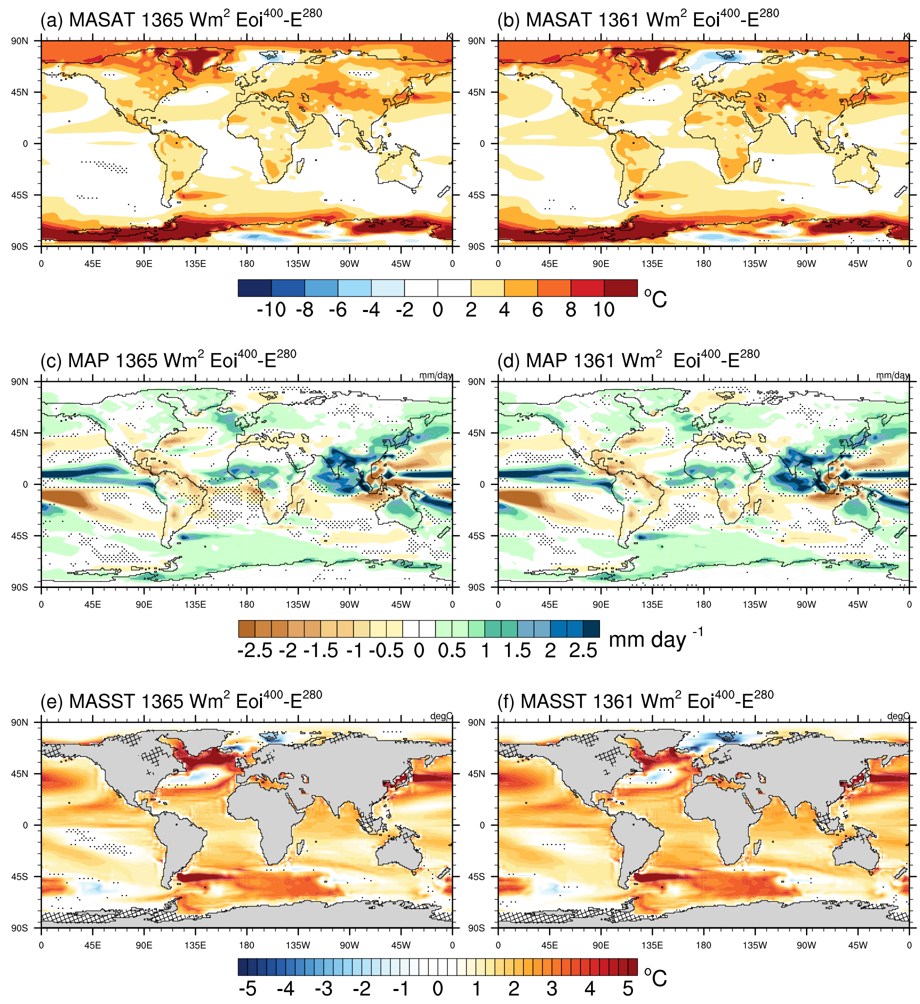

Figure 15. Sensitivity of Eoi^{400} -E^{280} anomalies on TSI values for (a and b) MASAT, (c and d) MAP, and (e and f) MASST. Stippling indicates regions in which results are not statistically significant at a 95% confidence criterion.

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

N°/	ID	Geography	PlioMIP2 component	Description
1	Eoi^{400}	Pliocene	CORE	Full enhanced boundary conditions with fixed vegetation and 400 ppm CO_2
2	Eoi^{450}	Pliocene	T1 P4F & P4P	As Eoi^{400} but with 450 ppm CO_2
3	Eoi^{350}	Pliocene	T1 P4F & P4P	As Eoi^{400} but with 350 ppm CO_2
4	Eoi^{280}	Pliocene	T2 P4F & P4P	As Eoi^{400} but with 280 ppm CO_2
5	E^{280}	PI	CORE	Standard pre-industrial boundary conditions with fixed vegegation vegetation and 280 ppm CO_2
6	E^{400}	PI	T2 P4F & P4P	As E^{280} but with 400 ppm CO_2
7	E^{560}	PI	T1 P4F	As E^{280} but with 560 ppm CO_2
8	${}_{orb}Eoi^{400}$	Pliocene	Additional sensitivity	As of Eoi^{400} but with 3.205 Ma orbit (KM5c)
9	${}_{1361}Eoi^{400}$	Pliocene	Additional sensitivity	As Eoi^{400} but with TSI=1361 Wm^{-2}
10	${}_{1361}E^{280}$	PI	Additional sensitivity	As E^{280} but with TSI=1361 Wm^{-2}

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 metrics for the seven PlioMIP2 protocol experiments. Globally integrated ($Ocean_{all}$) and surface Ocean (top 200m; $Ocean_{surf}$) climatological trends and Top of the Atmosphere Energy Balance (TOA_{EB}) are derived from the last 100 model years.

ID	$Ocean_{all}$ (°C $cent^{-1}$)	$Ocean_{surf}$ (°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 (MASAT) ~~decomposed into~~ and the mean annual surface air temperatures of the polar (poleward of 60°) and tropical (equaterward of 30°) regions. The Polar amplification factor is shown in square brackets and is defined as the *ratio* in the anomalies (against E^{280}) between the polar warming and the global mean warming.

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

Table 4. Globally integrated mean annual precipitation (MAP).

ID	MAP (mm day^{-1})
Eoi^{450}	3.041 ± 0.007
Eoi^{400}	3.025 ± 0.008
${}_{orb}Eoi^{400}$	3.027 ± 0.008
Eoi^{350}	3.012 ± 0.009
Eoi^{280}	2.979 ± 0.008
E^{280}	2.912 ± 0.008
E^{400}	2.975 ± 0.007
E^{560}	3.019 ± 0.008

Table 5. ~~Integrated~~ Climatological zonal 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 StJ is reported as it is more stable and persistent than the Polar Jet.

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 ± 1.9	33.9 ± 1.3
Eoi^{280}	32.0 ± 1.1	46.2 ± 1.9	44.7 ± 1.8	33.7 ± 1.5
E^{280}	30.3 ± 1.4	44.6 ± 3.0	42.5 ± 1.3	33.5 ± 1.8

Table 6. Global mean annual sea surface temperature (MASST) and ~~defining characteristics~~ various metrics for the spatial extent of the equatorial warm pool regions.

ID	MASST (°C)	GWP ($\times 10^6$ km^2)	$WHWP_{max}$ ($\times 10^6$ km^2)	$IPWP_{max}$ [year-round] ($\times 10^6$ km^2)
Eoi^{450}	20.3 ± 0.1	107.5 ± 2.5	25.2 ± 0.6	95.7 ± 2.8 [63.0 ± 2.8]
Eoi^{400}	19.9 ± 0.1	99.7 ± 2.6	24.4 ± 0.5	89.0 ± 3.3 [57.1 ± 2.1]
$_{orb}Eoi^{400}$	19.8 ± 0.1	98.5 ± 2.8	23.8 ± 0.5	87.4 ± 3.0 [56.2 ± 1.9]
Eoi^{350}	19.6 ± 0.1	92.1 ± 3.1	23.1 ± 0.5	82.4 ± 3.7 [50.9 ± 2.6]
Eoi^{280}	18.9 ± 0.1	78.8 ± 2.9	19.7 ± 1.2	71.7 ± 3.0 [38.6 ± 3.3]
E^{280}	18.1 ± 0.1	66.4 ± 4.5	15.0 ± 1.5	62.8 ± 3.9 [25.4 ± 3.1]
E^{400}	19.3 ± 0.1	91.5 ± 3.3	22.1 ± 1.3	85.6 ± 3.9 [50.8 ± 3.2]
E^{560}	20.4 ± 0.1	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 criterion. 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).

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

$AMOC_{max}$ 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 Circumpolar Current (ACC) within the Pliocene and pre-industrial experiments. From the barotropic streamfunction we derive the mean ACC latitude (the Polar front) from the centroid of the zonal transport, and the core width ~~derived~~ from the ± 50% boundary.

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 Wm^{-2}. Shown are the mean annual surface air temperature (MASAT), mean annual precipitation (MAP), mean annual sea surface temperature (MASST), Atlantic and Pacific meridional circulation ($AMOC_{max}$ and $PMOC_{+ve,-ve}$; Section 4.2.4), and Antarctic Circumpolar Current (ACC; Section 4.2.5).

ID	MASAT (°C)	MAP (mm day^{-1})	MASST (°C)	$AMOC_{max}$ (Sv)	$PMOC_{+ve,-ve}$ (Sv)	ACC (Sv)
E^{280}	14.0 ± 0.1	2.912 ± 0.008	18.1 ± 0.1	15.7 ± 1.2	33.4 ± 3.1, -8.6 ± 1.4	179.0 ± 11.1
$_{1361}E^{280}$	13.7 ± 0.1	2.885 ± 0.008	17.9 ± 0.1	16.3 ± 1.2	33.8 ± 3.9, -9.2 ± 1.5	180.0 ± 6.2
Eoi^{400}	16.9 ± 0.1	3.025 ± 0.008	19.9 ± 0.1	19.6 ± 1.0	40.6 ± 3.0, -9.1 ± 1.4	76.7 ± 2.8
$_{1361}Eoi^{400}$	16.7 ± 0.1	3.014 ± 0.010	19.7 ± 0.1	17.0 ± 0.9	37.7 ± 3.3, -8.5 ± 1.7	76.0 ± 2.5
Eoi^{400}-E^{280}	2.9 ± 0.1	0.113 ± 0.011	1.8 ± 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 ± 0.1	0.129 ± 0.013	1.8 ± 0.1	0.7 ± 1.5	3.9 ± 5.1, 0.7 ± 1.3	-104.0 ± 6.7