**This document includes a response to all the Reviewer and Editor comments. This is then followed by a revised version of the manuscript in which all our proposed changes are clearly highlighted. We thank both reviewers for their comments.**

# Reviewer 1

It is proposed to run sensitivity experiments to account for different sets of boundary conditions, and experiments with different CO2 levels to account for the uncertainties in the CO2 reconstructions, which is interesting to test climate sensitivity to CO2 under these conditions. With this perspective, the experimental design could be improved to better liaise with the CMIP6 exercise. In particular, the CMIP6 DECK includes a preindustrial and an abrupt4xCO2 experiment, in which the CO2 level is quadrupled from the pre-industrial level. The DeepMIP protocol recommends to run the pre-industrial as in CMIP6 but it would be very interesting for the groups to also run the CMIP6 DECK abrupt4xCO2 simulation. If the DeepMIP protocol also included a similar 4xCO2 experiment with the deep-time continents and ocean, then it would be easy to examine whether the deep time continents and oceans have an impact on the Earth's sensitivity to greenhouse gases increase, and how much can be inferred on climate sensitivity from these climates.

**Done. We agree that it would be very interesting to insist that all models carry out a CMIP6-style *abrupt-4xCO2* simulation, so we have added this.**

I would therefore argue for changing the priorities in the experimental design (cf page 7, lines 9-11) and to test 2x and 4xCO2 (and higher) first, rather than 3x and 6xCO2. The pre-industrial control and the abrupt4xCO2 experiments have also been proposed to be mandatory for modelling groups wishing to take part in the PMIP4 exercise, to better liaise with CMIP6, so the above recommendation would also warrant a better relation to PMIP4 activities.

**However, we do not agree with this. The value of 6×PI (1680ppmv) is chosen for the EECO because this is in agreement with the value reconstructed by Anagnostou et al (2016) of 1625±760ppmv. We have now made this clearer in the text. Furthermore, the CMIP6 *abrupt-4×CO2* CMIP6 simulation is an abrupt forcing, and only runs for 150 years, so is not directly comparable with our Eocene simulations anyway.**

Apart from the more specific comments below, what is missing from the manuscript at this stage is a table summarizing the experiments and boundary conditions, and the names given to the experiments so that all groups use these names. Additional figures could also be inserted to better illustrate the scope of the project and the different options in boundary conditions, as explained in the comments below.

**As suggested, we added a table of experiments (see Table 1). As many of the sensitivity studies are qualitative suggestions, without formal designs, we only include those sensitivity studies which are formally defined ($CO_2$ and palaeogeography).**

pages 2-3, section 2: this section on previous work could be illustrated by a figure showing what can be improved from this previous work.

**Done. See new Figure 1.**

page 3, section 3: for outsiders, it would be good to have a figure locating the three periods in a broader chronology of the Earth climate evolution.

**Done. See new Figure 2.**

page 4, section 4.2, lines 11-12: "There are three standard simulations" seem to contrast with the sentence at the top of the page: "The DeepMIP experimental protocol consists of four main simulations". It would be good to clarify this: three periods, but four simulations.

**Done. We now state "The DeepMIP experimental protocol consists of five main simulations (pre-industrial, future, two early Eocene, and one latest Paleocene/pre-PETM), plus a number of optional sensitivity studies (see Section 4.3).". And later… "There are three standard paleoclimate simulations (*deepmip-stand-3×CO2*, *deepmip-stand-6×CO2*, *deepmip-stand-12×CO2*), which differ only in their atmospheric CO2 concentration, plus a number of optional sensitivity studies."**

page 4, section 4.2.1: it would be good to stress at this point that the same paleogeography is used for all three periods.

**Done. This is also clear now in the new Table 1.**

Also, the main cautionary points in the implementation of the paleogeography, such as straits and shallow basins, should be highlighted, in relation with the sensitivity experiments proposed in section4.3.2.

**Done. Added "Care should be taken when defining the land-sea mask for the ocean component of the model that the various seaways are preserved at the model resolution; this may require some manual manipulation of the land-sea mask."**

page 5, lines 7ff, about the soils: I am not very familiar with this issue, but I would expect spatial heterogeneities in soil properties, so how can these be prescribed "homogeneously"?

**Yes, they should be globally constant as there is no robust data on the heterogeneities in soil properties. Clarified: "Parameters associated with soils should be given constant values over the globe, with values for these parameters (e.g. albedo, water-holding capacity etc.) given by the global-mean of the group's pre-industrial simulation."**

page 7, value of the solar constant: it has been revised to 1361 W/m2 (Matthes et al, http://www.geosci-model-dev-discuss.net/gmd-2016-91/). Since this paper is still in discussion, it will be worth referring to its final value when it is out. However, this has an impact on the discussion about early Eocene values in section 4.2.5 and on the sensitivity experiments proposed in section 4.3.5. Is the value found by Gough (1981) actually tied to a present value of 1365 W/m2?

**The original formula in Gough (1981) is relative to the modern value, and not an absolute. Therefore a change in the preindustrial control value also affects the Eocene value. We now state: "The solar constant in the CMIP6 *piControl* simulation is defined as 1361.0Wm$^{-2}$ (Matthes, in review, 2016). Although the early Eocene (51 Ma) solar constant was ~0.43% less than this (Gough, 1981), i.e. ~1355Wm$^{-2}$, ….".**

page 7, justification of not changing the solar constant in the DeepMIP experiment, to counteract the absence of elevated CH4 in the design. This should be better justified. Both forcings are not equivalent and it is rather easy to change the CH4 values in the models. At least the radiative forcing from the CH4 high values should be evaluated and compared to the non-changes in the solar constant.

**We have made a calculation of the radiative forcing due to the change in solar constant and due to an increase in $CH_4$ from preindustrial values to 3000 ppbv, which is a typical value found by Beerling et al. The radiative forcings are -1.03 W/m2 and +0.98 W/m2 respectively. As such, we do think we are justified in assuming these two forcings will approximately cancel out. Furthermore, it does make the sensitivity analysis of the causes of EECO/PETM warmth compared to modern much simpler. We have added this calculation to the text.**

page 9: sensitivity to paleogeography: maps of differences could be shown to convince modelling groups that it is worth investing the time to perform these sensitivity experiments.

**Done. Figure 3 now includes all 3 recommended palaeogeographies.**

A practical question is about where to actually find this other paleogeography.

**Table 2 now details where all files are located.**

page 12: the PMIP data base should be used ! this is the only way cross-period analyses can be performed and other groups can be involved, bringing additional diagnostics and analyses. So the list in Table 1 should be expressed in terms of PMIP/CMIP6 variables. In particular, the acronyms "FLNS", "FLNT" etc should be explained.

**Changed "Ideally" to "We strongly recommend that". Note that the FLNS and FLNT acronyms are explained in the footnote to the Table.**

page 2, line 7. Replace "paleo simulations" by "paleoclimate simulations" (we hope that the simulations are new, and not "paleo")

**Done throughout.**

page 2, line 15: "deep-time model intercomparison project". should this be "deep-time climates"? The project does not aim at comparing deep times, but rather their climates, doesn't it?

**We understand the reviewer's comment, but the name of the MIP is already defined, see www.deepmip.org.**

pages 4 and 5: references should be added for the CESM and CLM models.
**Done.**

page7, line 25: the Louvain-la-Neuve group has recommended to use the term “astronomical parameters” rather than “orbital parameters” since obliquity is not an element describing the orbit of the Earth.
**Done.**

page 9, line 9: reference to Appendix 1 should be changed to Appendix A.
**Done.**

page 10, line 27: the link to the section is missing
**Done.**

page 11, last line: parentheses are missing around the web site reference.
**Done.**

# Reviewer 2

In some places, some expansion of the text is required to clearly explain what may already be apparent to experts immersed in the science, but would be helpful information for the less well-versed. These mainly relate to summarising existing literature and would not be fundamental changes to the manuscript structure or protocol details.
**We have added new Figures 1 and 2 which illustrate the context of the various time periods, and the issues around model-data comparison.**

1. There needs to be better consistency between the way the core simulations are referred to:
a. Whether there are 3 or 4 (I understand that there are 3 palaeo simulations and 1 preindustrial simulation and that these are the core, but this is not clear enough in the manuscript when interchanging between describing 3 and 4 core simulations):
**We now refer consistently to “5 main simulations”, “3 standard palaeoclimate simulations”, “2 relevant simulations from CMIP6”, and “sensitivity studies”.**

b. How the palaeoclimate simulations are named as both ‘pre-PETM’, ‘PETM’ and ‘EECO’ versus ‘two early Eocene, and one latest Paleocene’ etc.; better to pick one convention and stick to it throughout. I think the pre-PETM, PETM and EECO nomenclature is clearer. E.g. page 4, line 2-3 (?); page 9 line 12, page 11 line 8, and others.
**We are now consistent. When referring to the time periods, we refer to ‘early Eocene’ or ‘latest Paleocene’. When referring to the simulations themselves, we us EECO/PETM/pre-PETM.**

c. Use the term ‘core’ instead of alternatives. e.g.: Page 4, line 2(?): change ‘four main simulations’ to ‘four core simulations’. Or, use ‘main’ instead of ‘core’ throughout. Page 11, line 11: ‘core’ instead of ‘standard’. Better to check throughout.
**We now refer consistently to “5 main simulations”, “3 standard palaeoclimate simulations”, “2 relevant simulations from CMIP6”, and “sensitivity studies”.**

2. ‘palaeo’ and ‘paleo’ are interchanged throughout. Better to choose one convention and stick to it, since GMD is an EGU journal, I recommend ‘palaeo’. Please correct throughout.
**We are now consistent. We use “palaeo” apart from for the official stratigraphic name “Paleocene” and for the official name “Paleoclimate Model Intercomparison Project”**

3. In sections 4.2.3 and 4.2.5, the choice to use a higher solar constant (1365 W m-2) than what is suggested for the latest Palaeocene-Eocene (1359 W m-2; Gough, 1981; see manuscript) is justified by stating that it will in part counteract using lower atmospheric CH4 than probably existed (and vice versa). I struggle to accept this justification. Using the updated CMIP6 preindustrial solar constant (see point 32) would provide a much smaller difference between the latest Palaeocene-Eocene and present day solar constants (+2 W m-2). Besides this, without a quantified effect of each (solar constant versus CH4), this speculation seems to be very vague, and the effects are likely to be non-linear, surely. Since these are relatively straight forward boundary conditions to implement in the model (compared to palaeogeography, for example), why not use a more suitable solar constant (presumably 1359 W m-2) and a representative CH4 – few of the boundary conditions are certain, but if we know CH4 was elevated then surely it should be in the model set-up. Otherwise what can be achieved by the model-data comparison?

**The original formula for solar constant in Gough (1981) is relative to the modern value, and not an absolute. Therefore a change in the preindustrial control value also affects the Eocene value. We now state: "The solar constant in the CMIP6 *piControl* simulation is defined as 1361.0Wm$^{-2}$ (Matthes, in review, 2016). Although the early Eocene (51 Ma) solar constant was ~0.43% less than this (Gough, 1981), i.e. ~1355Wm$^{-2}$, ….". Furthermore, we have made a calculation of the radiative forcing due to the change in solar constant and due to an increase in $CH_4$ from preindustrial values to 3000 ppbv, which is a typical value found by Beerling et al. The radiative forcings are -1.03 W/m2 and +0.98 W/m2 respectively. As such, we do think we are justified in assuming these two forcings will approximately cancel out. Furthermore, it does make the sensitivity analysis of the causes of EECO/PETM warmth compared to modern much simpler. We have added this calculation to the text.**

This also effects section 4.3.5. It is a valuable sensitivity study, but with regard to my comment on this above, this section might need rethinking/ phrasing (e.g. the sensitivity study to use the preindustrial value of 1361 W m-2, or others if the literature presents alternatives to 1359 W m-2/indicates the uncertainty on this).

**We now clarify that the suggested reduction is 0.43%, which for a modern solar constant of 1361W/m2 becomes 1355.15 W/m2.**

4. Page 2, line 5: 'Together with the CMIP6 preindustrial simulation, these form the first' (or other such indication that the preindustrial simulation is part of the core experiment; see comment 1)

**Done.**

5. Page 2, line 7: 'core palaeoclimate simulations, one core preindustrial simulation and a set of'

**Done.**

6. Page 2, line 17-18: 'It also aims to assess their relevance for our understanding of future climate change.' This would be a valuable addition, but I don't think it's really followed up later. I suggest adding a brief section to the article explicitly dealing with this.

**Added "In particular, we anticipate papers that explore the relevance of the DeepMIP simulations and climate proxy syntheses for future climate, for example through model developments that arise as a result of the model-data comparison, or emergent constraints (Bracegridle and Stephenson, 2013) on global-scale metrics such as climate sensitivity."**

7. Page 2, line 19: I checked in CMIP and PMIP and I don't think this will be part of CMIP, so maybe make this a little clearer here; from this line I was left with the impression that DMIP will be in CMIP6.

**With the new structure of CMIP6, all of PMIP (including DeepMIP) can be considered as being under the umbrella of CMIP6, so we think the current text is correct. Only a limited number of PMIP simulations are "Tier 1" CMIP6 simulations, but all of PMIP is within CMIP6.**

8. Page 2, line 22 and throughout: proxy for what? Suggest 'climate proxy'. This should be checked throughout and always amended so that it is clear what the 'proxy' is a proxy for.

**Done throughout.**

9. In general there is a misuse of 'which', when used for restrictive clauses it should be 'that', though maybe this is different in American English: a. Page 2, line 25 b. Page 2, line 26 c. Page 3, line 13 d. Page 5, line 3 e. Page 9, line 1(?) f. Page 9, line 22 g. Page 10, line 19 h. Page 11, line 28

**After googling this, I realise that I have been writing incorrect English for the last 35 years! Thanks for pointing this out. Now corrected throughout I think.**

10. Page 2, line 26: 'of particular relevance' for what?

**Added: "This is of particular relevance to models that are also used for future projection" [note use of "that" in relation to comment 9. directly above!]**

11. Page 3, line 2: suggest summarising the intriguing model-data mismatches and inconsistencies between 'proxies'.

**We now reference Figure 1 which highlights these issues explicitly. Also added "For example, proxy-derived SST estimates indicate a weak meridional temperature gradient during the early Eocene which cannot easily be reconciled with model simulations"**

12. Page 3, line 3-4: insert commas after 'Gasson et al. (2014)', 'Lunt et al. (2013)' and 'Carmichael et al. (2016)'. Change comma to semi-colon after 'inception' and 'Eocene simulations'.

**Done.**

13. Page 3, line 8: suggest rephrasing 'proxy-proxy differences' (see comment 8. 'data' used previously, or could be more specific: 'differences between geological data').

**Done. Changed to "and a greater understanding for the reasons behind differences between different climate proxies"**

14. Page 3, line 9-10: suggest reordering the time periods so that they are chronological (and again below in lines 19-21).

**They are chronological! (from a geologists point of view). We also prefer this way because then we can introduce the PETM acronym before using pre-PETM.**

15. Page 3, lines 19-21: as well as reordering (comment 14), suggest adding a brief description of these time periods to make it clear what they are and why they were specifically chosen (e.g. a brief description under each numbered list element); otherwise that information is lacking. In particular, this information should explicitly (but not exclusively) tie-back to (i), (ii) and (iii) from lines 11-14; perhaps at least one sentence on each.

**Done. Note that (i),(ii), and (iii) are covered in the subsequent sentences.**

16. Page 3, line 23-24: 'The pre-PETM: : :and the EECO'. I'm sure this is true, but it's not very clear how or why this is true. Addressing comment 15 would probably solve this.

**Done.**

17. Page 3, line 29-30: after 'recent interest in: : :relevance to future warming' add some example references.

**Done: "Furthermore, due at least in part to interest in the Eocene and PETM for providing information of relevance to the future (e.g. Anagnostou et al, 2016; Zeebe et al, 2016), there is a relative wealth of climate proxy data with which the model results can be compared."**

18. Page 4, line 8-9: so would this then constitute 5 core simulations for those groups?

**As suggested, we have now changed the naming conventions. We now refer consistently to "5 main simulations", "3 standard palaeoclimate simulations", "2 relevant simulations from CMIP6", and "sensitivity studies".**

19. Page 4, line 10: add simulation names in header '(pre-PETM, PETM, EECO)'

**Done.**

20. Page 4, line 11: clarify that 'three core palaeoclimate simulations'; there are four (or five – comment 18) core simulations.

**We now refer consistently to "5 main simulations", "3 standard palaeoclimate simulations", "2 relevant simulations from CMIP6", and "sensitivity studies".**

21. Section 4.2: It's a little unclear as to what boundary conditions relate to which of the three core palaeoclimate simulations. It would be helpful if this could be clarified through the text in this section.

**Table 1 clarifies the relationship between the boundary conditions and the simulations.**

22. Section 4.2.1: So, are all groups expected to adjust their model's bathymetry in line with the boundary conditions? Can/will all groups do this? If not, maybe add a few lines on this so it's clear.

**All groups should change the bathymetry. Given the large change in land-sea mask, it is hard to imagine groups attempting to change the land-sea mask but not the bathymetry.**

23. Page 4, line 14: remove back-to-back parentheses, adjust to ‘Herold et al. (2014; henceforth H14)’

**Done.**

24. Section 4.2.2 (iv) river runoff: do some models compute this from their orography and land-sea mask?

**As far as we are aware, most models allow this field to be prescribed. We added the filename and variable to Table 2.**

25. Section 4.2.3: it would be helpful to add a figure compiling and summarising the greenhouse gas concentrations (at least for CO2) over this period from the geological data, including uncertainty. I understand the time axis would probably need to expand over a substantially wider period that these simulations cover, but then the periods represented by the three palaeoclimate simulations could be highlighted (e.g. vertical shaded bars if time is on x-axis). It would give helpful context as well as summarise the uncertainty. The 1x, 3x, 6x and 12x CO2 values (plus 2x and 4x?) could also be indicated (e.g. dashed horizontal lines).

**Done – see new Figure 5.**

26. Section 4.2.3: This is entitled ‘Greenhouse gas concentrations’, but really only addresses CO2. I suggest at least adding a discussion and presentation of CH4 boundary conditions (see comment 3), but otherwise rename this section appropriately.

**We now discuss CH4 in more detail, and have added an additional sensitivity study to CH4 in the latter sections, especially for those groups who can predict CH4 interactively.**

27. Page 6: line 7-8: add refs for the records showing this (CO2 and extant temperature records). Possibly also clarify what ‘extant temperature records’ means in this context; is it the temperature proxy archive that survives or the temperature reconstruction?

**We clarify by citing the benthic oxygen isotope record. This implies that PETM temperatures were similar to EECO temperatures, which implies the CO2 concentrations were also similar.**

28. Page 7: some extra commas are needed: Line 5 after ‘(see Section 4.2.5)’ Line 6 after ‘In effect’

**Done.**

29. Page 7, line 6: ‘at the CMIP6 preindustrial concentrations’?

**Done.**

30. Page 7, line 8: ‘terms of global surface temperature’? This is unclear so needs clarifying.

**We have removed this sentence.**

31. Page 7, line 10-11; can this also be justified scientifically? What are the implications/ added value of the results of these 2x and 4x CO2 simulations?

**Added “In this way, the modelled Eocene climate sensitivity and its nonlinearities can be investigated.”**

32. Page 7, line 27: the solar constant is out of date. The CMIP6 preindustrial value will be 1361.0 W m$^{-2}$ (Matthes et al., 2016). Also affects page 10, line 23.

**Done.**

33. Page 8, line 6: replace ‘SSTs’ with ‘Sea Surface Temperatures (SSTs)’

**Done.**

34. Page 8, line 24: Do you mean ‘hydrological’ instead of ‘geological’? Otherwise I’m not sure what is meant by ‘geological cycling’.

**Replaced with “on these timescales long-term geological sources and sinks of NaCl associated with crustal recycling also play an important role;….”**

35. Page 9, line 7: what is the address/location/reference for the PMIP database?

**This has not yet been set up or decided. Added “…uploaded to the anticipated PMIP database”.**

36. Page 9, line 7: replace ‘in the Appendix’ with ‘in Appendix 1, including Tables 1-3’.

**Done.**

37. Page 9, line 9: ‘Appendix 1, Tables 1-3’.

**Done.**

38. Page 9: some extra commas are needed: line 26: after ‘Ideally’ line 30: after ‘studies’

**Done.**

39. Page 10, lines 4-6: why carry out sensitivity studies of ‘widening/constricting and shallowing/deepening key ocean gateways, raising/lowering mountain ranges, and changing the bathymetry of ocean shelves’? Please summarise (from the literature) the kind of changes or uncertainties in these boundary conditions that are thought to have taken place during this period, and what effect they may/may not have had?

**Added “The exact geometry and state of these features are not all well constrained geologically; therefore it is interesting to explore the uncertainties in climate which may result from uncertainties in their configuration.”**

40. Page 10, line 27: what should be there instead of ‘Section ??’; is it ‘Section 4.2.6’ or ‘Section 4.2.7’? Where is this discussed? I think the discussion needs adding to one of these sections (4.2.6 or 4.2.7 or both).

**Done.**

41. Page 10, line 28: ‘will be a function of’.

**Done.**

42. Page 11, line 17: ‘will be to develop new ways’.

**Done.**

43. Page 11, line 22: remove parentheses from within parentheses: ‘see Dowsett et al., 2012)’.

**Done.**

44. Page 11, line 29: add comma: ‘In this respect, we are’

**Done.**

45. Page 11, line 29: reference the PlioMIP special issue properly, because I assume that is why the URL is given (i.e. in addition to the Haywood et al. ref).

**Done.**

46. Page 12, line 8: Change ‘Appendix A’ to ‘Appendix 1’ (or vice versa earlier).

**Done.**

47. Page 12, line 9: ‘variables below (Tables 1-3) should be submitted’

**Done.**

48. Table 2: replace ‘SST’ with ‘Sea surface temperature’, replace ‘T’ with ‘potential temperature’ (I assume it is potential temperature?), replace ‘S’ with ‘salinity’.

**Done.**

## Editor comments

1. To improve comprehension for those not immersed in DeepMIP intervals, I need to see some kind of visual timeline which indicates what the climate was like during these intervals. Then I can see when the intervals were, and have some understanding of what the differences in climate were both between the intervals and relative to the climate throughout the Earth's history.

**Done. See new Figure 2.**

2. Paleoclimate simulations are meaningless without data and the data section is worryingly fanciful. I want to see actual description of datasets, or if these are being developed as part of the project, then a much clearer timeline of what will be made available when (how many points are expected for what variables etc). If this is presently impossible, then there would be the possibility of writing a companion paper to this one outlining the data sets (from the GMD Manuscript Types page, ".Papers describing data sets designed for the support and evaluation of model simulations are within scope. These data sets may be syntheses of data which have been published elsewhere. The data sets must also be made available, and any code used to create the syntheses should also be made available.").

**Yes, we do intend to write a paper summarising the vision for these datasets, and have already embarked on this process. This may well end up being a companion GMD paper.**

Finally: GMD is indeed an EGU journal and papers should be in English, but a while ago they changed from requiring British English to allowing whatever flavour of English you prefer. But, as one of the reviewers says, you are supposed to be consistent within the paper. [Surely it's Palæo ? :-) ]

**We are now consistent. We use "palaeo" apart from for the official stratigraphic name "Paleocene" and for the official name "Paleoclimate Model Intercomparison Project".**

## Other Changes

**We have added 5ºC to our recommended initial temperature state for the ocean. This is to likely shorten the timescale of equilibration of the simulations.**

**We have made a number of additional minor spelling and grammatical changes**

**We added the following co-authors because they have contributed to the paper and/or DeepMIP: Jeff Kiehl, Eleni Anagnostou, Aradhna Tripati, Gordon Inglis, Stephen Jones, and Henk Dijkstra.**

# DeepMIP: experimental design for model simulations of the EECO, PETM, and pre-PETM.

Daniel J. Lunt[1], Matthew Huber[2], Eleni Anagnostou[9], Michiel L.J. Baatsen[3], Rodrigo Caballero[4], Rob DeConto[5], Henk A. Dijkstra[3], Yannick Donnadieu[6], David Evans[31], Ran Feng[8], Gavin Foster[9], Ed Gasson[5], Anna S. von der Heydt[3], Chris J. Hollis[10], Gordon N. Inglis[32], Stephen M. Jones[34], Jeff Kiehl[29], Sandy Kirtland Turner[11], Robert L. Korty[12], Reinhardt Kozdon[13], Srinath Krishnan[7], Jean-Baptiste Ladant[6], Petra Langebroek[14], Caroline H. Lear[15], Allegra N. LeGrande[16], Kate Littler[17], Paul Markwick[18], Bette Otto-Bliesner[8], Paul Pearson[15], Christopher J. Poulsen[19], Ulrich Salzmann[20], Christine Shields[8], Kathryn Snell[21], Michael Starz[22], James Super[7], Clay Tabor[8], Jess Tierney[23], Gregory J.L. Tourte[1], Aradhna Tripati[33], Gary R. Upchurch[24], Bridget S. Wade[25], Scott L. Wing[26], Arne M.E. Winguth[27], Nicky Wright[28], James C. Zachos[29], and Richard Zeebe[30]

[1]School of Geographical Sciences, University of Bristol, UK
[2]Department of Earth Sciences, University of New Hampshire, USA
[3]Institute for Marine and Atmospheric research Utrecht (IMAU), Utrecht University, Netherlands
[4]Department of Meteorology (MISU), Stockholm University, Sweden
[5]Department of Geosciences, University of Massachusetts-Amherst ,USA
[6]Laboratoire des Sciences du Climat et de l'Environnement, CNRS/CEA, France
[7]Department of Geology and Geophysics, Yale University, USA
[8]National Centre for Atmospheric Research, USA
[9]Ocean and Earth Science, National Oceanography Centre Southampton, University of Southampton, UK
[10]GNS Science, New Zealand
[11]Department of Earth Sciences, University of California - Riverside, USA
[12]Department of Atmospheric Sciences, Texas A&M University, USA
[13]Lamont-Doherty Earth Observatory of Columbia University, USA
[14]Uni Research Climate, Bjerknes Centre for Climate Research, Norway
[15]School of Earth and Ocean Sciences, Cardiff University
[16]NASA-GISS, USA
[17]Camborne School of Mines, University of Exeter, UK
[18]Getech Group plc, UK
[19]Department of Earth and Environmental Sciences, University of Michigan, USA
[20]Department of Geography, Northumbria University, UK
[21]Department of Geological Sciences, University of Colorado, USA
[22]Alfred Wegener Institute, Germany
[23]Department of Geosciences, University of Arizona, USA
[24]Department of Biology, Texas State Univesity, USA
[25]Department of Earth Sciences, University College London, UK
[26]Department of Paleobiology, Smithsonian Institution, USA
[27]Earth and Environmental Science, University of Texas - Arlington, USA
[28]School of Geosciences, University of Sydney, Australia
[29]PBSci-Earth & Planetary Sciences Department, Institute of Marine Sciences, University of California - Santa Cruz, USA
[30]Department of Oceanography, University of Hawaii at Manoa, USA
[31]Earth Sciences, University of St Andrews, UK
[32]School of Chemistry, University of Bristol, UK

[33]Earth, Planetary, and Space Sciences, Atmospheric and Oceanic Sciences, Institute of the Environment and Sustainability, University of California - Los Angeles, USA
[34]School of Geography, Earth and Environmental Sciences, University of Birmingham, UK

*Correspondence to:* Dan Lunt (d.j.lunt@bristol.ac.uk)

**Abstract.** Past warm periods provide an opportunity to evaluate climate models under extreme forcing scenarios, in particular high (>800 ppmv) atmospheric $CO_2$ concentrations. Although a post-hoc intercomparison of Eocene (~50 million years ago, Ma) climate model simulations and geological data has been carried out previously, models of past high-$CO_2$ periods have never been evaluated in a consistent framework. Here, we present an experimental design for climate model simulations of three warm periods within the ~~latest Paleocene and the early Eocene. Together~~ early Eocene and the latest Paleocene (the EECO, PETM, and pre-PETM). Together with the CMIP6 preindustrial control and abrupt $4\times CO_2$ simulations, and additional sensitivity studies, these form the first phase of DeepMIP – the ~~deep-time model intercomparison project~~Deep-time Model Intercomparison Project, itself a group within the wider Paleoclimate Modelling Intercomparison Project (PMIP). The experimental design ~~consists of three core paleo simulations and a set of optional sensitivity studies. The experimental design~~ specifies and provides guidance on boundary conditions associated with palaeogeography, greenhouse gases, ~~orbital~~ astronomical configuration, solar constant, land surface ~~parameters~~processes, and aerosols. Initial conditions, simulation length, and output variables are also specified. Finally, we explain how the geological datasets, which will be used to evaluate the simulations, will be developed.

## 1 Introduction

There is a large community of Earth scientists ~~who focus on~~ with strong interests in ‘deep-time’ palaeoclimates, here defined as climates of the pre-Pliocene (i.e., prior to ~5 Ma). Recently, a growing community of modelling groups focussing on these periods is also beginning to emerge. DeepMIP – the ~~deep-time model intercomparison project~~ Deep-time Model Intercomparison Project – brings together ~~these modellers, and~~ modellers, the data community, and other scientists, into a multidisciplinary international effort dedicated to conceiving, designing, carrying out, analysing, and disseminating an improved understanding of these time periods. It also aims to assess their relevance for our understanding of future climate change. DeepMIP is a working group in the wider Paleoclimate Modelling Intercomparison Project (PMIP), which itself is a part of the sixth incarnation of the Coupled Model Intercomparison Project (CMIP6). In DeepMIP, we will focus on three time periods in the latest Paleocene and early Eocene (~55–50 Ma), and for the first time, carry out a formal coordinated ~~model–model–data~~ model–data intercomparison. In addition to the experimental design presented here, DeepMIP will synthesise existing climate proxy records, and develop new ones if appropriate~~, and carry out the model–model–data comparison~~. The aim will be to best characterise our understanding of the palaeoclimate of the chosen interval through the synthesis of climate proxy records, to compare this with the model simulations, and to understand the reasons for the intra and inter model and data differences. The ultimate aim is to encourage ~~development of models~~ model development in response to any robust model deficiencies ~~which~~ that emerge from the model–data comparison. This is of particular relevance to models that are also used for future climate projection, given the relative warmth and high $CO_2$ ~~which~~ that characterises many intervals of deep-time.

## 2 Previous Work

An informal, post-hoc ~~model–model–data~~ model–data intercomparison has previously been carried out for the early Eocene (Lunt et al., 2012). This compared the results of four models from five modelling groups with marine and terrestrial data syntheses, and explored the reasons for the model–model differences using energy balance diagnostics. That study contributed to the recent IPCC AR5 report (Box 5.1, Fig. 1), but it also revealed challenging differences between model simulations of this period, intriguing model–data mismatches, as well as inconsistencies between proxies ~~.~~ (Figure 1). For example, proxy-derived SST estimates indicate a weak meridional temperature gradient during the early Eocene which cannot easily be reconciled with the model simulations. Further work resulting from this intercomparison included Gasson et al. (2014), which investigated the $CO_2$ thresholds for Antarctic ice sheet inception~~, Lunt et al. (2013)~~; Lunt et al. (2013), which compared the ensemble and data to further Eocene simulations~~, and Carmichael et al. (2016)~~; and Carmichael et al. (2016), which investigated the hydrological cycle across the ensemble and compared model results with proxies for precipitation.

The ~~exercise pointed~~ previous exercise points to the need for a more coordinated experimental design (different modelling groups had carried out simulations with different boundary conditions, and different initial conditions etc.), and a greater understanding for the reasons behind ~~proxy–proxy differences~~ differences between different climate proxies. Those challenges provide the motivation for DeepMIP.

## 3 The chosen intervals – the Early Eocene Climatic Optimum (EECO) the ~~Palaeocene–Eocene~~ Paleocene–Eocene Thermal Maximum (PETM), and the pre-PETM.

The choice of time interval on which to focus is based on a balance between (i) the magnitude of the anticipated climate signal (larger signals have a higher signal-to-uncertainty ratio, and larger signals provide a greater challenge to models), (ii) the uncertainties in boundary conditions ~~which~~ that characterise the interval (small uncertainties result in more robust conclusions as to the models' abilities, and minimise the model sensitivity studies required to explore the uncertainties), and (iii) the amount and geographic distribution of palaeoclimate data available with which to evaluate the model simulations.

We have chosen to focus on the latest Paleocene and early Eocene – $\sim$55 to $\sim$50 Ma (the Ypresian stage), as it is the most recent geological interval characterised by high (>800 ppmv) atmospheric $CO_2$ concentrations. Within the latest Paleocene and early Eocene, DeepMIP will focus on three periods (see Figure 2):

1. The Early Eocene Climatic Optimum (EECO, $\sim$53–51 Ma)
   which is the period of greatest sustained (>1 Myr) warmth in the last 65 million years.

2. The ~~Palaeocene-Eocene~~ Paleocene-Eocene Thermal Maximum (PETM, $\sim$55 Ma)
   which is the event of greatest warmth in the last 65 million years.

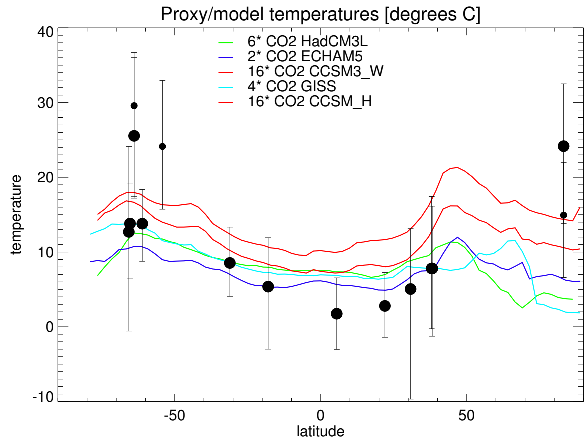



**Figure 1.** Zonal mean Eocene sea surface temperature warming, presented as an anomaly relative to present/pre-industrial. Warming from the five models in 'Eomip' (Lunt et al., 2012) are shown as coloured lines; for each model only the $CO_2$ concentration that best fits the temperature proxy observations is shown. Warming derived from the proxies are shown as filled circles, with error bars representing the range of uncertainty associated with proxy calibration and temporal variability. Larger symbols represent 'background' early Eocene state, smaller symbols represent the EECO. Adapted from Figure 8a in Lunt et al. (2012).

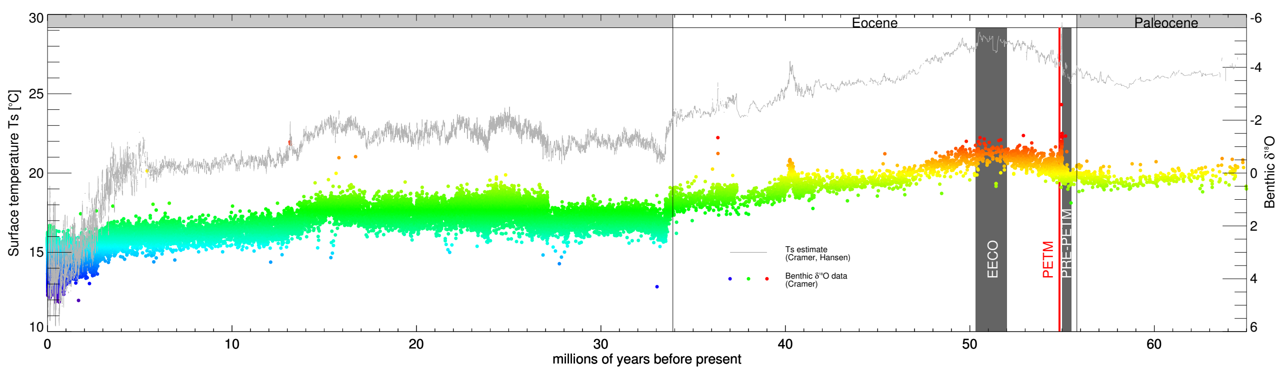



**Figure 2.** The three DeepMIP palaeo intervals - EECO (grey shaded region), pre-PETM (grey shaded region), and the PETM (vertical red line). Also shown for context is the climate evolution over the last 65 million years, as expressed by the benthic oxygen isotope record of Cramer et al. (2009) (coloured dots), and a surface temperature record produced by applying the methodologies of Hansen et al. (2013) to the Cramer et al. (2009) $\delta^{18}O_{\text{benthic}}$ data, and applying a 10-point running average (grey line). Note that the formal definition of the start and end date of each time period is still to be finalised.

3. The period just before the PETM (pre-PETM, or latest Paleocene) which is relatively warm compared with modern, but is cooler than both the PETM and the EECO.

~~These three~~

**Table 1.** Summary of simulations associated with DeepMIP, including two relevant simulations from CMIP6 (*piControl* and *abrupt-4×CO2*), the three standard simulations (*deepmip-stand-X*), and some of the suggested sensitivity studies (*deepmip-sens-X*).

| Simulation Name | Simulation description | $CO_2$ [ppmv] | palaeogeography |
|---|---|---|---|
| *piControl* | preindustrial control (Eyring et al., 2016) | 280[1] | modern |
| *abrupt-4×CO2* | abrupt increase to 4× $CO_2$ concentrations (Eyring et al., 2016) | 1120 | modern |
| *deepmip-stand-3×CO2* | pre-PETM, at 3×preindustrial $CO_2$ | 840 | Herold et al. (2014) |
| *deepmip-stand-6×CO2* | EECO/PETM, at 6×preindustrial $CO_2$ | 1680 | Herold et al. (2014) |
| *deepmip-stand-12×CO2* | EECO/PETM, at 12×preindustrial $CO_2$ | 3360 | Herold et al. (2014) |
| *deepmip-sens-Y×CO2* | Sensitivity study at $Y$×preindustrial $CO_2$ | $Y$×280 | Herold et al. (2014) |
| *deepmip-sens-geoggetech* | Sensitivity study with modified palaeogeography | 840, 1680, 3360[2] | Lunt et al. (2016) |
| *deepmip-sens-geogpalmag* | Sensitivity study with modified palaeogeography | 840, 1680, 3360[2] | *This paper* |

[1] If a value different from 280 ppmv is used for $piControl$, then all other $CO_2$ values in the table should be changed accordingly.
[2] Order of priority, highest priority first.

These intervals have been the focus of numerous studies in the geological literature, and some syntheses of proxies from these intervals already exist (e.g. Huber and Caballero, 2011; Lunt et al., 2012; Dunkley Jones et al., 2013). The pre-PETM provides a reference point for both the PETM and the EECO. In addition, all three time periods can be referenced to modern or pre-industrial. This is in recognition that both modelling and proxies are ~~strongest~~ most robust when considering relative changes, as opposed to absolutes.

Compared to earlier warm periods, such as the mid-Cretaceous, the palaeogeography during the early Eocene is reasonably well constrained, and freely available digital palaeogeographic datasets exist; however, there are wide uncertainties in estimates of atmospheric $CO_2$ at this time. Furthermore, due ~~to the recent~~ at least in part to interest in the Eocene and PETM for providing information of relevance to ~~future warming~~the future (e.g. Anagnostou et al., 2016; Zeebe et al., 2016), there is a relative wealth of ~~palaeoclimate~~ climate proxy data with which the model results can be compared.

## 4 Experimental design

The DeepMIP experimental protocol consists of ~~four main simulations (~~five main simulations - pre-industrial, ~~two early Eocene~~future, two in the early Eocene (EECO and PETM), and one ~~latest Paleocene~~in the latest Paleocene (pre-PETM), plus a number of optional sensitivity studies (see Section 4.3). The simulations are summarised in Table 1.

### 4.1 Pre-industrial ~~simulation~~and future simulations

The pre-industrial simulation should be as close as possible to the CMIP6 standard~~as possible~~, *piControl* (Eyring et al., 2016). Many groups will already have carried out this simulation as part of CMIP6. Some groups may need to make changes to their

CMIP6 model ~~configuation~~ configuration for the DeepMIP ~~paleo~~ palaeoclimate simulations (for example changes to ocean diffusivity). If this is the case, we encourage groups to ~~also~~ carry out a ~~non-CMIP6~~ new preindustrial simulation with the model configuration used for DeepMIP ~~paleo~~ palaeoclimate simulations.

### 4.2 ~~Latest Paleocene and early Eocene simulations~~

The future simulation is the CMIP6 standard *abrupt-4×CO2* simulation (Eyring et al., 2016), which branches off from the *piControl* simulation, and in which atmospheric $CO_2$ is abruptly quadrupled and then held constant for at least 150 years.

### 4.2 EECO/PETM and pre-PETM simulations

This section describes the DeepMIP ~~paleo~~ palaeoclimate simulations. There are three standard ~~simulations~~palaeoclimate simulations (*deepmip-stand-3×CO2*, *deepmip-stand-6×CO2*, *deepmip-stand-12×CO2*), which differ only in their atmospheric $CO_2$ concentration, plus a number of optional sensitivity studies. In general terms, we consider the *deepmip-stand-3×CO2* simulation as representative of the pre-PETM, and the other two simulations as representing two different scenarios for the EECO and/or PETM.

#### 4.2.1 Palaeogeography and land-sea mask

~~Herold et al. (2014) (henceforth H14)~~ Herold et al. (2014, henceforth H14) is a peer-reviewed, traceable, freely-available digital reconstruction of the early Eocene interval. It includes land-sea mask, topography and sub-gridscale topography, bathymetry, tidal dissipation, vegetation, aerosol distributions, and river runoff. The palaeogeography and land-sea mask from H14 should be used for ~~the DeepMIP paleo simulations~~ all the standard DeepMIP palaeoclimate simulations (see Table 1); they are provided digitally in netcdf format in the Supplementary Information of H14 (see Table 2), at a resolution of $1° \times 1°$, and are illustrated here in Fig. 3(a). The palaeogeographic height should be applied as an absolute, rather than as an anomaly to the pre-industrial topography. Most models additionally require some fields related to the subgridscale orography to be provided. Because subgridscale orographies are very sensitive to the resolution of the underlying dataset, the subgridscale orography (if it is required by the model) can be estimated based on fields also provided in Supplementary Information of H14. This can be implemented as the modelling groups see fit, but care should be taken that the pre-industrial and Eocene subgridscale topographies are as consistent as possible. In addition, the code used to calculate the subgridscale orographies in the CESM (Gent et al., 2011) model is also provided in the Supplementary Information of H14. Care should be taken when defining the land-sea mask for the ocean component of the model that the various seaways are preserved at the model resolution; this may require some manual manipulation of the land-sea mask.

Included in the Supplementary Information of this paper are palaeorotations such that the modern location of gridcells in the ~~early~~ Eocene palaeogeography can be identified, as can the ~~early~~ Eocene location of modern gridcells.

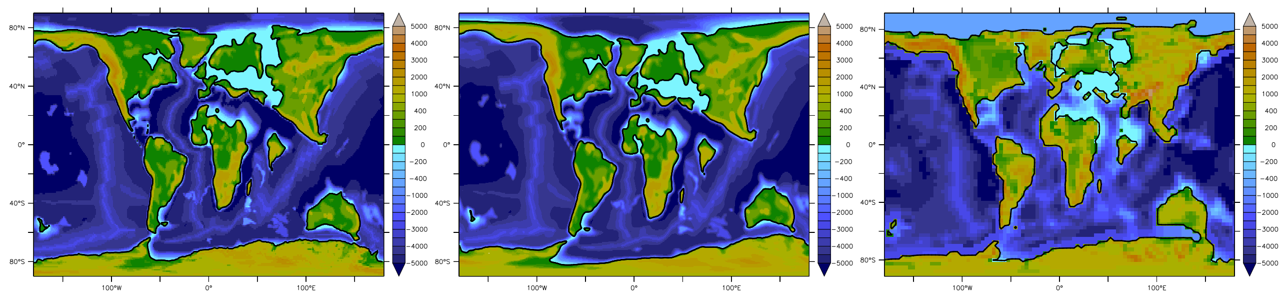
We encourage sensitivity studies to the palaeogeography - see Section 4.3.2.

**Table 2.** Location and filenames for some of the DeepMIP boundary conditions

| Simulation Name(s) | Boundary Condition | Location | Filename | Variable Name |
|---|---|---|---|---|
| *deepmip-stand-X×CO2*[1] | Topography | Supp Info of H14 | herold_etal_eocene_topo_1x1.nc | topo |
| *deepmip-stand-X×CO2* | Vegetation | Supp Info of H14 | herold_etal_eocene_biome_1x1.nc | eocene_biome[3] |
| *deepmip-stand-X×CO2* | Runoff | Supp Info of H14 | herold_etal_eocene_runoff_1x1.nc | RTM_FLOW_DIRECT |
| *deepmip-sens-geoggetech* | Topography | Supp Info of Lunt et al. (2016) | bath_ypr.nc, orog_ypr.nc | bathuk, oroguk |
| *deepmip-sens-geogpalmag* | Topography | Supp Info of this paper | Herold2014_TPW.nc | Band1 |

[1] Where *X* can be 3,6, or 12.

[3] 27 biomes. For simplified 11 biomes, use variable eocene_biome-hp.



(a) (b) (c)

**Figure 3.** Orography and bathymetry for the ~~paleo~~ palaeoclimate simulations in DeepMIP [metres]. ~~A netcdf file of the data at~~ (a~~1°×1° resolution is available~~) The Herold et al. (2014) palaeogeography, as used in the ~~Supplementary data of~~ standard palaeoclimate simulations (*deepmip-stand-3×CO2,deepmip-stand-6×CO2,deepmip-stand-9×CO2*). (b) The Herold et al. (2014) palaeogeography, but in the rotation framework given by Torsvik (2011), which is based on a palaeomagnetic reference frame (Baatsen et al., 2016). (c) The Ypresian palaeogeography from Lunt et al. (2016). The location of digital versions of these three palaeogeographies is given in Table 2.

### 4.2.2 Land surface

*(i) vegetation:*

The vegetation in the DeepMIP ~~paleo~~ palaeoclimate simulations should be prescribed as that in H14, which is included digitally as a netcdf file in the Supplementary Information of H14 (Table 2; note that the BIOME4 vegetation should be used rather than the Sewall vegetation, and that groups may choose to base their vegetation either on the 27 biomes or the 10 megabiomes), and shown here in Fig. 4. Groups should make a lookup table for converting the H14 Eocene dataset to a format ~~which~~ that is appropriate for their model. To aid in this process, a modern vegetation dataset is also provided in the Supplementary Information of H14, using the same Plant Functional types as in the H14 Eocene reconstruction; in addition, the lookup table for the CLM (Oleson et al., 2010) land model is provided as a guide.

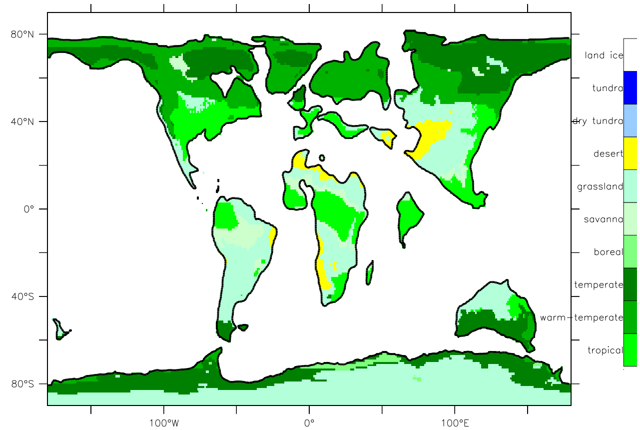



**Figure 4.** Vegetation, expressed as megabiomes, for the ~~paleo~~ palaeoclimate simulations in DeepMIP. A netcdf file of the data at a $1^{\circ} \times 1^{\circ}$ resolution is available in the Supplementary ~~data~~ Information of Herold et al. (2014) (see Table 2).

*(ii) soils:*

~~Soils should be classified homogeneously~~ Parameters associated with soils should be given constant values over the globe, with ~~properties~~ values for these parameters (e.g. albedo, water-holding capacity etc.) given by the global-mean of the group's pre-industrial simulation.

*(iii) lakes:*

No lakes should be prescribed in the DeepMIP ~~paleo model~~ palaeoclimate simulations, unless these are predicted dynamically by the model.

*(iv) river runoff:*

River runoff should be taken from the H14 reconstruction~~and~~ , which is included digitally as a netcdf file in the Supplementary ~~information~~ Information of H14 (see Table 2).

### 4.2.3 Greenhouse gas concentrations

Each group should carry out three simulations at three different atmospheric $CO_2$ concentrations, expressed as multiples of the value in the pre-industrial simulation (typically $280\,\mathrm{ppmv}$, Section 4.1): (i) $3\times$ pre-industrial (typically $840\,\mathrm{ppmv}$), (ii) $6\times$ pre-industrial (typically $1680\,\mathrm{ppmv}$), and (iii) $12\times$ pre-industrial (typically $3360\,\mathrm{ppmv}$). ~~Extant temperaturerecords imply~~ Assuming a simple relationship between $CO_2$ and temperature, the benthic oxygen isotope record (see Figure 2) implies that, within uncertainty of the $CO_2$ proxies, $CO_2$ concentrations in the EECO and PETM were similar. As such, whereas the low-$CO_2$ simulation can be considered as representing the pre-PETM, the two higher $CO_2$ simulations are intended to represent a range of possible PETM and EECO climate states. The values themselves are based primarily on recent work using boron isotopes (Anagnostou et al., 2016), which indicates that EECO $CO_2$ was $1625\,\mathrm{ppmv} \pm 760\,\mathrm{ppmv}$ (Figure 5).

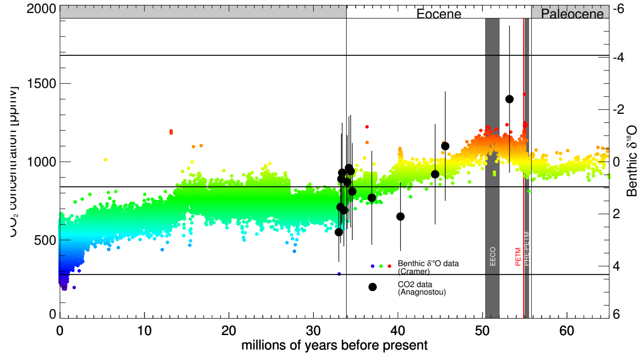



**Figure 5.** Atmospheric $CO_2$ as derived from boron isotopes in the Eocene by (Anagnostou et al., 2016) (black circles and error estimates). Horizontal lines show 280 ppmv (typical preindustrial value), and 840ppmv and 1680 ppmv, corresponding to the *deepmip-stand-3×CO2* and *deepmip-stand-6×CO2* simulations. Also shown are the DeepMIP palaeo intervals - EECO (grey shaded region), pre-PETM (grey shaded region), and the PETM (vertical red line), and the climate evolution over the last 65 million years, as expressed by the benthic oxygen isotope record of Cramer et al. (2009) (coloured dots). Note that the formal definition of the start and end date of each time period is still to be finalised.

It is thought that non-$CO_2$ greenhouse gases during the early Eocene were elevated relative to pre-industrial, especially $CH_4$ (e.g., $\sim 3000\,\mathrm{ppbv}$, Beerling et al., 2011). However, there is considerable uncertainty as to exactly how elevated they were. Given these uncertainties, and the fact that we have chosen to use a modern solar constant as opposed to a reduced solar constant (see Section 4.2.5), which would otherwise ~~partially~~ offset the $CH_4$ increase, all non-$CO_2$ greenhouse gases and trace gases should be set at the CMIP6 pre-industrial concentrations. In effect, we assume that the $CO_2$ forcing represents the $CO_2$, $CH_4$ (and other non-$CO_2$ greenhouse gases), and solar forcings. ~~Although a solar forcing and a forcing have a differing regional expression, the response of the system in terms of surface temperature is similar (Lunt et al., 2008)~~For reference, the radiative forcing associated with an increase in $CH_4$ concentrations from preindustrial values to $3000\,\mathrm{ppbv}$ is $+0.98\,\mathrm{W\,m^{-2}}$ (Byrne and Goldblatt, 2014), and the radiative forcing associated with an decrease in solar constant from $1361\,\mathrm{W\,m^{-2}}$ to $1355.15\,\mathrm{W\,m^{-2}}$ (see Sections 4.2.5 and 4.3.5) is $-1.03\,\mathrm{W\,m^{-2}}$ (assuming a planetary albedo of 0.3).

Some groups may find the higher $CO_2$ simulations problematic as some models are known to develop a runaway greenhouse at high $CO_2$ (Malte Heinemann, pers comm). In this case, in addition to the $3\times$ simulation, groups can carry out simulations at $2\times$ and $4\times$. In this way, the modelled Eocene climate sensitivity and its nonlinearities can still be investigated.

If groups only have the computational ~~resource~~ resources to carry out two simulations, they should carry out the $3\times$ and $6\times$ simulations. For groups that can only carry out a single simulation, the analysis of the runs will be limited due to the focus on anomalies in DeepMIP, but we still encourage such groups to participate; in this case they should just carry out the $3\times$ simulation.

For groups with extensive computational ~~resource~~resources, we encourage them to carry out additional sensitivity simulations over a range of $CO_2$ values, and in particular at $1\times$, see Section 4.3.1.

#### 4.2.4 Aerosols

The representation of aerosols (including mineral dust) in Earth system models is undergoing a period of rapid development. Therefore, we leave the implementation of aerosol fields or emissions rather flexible, and give several options. Groups may choose to (i) leave aerosol distributions or emissions identical to pre-industrial (taking account of the changed land-sea mask), or (ii) treat aerosols prognostically, or (iii) use aerosol ~~emissions~~ concentrations (including mineral dust) from H14, or (iv) use aerosol ~~distributions~~ optical depths from H14, or (v) some combination of the above, depending on the aerosol type. The crucial thing is that groups are asked to document exactly how they have implemented aerosols.

#### 4.2.5 Solar constant and ~~orbital~~ astronomical parameters

All simulations should be carried out with ~~modern~~ the same solar constant and ~~orbital parameters .~~ astronomical parameters as in the preindustrial simulation. The solar constant in the CMIP6 *piControl* simulation is defined as $1361.0\,\mathrm{W\,m^{-2}}$ (Matthes et al., in review, Although the early Eocene (51 Ma) solar constant was ~~(Gough, 1981)compared with a modern value of ,~~ ~0.43% less than this (Gough, 1981), i.e. ~$1355\,\mathrm{W\,m^{-2}}$, we choose to use a modern value in order to (i) aid comparison of any $1\times$ $CO_2$ simulations (see Section 4.3.1) with pre-industrial, and (b) to offset the absence of elevated $CH_4$ in the experimental design (see Section 4.2.3). As with all of Earth history, ~~orbital~~ astronomical conditions varied throughout the early Eocene. There is some evidence that the PETM and other ~~Palaeogene~~ Paleogene hyperthermals may have been paced by ~~orbital~~ astronomical forcing (Lourens et al., 2005; Lunt et al., 2011), but the phase of the response relative to the forcing is unknown. The modern orbit has relatively low eccentricity, and so represents a forcing close to the long-term average, and also facilitates comparison with the control pre-industrial simulation. However, we do encourage ~~sensitiity studies to orbital~~ sensitivity studies to astronomical configuration (see Section 4.3.3).

#### 4.2.6 Initial conditions

*(i) Atmosphere and land surface:*

Simulations may be initialised with any state of the atmosphere and land surface, as long as the initial condition would not typically take longer than ~50 years to spin up in a model with fixed ~~SSTs~~sea surface temperatures; for example, initial snow cover should not be hundreds of metres depth.

*(ii) Ocean:*

Given that even with relatively long simulations, some vestiges of the initial ocean temperature and salinity structure will remain at the end of the simulations, we ~~strongly reccommend~~ recommend that all groups adopt the same initialisation procedure for the ocean, but encourage groups to carry out sensitivity studies to the initialisation (see Section 4.3.7). The ocean should be initialised as stationary, with no initial sea ice, and a zonally symmetric temperature ($T$, °C) and globally constant salinity

($S$, psu) distribution given by:

$$T\,[^\circ\mathrm{C}] = \begin{cases} \left(\frac{5000-z}{5000}\,25\cos(\phi)\right)+15 & \text{if } z \leq 5000\,\mathrm{m} \\ 15 & \text{if } z > 5000\,\mathrm{m} \end{cases}$$
$$S\,[\mathrm{psu}] = 34.7 \tag{1}$$

Where $\phi$ is latitude, and $z$ is depth of the ocean (metres below surface).

Some groups have previously found that initialising the model with relatively cold (<$10\,^\circ\mathrm{C}$) ocean temperatures at depth results in a relatively long spinup (> $5000\,\mathrm{years}$), due to the suppression of convection – hence the relatively warm initial temperatures at depth prescribed here. Groups for which the ~~reccommended~~ recommended initial temperature structure still results in a ~~stratififed~~ stratified ocean with little convection, and hence likely long equilibration timescales (for example those with a model with a particularly high climate ~~senstivity~~sensitivity), may wish to initialise their model with warmer deep ocean temperatures. If so, this should be clearly documented.

The value of $34.7\,\mathrm{psu}$ is the same as the modern mean ocean value. Although the lack of ice sheets in the Eocene would result in a decrease in mean ocean salinity relative to the modern of about $0.6\,\mathrm{psu}$, on these timescales ~~geological cycling also plays~~ long-term geological sources and sinks of $\mathrm{NaCl}$ associated with crustal recycling also play an important role; Hay et al. (2006) estimate mean ocean salinity to be between 35.1 and 36.5 during the Eocene. Given the uncertainties we choose a modern value for simplicity. If groups prefer to initialise salinity with a non-homogeneous distribution, or with a different absolute value, they may do this, but it should be documented.

For simulations in which oxygen, carbon or other isotopic systems or passive tracers are included, these can be initialised as each individual group sees fit.

#### 4.2.7 Length of simulation

Simulations should be carried out for as long as possible. Ideally, simulations should be (a) at least 1000 years in length, and (b) have an inbalance in the top-of-atmosphere net radiation of less than $0.3\,\mathrm{W\,m^{-2}}$ (or have a similar inbalance to that of the pre-industrial control), and (c) have ~~SSTs which~~ sea surface temperatures that are not strongly trending (less than $0.1\,^\circ\mathrm{C}$ per century in the global mean). Climatologies should be calculated based on the final 100 years of the simulation.

#### 4.2.8 Output format

~~Ideally, all~~ We strongly recommend that all model output should be provided in CMIP6-compliant netcdf format, including the standard PMIP variables, and uploaded to the anticipated PMIP database. However, if this is not possible, then netcdf files of the variables in ~~the Appendix~~ Appendix A, including Tables 3-5, should be uploaded to the DeepMIP Modelling Database, which will be set up if and when required. In any case, for the 'highest priority' variables in Appendix ~~1,~~ A, Tables 3-5, all months of the simulations should be retained, such that averages can be calculated from arbitrary years of the simulation, and such that equilibrium states can be estimated using the approach of Gregory et al. (2004).

### 4.3 Sensitivity Studies

~~The above gives~~ Sections 4.1 and 4.2 give a summary of the ~~four core simulations(pre-industrial and two early Eocene and one latest Paleocene). Below are~~ five main simulations. Here we outline some optional sensitivity studies that groups may wish to carry out, although there is no guarantee that other groups will do the same simulations.

#### 4.3.1 Sensitivity to $CO_2$

Groups may wish to explore more fully the sensitivity of their model to $CO_2$, and associated non-linearities ~~(Caballero and Huber, 2013)~~(e.g by carrying out additional simulations over a range of $CO_2$. Normally these would be multiples of the pre-industrial concentration, in addition to the standard $3\times$, $6\times$, and $12\times$ simulations. In particular, we encourage groups to carry out a $1\times$ simulation, for comparison with the pre-industrial control – this simulation enables the contribution of non-$CO_2$ forcings (palaeogeography and ice sheets) to early Eocene warmth to be evaluated.

#### 4.3.2 Sensitivity to palaeogeography

Getech ~~Plc~~ Group plc (www.getech.com) have provided an alternative palaeogeographic reconstruction ~~which~~ that may be used for sensitivity studies, in particular simulation *deepmip-sens-geoggetech* (see Tables 1,2). It is included digitally in Lunt et al. (2016) as a netcdf file at a resolution of 3.75° longitude × 2.5° latitude, and is shown in Figure 3(c). Because a high resolution version of this topography is not available, groups will need to use the subgridscale palaeogeography from the H14 reconstruction, and interpolate to the new land-sea mask as appropriate. The vegetation, river routing etc. from H14 will also need to be extrapolated to the new land-sea mask. Ideally, groups would carry out these simulations at the same three $CO_2$ levels as in the standard simulations, but if groups can only carry out a limited number of simulations with this palaeogeography, they should carry them out in the following order of priority (highest priority first): $3\times$, $6\times$, $12\times$.

Both Getech and H14 use the plate rotation model of Müller et al. (2008), which is derived from relative plate motions tied to a mantle reference frame. van Hinsbergen et al. (2015) argue that for ~~paleoclimate studies~~palaeoclimate studies, plate motions should be tied to the spin axis of the Earth using a ~~paleomagnetic~~ palaeomagnetic reference frame in order to obtain accurate estimates of ~~paleolatitude~~palaeolatitude. For this reason~~we will~~, we also provide an additional ~~palaeogeography~~ version of the H14 palaeogeography, but rotated to a palaeomagnetic reference frame based on the methods outlined by van Hinsbergen et al. (2015) and ~~Baatsen et al. (2015).~~ Baatsen et al. (2016), for use in sensitivity study *deepmip-sens-geogpalmag* (see Tables 1,2). This is shown in Figure 3(b), and provided in the Supplementary Information to this paper.

~~In addition, groups are~~ Furthermore, some of the topographic features could have evolved significantly throughout the ~55-51 Ma period of interest, making it unlikely that a single palaeogeography can represent all the DeepMIP time periods to the same extent. Groups are therefore encouraged to carry out sensitivity studies around the H14 palaeogeography~~. This~~, to explore the uncertainties in climate which may result from uncertainties in the spatial and temporal evolution of different topographic features. These studies may include widening/constricting and shallowing/deepening key ocean gateways, changing the bathymetry and extent of ocean shelves, and raising/lowering mountain ranges~~, and changing the bathymetry of ocean~~

~~shelves.~~ . In particular, we encourage groups to carry out sensitivity studies in which the NE Atlantic-Arctic gateway to the east of Greenland is closed. This is because there is evidence that a short, transient period of ∼kilometer-scale tectonic uplift of NW Europe and Greenland, associated with the North Atlantic Large Igneous Province, severely restricted the NE Atlantic-Arctic oceanic gateway during the PETM period in comparison with the pre-PETM and EECO periods (Hartley et al., 2011; Jones and White, 200

#### 4.3.3 Sensitivity to ~~orbit~~astronomical parameters

Evidence of cyclicity during the Paleocene and early Eocene indicates that ~~part~~ a component of the warmth of the PETM may be ~~orbitally forced on eccentricity timescales (Lourens et al., 2005; Westerhold et al., 2007; Galeotti et al., 2010). This is consistent with the ∼50 kyr length of the core of the PETM.~~ astronomically forced (Lourens et al., 2005; Westerhold et al., 2007; Galeotti e As such, we encourage sensitivity studies to ~~orbital~~ astronomical configuration. As the standard DeepMIP ~~paleo simulations are with~~ palaeoclimate simulations are configured with a modern orbit, which has relatively low eccentricity, we suggest groups carry out additional simulations with high eccentricity ($e = 0.054$ compared with a modern value of $e = 0.017$), and northern hemisphere winter corresponding with both aphelion and perihelion.

#### 4.3.4 Sensitivity to vegetation

~~For those groups with dynamic vegetation , they~~ Those groups which have a model that includes dynamic vegetation may carry out sensitivity studies ~~using a dynamic vegetation component~~with dynamic vegetation turned on. The initial condition should be broadleaf or needleleaf trees at all locations. Ideally groups would carry out these simulations at the same three $\mathrm{CO_2}$ levels as in the standard simulations, but if groups can only carry out a limited number of simulations with the dynamic vegetation, they should carry them out in the following order of priority (highest priority first): $3\times$, $6\times$, $12\times$. Groups with models ~~which~~ that include a dynamic vegetation component can choose to pass to their vegetation model either the ambient atmospheric $\mathrm{CO_2}$, or a lower concentration if required for model stability.

#### 4.3.5 Sensitivity to solar constant

Groups may wish to explore the relative radiative forcing of the solar luminosity compared with other forcings, by carrying out an Eocene simulation with a reduced solar luminosity. ~~An appropriate reduction would be from~~ The suggested reduction is 0.43% (Gough, 1981), which would normally be from $1361.0\,\mathrm{W\,m^{-2}}$ in the modern to $1355.15\,\mathrm{W\,m^{-2}}$ in the Eocene~~(Gough, 1981)~~. This would typically be carried out at a $\mathrm{CO_2}$ level of $3\times$.

#### 4.3.6 Sensitivity to non-$\mathrm{CO_2}$ greenhouse gases

Groups may choose to explore sensitivity to non-$\mathrm{CO_2}$ greenhouse gases (see Section 4.2.3 for discussion of $\mathrm{CH_4}$), in particular if these can be predicted by the model interactively.

#### 4.3.7 Sensitivity to initialisation

We encourage groups to carry out sensitivity studies to the initialisation of the ocean temperature and salinity. It is possible that models will exhibit bistability with respect to initial condition, and as discussed in Section ~~??~~ 4.2.6 we expect that the ~~speed of equilibrium will~~ equilibration time will be a function of the initial conditions and will be different for different models.

#### 4.3.8 'Best in Show'

Participants are invited to carry out simulations in which they attempt to best match existing climate proxy data. This may be done in a number of ways, for example by modifying the aerosols (Huber and Caballero, 2011), cloud properties (Kiehl and Shields, 2013), physics parameters (Sagoo et al., 2013), using very high $CO_2$ (Huber and Caballero, 2011), incorporating dynamic vegetation (Loptson et al., 2014), modifying gateways (Roberts et al., 2009), modifying orbital configuration, including non-$CO_2$ greenhouse gases, or a combination of the above and other modifications.

## 5 Climate Proxies

A major focus of DeepMIP will be to develop a new synthesis of climate proxy data for the latest Paleocene and early Eocene, focussing on the three targetted time intervals: pre-PETM, PETM and EECO. The main focus of DeepMIP will be on temperature and precipitation proxies. Two working groups have been set up to compile these data from marine and terrestrial records. These groups will also work together to generate new data sets for poorly documented regions, such as the tropics, and will seek multiple lines of evidence for climate reconstructions wherever possible. The marine working group is excited by the possibility of using innovative analytical techniques (e.g. Kozdon et al., 2013) to recover robust estimates for sea surface temperature from planktic foraminiferal assemblages within legacy sediment cores of the International Ocean Discovery Program. Published data sets will be combined into an open-access online database. The EECO and PETM/pre-PETM marine compilations of Lunt et al. (2012), Hollis et al. (2012), and Dunkley Jones et al. (2013), and EECO terrestrial compilations of Huber and Caballero (2011) provide a starting point for this database. One of the great challenges for these working groups will be to develop new ways to assess climate proxy reliability and quantify uncertainties. In some cases, it may be more straightforward to consider relative changes in proxies rather than report absolute values. ~~Proxy~~ Climate proxy system modelling (Evans et al., 2013) coupled with Bayesian analysis (e.g. Khider et al., 2015; Tierney and Tingley, 2014) has great potential for improving estimation of uncertainties and directly linking our climate proxy compilation with the climate simulations. In addition to these quantitative estimates of uncertainty, all data will be qualitatively assessed based on expert opinion, for example characterising proxies as high, medium, or low confidence ~~(as has been done in PlioMIP, see Dowsett et al. (2012))~~(as has been done in PlioMIP, see Dowsett et al., 2012).

We anticipate a companion paper to this one in which we will give more details of the DeepMIP data and associated protocols.

## 6 Products

In addition to this experimental design paper, and papers describing the new climate proxy syntheses, once the model simulations are complete we anticipate producing overarching papers describing the ‘large-scale features’ of the model simulations, and model–data comparisons. Following this, we anticipate a number of spin-off papers looking at various other aspects of the model simulations (e.g., ENSO, ocean circulation, monsoons~~etc.).~~). In particular we expect papers that explore the relevance of the DeepMIP simulations and climate proxy syntheses for future climate, for example through model developments that arise as a result of the model-data comparison, or emergent constraints (Bracegirdle and Stephenson, 2013) on global-scale metrics such as climate sensitivity. Furthermore, we will encourage modelling participants to publish individual papers ~~which~~ that describe their own simulations in detail, including how the boundary conditions were implemented. In this respect, we are basing our dissemination strategy on that of PlioMIP ~~(Haywood et al., 2013)~~(Haywood et al., 2013); see their Special Issue at http://www.geosci-model-dev.net/special_issue5.html.

## 7 Data availability

The boundary conditions for the ~~DeepMIP paleo~~ standard DeepMIP palaeoclimate simulations are supplied as ~~Suppleemntary~~ Supplementary Information in H14 (Herold et al., 2014)~~.~~; see Table 2. For availability of other data, also see Table 2.

## Appendix A: Output variables

If the PMIP database is not used, the variables ~~below~~ in Tables 3-5 should be submitted to the (yet to exist) DeepMIP Model Database. Climatological averages of the final 100 years of the simulation should be supplied for each month (12 fields for each variable). In addition, for the highest priority variables, all months of the simulation should be supplied.

Furthermore, as many groups are interested in hydrological extremes, groups should aim to produce ten years of hourly precipitation, evaporation and runoff data.

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**Table 3.** Atmosphere variables

| Variable | Units | Highest priority |
|---|---|---|
| Near surface ($1.5\,\mathrm{m}$) air temperature | $^\circ\mathrm{C}$ | X |
| Surface skin temperature | $^\circ\mathrm{C}$ | |
| Precipitation | $\mathrm{kg\,m^2\,s^{-1}}$ | X |
| Total evaporation | $\mathrm{kg\,m^2\,s^{-1}}$ | |
| Total cloud cover | [0,1] | |
| FLNS | $\mathrm{W\,m^{-2}}$ | |
| FLNT | $\mathrm{W\,m^{-2}}$ | X |
| FSDS | $\mathrm{W\,m^{-2}}$ | |
| FSNS | $\mathrm{W\,m^{-2}}$ | |
| FSNT | $\mathrm{W\,m^{-2}}$ | X |
| FSDT | $\mathrm{W\,m^{-2}}$ | |
| sensible heat flux | $\mathrm{W\,m^{-2}}$ | |
| latent heat flux | $\mathrm{W\,m^{-2}}$ | |
| Near surface ($10\,\mathrm{m}$) u wind | $\mathrm{m\,s^{-1}}$ | |
| Near surface ($10\,\mathrm{m}$) v wind | $\mathrm{m\,s^{-1}}$ | |
| surface wind stress (x) | $\mathrm{N\,m^{-2}}$ | |
| surface wind stress (y) | $\mathrm{N\,m^{-2}}$ | |
| mean sea-level pressure | $\mathrm{Pa}$ | |
| surface pressure | $\mathrm{Pa}$ | |
| u winds on model atmospheric levels | $\mathrm{m\,s^{-1}}$ | |
| v winds on model atmospheric levels | $\mathrm{m\,s^{-1}}$ | |
| w winds on model atmospheric levels | $\mathrm{m\,s^{-1}}$ | |
| u wind at $200\,\mathrm{mbar}$ | $\mathrm{m\,s^{-1}}$ | |
| v wind at $200\,\mathrm{mbar}$ | $\mathrm{m\,s^{-1}}$ | |
| u wind at $500\,\mathrm{mbar}$ | $\mathrm{m\,s^{-1}}$ | |
| v wind at $500\,\mathrm{mbar}$ | $\mathrm{m\,s^{-1}}$ | |
| u wind at $850\,\mathrm{mbar}$ | $\mathrm{m\,s^{-1}}$ | |
| v wind at $850\,\mathrm{mbar}$ | $\mathrm{m\,s^{-1}}$ | |
| geopotential height at $200\,\mathrm{mbar}$ | $\mathrm{m}$ | |
| geopotential height at $500\,\mathrm{mbar}$ | $\mathrm{m}$ | |
| geopotential height at $850\,\mathrm{mbar}$ | $\mathrm{m}$ | |
| temperature at $200\,\mathrm{mbar}$ | $^\circ\mathrm{C}$ | |
| temperature at $500\,\mathrm{mbar}$ | $^\circ\mathrm{C}$ | |
| temperature at $850\,\mathrm{mbar}$ | $^\circ\mathrm{C}$ | |
| specific humidity at $200\,\mathrm{mbar}$ | $\mathrm{kg\,kg^{-1}}$ | |
| specific humidity at $500\,\mathrm{mbar}$ | $\mathrm{kg\,kg^{-1}}$ | |
| specific humidity at $850\,\mathrm{mbar}$ | $\mathrm{kg\,kg^{-1}}$ | |

N.B. F*XYZ* notation
F = flux
*X* = S(hortwave) or L(ongwave)
*Y* = D(own) or N(et)
*Z* = S(urface) or T(op of atmosphere)

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**Table 4.** Ocean Variables

| Variable | Units | Highest priority |
|---|---|---|
| ~~SST~~ sea surface temperature | $^\circ\mathrm{C}$ | X |
| sea-ice fraction | [0,1] | X |
| u,v,w on model levels | $\mathrm{cm\,s^{-1}}$ | |
| ~~T~~ potential temperature on model levels | $^\circ\mathrm{C}$ | |
| ~~S~~ salinity on model levels | psu | |
| barotropic streamfunction | $\mathrm{cm^3\,s^{-1}}$ | |
| mixed-layer depth | m | |
| global overturning streamfunction | Sv | |

**Table 5.** Boundary conditions

| Variable | Units |
|---|---|
| land-sea mask | [0,1] |
| topography | m |
| bathymetry | m |


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