The PMIP4 contribution to CMIP6 – Part 1: Overview and over-arching analysis plan – response to the reviewer and editor (3rd revision)

Dear Editor, dear reviewers of the successive versions of this manuscript,

This is the fourth version of the manuscript describing the PMIP4 contribution to CMIP6. It is probably useful that at this stage, we summarise the different stages it went through. The first version was written according to the CMIP Panel's recommendations, namely, as stated in Eyring et al. (2016) and restated in the comment from the CMIP Panel on our manuscript:

"Each of the 21 CMIP6-Endorsed MIPs is described in a separate invited contribution to this Special Issue. These contributions will detail the goal of the MIP and the major scientific gaps the MIP is addressing, and will specify what is new compared to CMIP5 and previous CMIP phases. The contributions will include a description of the experimental design and scientific justification of each of the experiments for Tier 1 (and possibly beyond), and will link the experiments and analysis to the DECK and CMIP6 historical simulations. They will additionally include an analysis plan to fully justify the resources used to produce the various requested variables, and if the analysis plan is to compare model results to observations, the contribution will highlight possible model diagnostics and performance metrics specifying whether the comparison entails any particular requirement for the simulations or outputs (e.g. the use of observational simulators). In addition, possible observations and reanalysis products for model evaluation are discussed and the MIPs are encouraged to help facilitate their use by contributing them to the obs4MIPs/ana4MIPs archives at the ESGF (see Section 3.3). In some MIPs additional forcings beyond those used in the DECK and CMIP6 historical simulations are required, and these are described in the respective contribution as well."

We therefore tried to fulfill these requirements, and at the same time made sure that all the PMIP community, modellers and experts on the forcings and boundary conditions, agreed on the rationale and protocol described in this manuscript. The manuscript was therefore the result of long discussions and different types of compromises, with the main objective of the simulations were driven by the science that the community wants to investigate and that it also fits with scientific and technical constraints from CMIP6. This was also done while coordinating the content of the companion papers that focus more on the way the boundary conditions were determined for each period and how the PMIP4-CMIP6 periods fit in a more complete set of PMIP4 simulations. The resulting manuscript was 20 pages long for the main text, included 14 pages of references, 3 tables and 7 figures.

In the second version, following the reviewers' comments, we actually lengthened the manuscript to have more complete protocols and more complete information concerning the analysis plan. On the other hand we tried to shorten the introduction and "history" parts which were deemed boring. This more complete manuscript had 24 pages of main text, 16 pages of references, 4 tables and 6 figures.

This second version was not sent to review. Instead, the Editor wrote:

"There has been some deliberation over this paper among the three editors handling the PMIP experiment description paper (one of whom has a self-declared conflict of interest, which was taken into account).

Fundamentally none of us consider the paper satisfactory at present, but James Annan and I (who do not have a conflict of interest) have come up with a potential solution, which should allow this PMIP4 "bookmark" to appear in the tome of the CMIP6 special issue.
We think that <u>the paper should be reformulated as a review or summary paper</u>. One framing could be to think in terms of being of interest and use to people currently of outside of the PMIP mainstream, who would benefit from an introduction to PMIP and a rough guide to which experiments they might be able to do. They probably wouldn't be so willing to wade through 4 different detailed experimental protocol papers to see if they would work out which are relevant to them and what the important differences are. Such people exist! We have met them! I imagine that the resulting summary would also be useful to new PMIP researchers as well as those who so far have only been involved in one of the PMIP sub-MIPs, but are interested in getting a wider appreciation of the whole project.
<u>In order to fulfil these requirements the paper needs a major overhaul</u>. The manuscript is too long and does not need to cover so much detail, I don't think it needs so much background, and many of the figures seem unnecessary, and they are anyway rather incomplete (eg 3 and 4 are two sets of partial forcings for a couple of experiments, 2 and 5 are bits of analysis that people have done for past PMIPs, but are by no means comprehensive). The tables are better, although they will need updating with the information from the now accepted/published sub-MIP papers. The text also needs to be made consistent with the other three papers, which we went to some lengths to coordinate, in terms of both the language and the actual requirements of the different MIPs."

This was quite at odds with the first requirements from the CMIP6 panel. Nonetheless, we prepared a third version of the manuscript, by shortening the second version, especially sections 1 and 2 (again) and section 3 on the protocol. Section 4, on the analysis, was left after the protocol section. We chose to keep quite a complete protocol because it was a necessary requirement from the CMIP6 panel, and also because the other papers refer to it. This third version has 21 pages of text, 14 pages of references, 5 tables and 5 figures. It was meant to give an overview of the PMIP4 experiments for CMIP6, an overview of the protocol, in particular of new features of the protocol. This overview allowed a comparison of the forcings of the 5 PMIP4-CMIP6 periods and an overview of possible analyses, focusing on multi-period analyses, since single period protocols and analyses are now presented in full detail in the companion PMIP4 GMD papers. As such, we thought it would fulfill the CMIP6 panel requirements and the wishes of the Editor.

At this stage, the manuscript was sent to a fourth, new reviewer, who advised to reject the paper on the motive that it was found "neither particularly useful nor exciting to read". The Editor then took her decision (of asking major revision, this is very kind of her) based solely on this review and her own opinion, which obviously agreed with the review. She now asks for "*an enlightening overview of PMIP activities*". So the requirement has changed again. It should be noted that the CMIP6 panel never asked for "an enlightening review" from the start of the process. The requirements for this manuscript have now changed four times, we have made efforts to adapt each time, to fulfill the changing requirements, but we are now wondering if the process will ever stop.

Thus, we are now submitting the fourth version of the manuscript. The main text is 15 pages long (13 if the title page and abstract are not taken into account). There is 1 page of appendix, 14 pages of references (should we cut these too? this is not very nice for researchers who provided the work thanks to which PMIP can be conducted), 5 tables, 4 figures in the main text, 1 in the appendix.

In this version, we have followed the suggestion from the reviewer and the Editor to place the scientific motivation first. The paper is now structured as follows (changing the order of sections 3 and 4):

- 1) introduction (with some examples of challenging questions rising from the previous phases of PMIP),

- 2) description of the PMIP4-CMIP6 periods,

- 3) examples of scientific questions (termed "analyses" to fit the CMIP6 suggestion) which will benefit from the full PMIP4-CMIP6 and other CMIP6 experiments,

- 4) a short section on model configuration and experimental set up, which largely refers to the companion papers for single experiments but better documents the rationale of the requested documentation and output. For us, this section is mandatory because the companion papers, already published, refer to this one as this one gives common requirements for all PMIP4-CMIP6 experiments.

- 5) a short conclusion.

We hope that this version now reads better and fulfils both the CMIP6 panel and GMD requirements. At this stage, we may add that this manuscript was never meant to be a thrilling text. It was meant to be a protocol paper for GMD, following the CMIP6 panel recommendation. The solution found by the Editor so that we do not end up with very long paper including all justifications, experimental set up and analysis plans for all the periods (i.e. splitting the manuscript in this overview and companion papers) is much appreciated, but we feel her expectations might be too high with respect to what was initially expected from the CMIP6 panel.

Response to reviewer 4

We reproduce the reviewer's comments in *italic* and provide our reply in blue.

This manuscript aims at providing an overview of the paleo climate modelling inter comparison (PMIP) contributions within CMIP6, as the detailed descriptions of the experiments are distributed over four separate manuscripts. The protocol is also sketched and some ideas for future analysis is provided in the contribution.

I struggled to find a good reason for publishing this paper, as I find it neither particularly useful nor exciting to read. As an introduction to the other four papers, it could have placed the scientific questions first and spend more energy on explaining how the new experiments are exciting and can be analysed in ways that were not possible before, e.g. multi-state constraints, but this part (section 4) appears more to be an afterthought and not particularly concrete. This could have been done in a shorter format.

Instead the reader is dragged through the experiment protocols, which are, at best redundant. In the worst case, however, the redundancy of protocol is confusing and can lead to errors in implementation. I therefore recommend stripping the manuscript of experimental protocol information, i.e. practically all of section 3 and parts of section 4.

As explained above, the manuscript submitted to the fourth reviewer resulted from a rather long history of requirements from both the CMIP6 panel and the Editor, which were sometimes contradictory. We apologize for the text not being "particularly useful nor exciting to read" and have reorganized the text keeping the reviewer's suggestion in mind, i.e. putting the scientific questions first and keeping the information on the protocol to a minimum. To keep the analysis plan short, we focus on the multi-period analyses and benchmarking.

We have kept a section on the protocol, though, to warrant consistency in the set up for the different periods, which are now fully described in the "companion" papers. We have reduced this section to the bare minimum. However we still want this protocol section to be in, to ensure consistency of all the PMIP4-CMIP6 experiments and because the other papers refer to this paper for common aspects and documentation of the simulations.

A perhaps more salient point concerns the repeated statements that the paleo experiments offer "out-of-sample" tests of models and that these will facilitate "to assess whether they have the correct sensitivity to forcing":

- The idea that paleo climate experiments are out-of-sample tests is strictly speaking only true the first time a particular experiment is conducted. Once the results are known to people that prepare the next round of experiments then it is no longer out of sample, rather there is a risk that protocol, boundary conditions, or even the models are modified such as to perform better, in some sense. That this is happening is admitted to on page 7, lines 8-10. Since this is now the fourth PMIP there can really be no justification of claiming the experiments are out of sample.

- There can be no such thing as a model with "correct sensitivity to forcing" as all models are wrong to begin with. Instead one can use model runs in different climates to constrain sensitivity using so-called emergent constraints, and/or one can see where models collectively or partly is inconsistent with proxies. I would suggest scanning the document for the word "correct" and rewrite these sentences.

These ideas have been rephrased and now reads (first paragraph of the introduction):

"In making future projections, models are operating well outside the conditions under which they have been developed and validated. Changes in the recent past provide only limited evidence about how climate responds to changes in external factors and internal feedbacks of the magnitude expected in the future. Paleoclimate states radically different from those of the recent past provide a way to test model performance outside the range of recent climatic variations and to study the role of forcings and feedbacks in establishing these climates. Although palaeoclimate simulations strive for verisimilitude in terms of forcings and the treatment of feedbacks, none of the models used for future projection have been developed or calibrated to reproduce past climates."

As I doubt the editor would follow my recommendation to postpone publication of this paper, I would recommend at least addressing the above before publication. I would, however, suggest that the authors try to learn from this, as they plan their future publications, that the papers should each have a clear purpose.

Again, we apologize for this manuscript not being what the Editor and reviewer thought it should be, but as stated above, the purpose of the manuscript and the requirements from the Editor and reviewers have changed quite a lot. We hope that this version will be easier and less boring to read.

Response to the Editor

The reviewer recommends rejection. If this manuscript were merely a review of the PMIP experiments as presented in the GMD/CP special issue, then I would reject, and encourage the authors to simply write a non-peer-reviewed preface to the special issue. However, this manuscript is also part of the CMIP6 special issue, and has value in that context, as an overview paper that summarises PMIP activities to non-PMIP modellers (and to PMIP modellers that are involved in only part of the project).

My first impression of this revision was that the manuscript is still much too long to serve its purpose as an enlightening overview of PMIP activities. However, other scientists are usually more patient than I am with overly long papers, so I decided to send the manuscript back out for review. I chose the reviewer quite carefully to be someone who I think is precisely the kind of scientist to whom the manuscript should be of interest (a paleo-curious climate modeller). It is therefore thoroughly disappointing that they find the manuscript "neither particularly useful nor exciting to read". The reviewer's general suggestions sound very attractive, "As an introduction to the other four papers, it could have placed the scientific questions first and spend more energy on explaining how the new experiments are exciting and can be analysed in ways that were not possible before, e.g. multi-state constraints, but this part (section 4) appears more to be an afterthought and not particularly concrete. This could have been done in a shorter format. ... In the worst case, however, the redundancy of protocol is confusing and can lead to errors in implementation. I therefore recommend stripping the manuscript of experimental protocol information, i.e. practically all of section 3 and parts of section 4."

A reduction in length of 50% would not be inappropriate in my (possibly still a bit extreme!) opinion.

I suspect that the other comments from the reviewer (about the out of sample-ness of the experiments and correctness of forcing) really refer to a slight imprecision in language rather than any fundamental disagreement, and so it is worth amending the text to make sure that such misunderstandings are minimised.

We hope we have now addressed all concerns with this manuscript. We reduced it by 9 pages compared to the longest version, and the main text now holds in 12 1/2 pages, which is very short compared to the other papers in the CMIP6 special issue. We did not plan to write “an enlightening overview of PMIP activities” from the start, this will come in due time, when the PMIP4 results are out and numerous enough to perform enlightening analyses.

The PMIP4 contribution to CMIP6 – Part 1: Overview and over-arching analysis plan*

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* This paper is the first of a series of 4 GMD papers on the PMIP4-CMIP6 experiments. Part 2 (Otto-Bliesner et al. 2017) gives the details about the two PMIP4-CMIP6 interglacial experiments, Part 3 (Jungclaus et al., 2017) about the last millennium experiment, and Part 4 (Kageyama et al., 2017) about the Last Glacial Maximum experiment. The mid Pliocene Warm Period experiment is part of the Pliocene Model Intercomparison Project (PlioMIP) - Phase 2, detailed in Haywood et al. (2016).

Abstract.

The goal of the Paleoclimate Modelling Intercomparison Project (PMIP) is to understand the response of the climate system to different climate forcings and feedbacks for documented climatic states very different from the present and historical climates. Through comparison with observations of the environmental impact of these climate changes, or with climate reconstructions based on physical, chemical or biological records, PMIP also addresses the issue of how well state-of-the-art numerical models simulate climate change. Climate models are usually developed using the present and historical climates as references, but climate projections show that future climates could lie well outside these conditions. Paleoclimates very different from these reference states therefore provide stringent tests for the state-of-the-art models and a way to assess whether their sensitivity to forcings and feedbacks is compatible with paleoclimatic evidence. Simulations of five different periods have been designed to address the objectives of the sixth phase of the Coupled Model Intercomparison Project (CMIP6): the millennium prior to the industrial epoch (CMIP6 name: *past1000*), the mid-Holocene, 6,000 years ago (*midHolocene*); the Last Glacial Maximum, 21,000 years ago (*lgm*); the Last Interglacial, 127,000 years ago (*lig127k*) and mPWP, the mid-Pliocene Warm Period, 3.2 million years ago (*midPliocene-eoi400*). These climatic periods are well documented by paleoclimatic and paleoenvironmental records, with climate and environmental changes relevant for the study and projections of future climate changes. This manuscript describes the motivation for the choice of these periods and the design of the numerical experiments and database requests, with a focus on their novel features compared to the experiments performed in previous phases of PMIP and CMIP. It also outlines the analysis plan that takes advantage of the comparisons of the results across periods and across CMIP6 in collaboration with other MIPs.

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1 Introduction

Instrumental meteorological and oceanographic data show that the Earth has undergone a global warming of ~0.85°C since the beginning of the industrial revolution (Hartmann et al., 2013), largely in response to the increase of atmospheric greenhouse gases. Concentrations of atmospheric greenhouse gases are projected to increase significantly during the 21st century, reaching levels well outside the range of recent millennia. In making future projections, models are operating well outside the conditions under which they have been developed and validated. Changes in the recent past provide only limited evidence about how climate responds to changes in external factors and internal feedbacks of the magnitude expected in the future. Paleoclimate states radically different from those of the recent past provide a way to test model performance outside the range of recent climatic variations and to study the role of forcings and feedbacks in establishing these climates. Although palaeoclimate simulations strive for verisimilitude in terms of forcings and the treatment of feedbacks, none of the models used for future projection have been developed or calibrated to reproduce past climates.

We have to look back ca. 3 million years to find a period of Earth's history when atmospheric CO_2 concentrations were similar to the present day (the mid-Pliocene Warm Period) and several tens of million years (e.g. the early Eocene, ~55 to 50 million years ago) to find concentrations similar to those projected for the end of this century. The latter period can offer key insights into climate processes that operate in a higher CO_2, warmer world although their geographies are different from today (e.g. Lunt et al., 2012; Caballero and Huber, 2010). During the Quaternary (2.58 million years ago to present), the Earth's geography was similar to today and the main external factors driving climatic changes are the astronomical parameters, which determine the seasonal and latitudinal distribution of incoming solar energy. Changes in greenhouse gas concentrations and in ice sheets acted as additional forcing factors on the dynamics of the atmosphere and the ocean. In addition, rapid climate transitions, on human-relevant timescales (decades to centuries), have been documented for this most recent period (e.g. Marcott et al., 2014; Steffensen et al., 2008).

By combining several past periods, the credibility of climate projections can be assessed using information about longer-term paleoclimate changes that are as large as the anticipated future change. Replicating the totality of past climate changes with state-of-the-art climate models, driven by appropriate forcings (e.g. insolation, atmospheric composition) and boundary conditions (e.g. ice sheets), is a challenge (Braconnot et al., 2012; Harrison et al., 2015). It is challenging, for example, to represent the correct amplitude of past climate changes such as glacial-interglacial temperature differences (e.g. between the Last Glacial Maximum, (LGM, ~21,000

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years ago), and the pre-industrial temperatures, cf. Harrison et al., 2014) or to represent the northward extension of the African monsoon during the mid-Holocene, (MH, ~ 6,000 years ago) (Perez-Sanz et al., 2014). Interpreting paleo-environmental data can also be challenging, particularly disentangling the relationships between changes in large-scale atmospheric or oceanic circulation, broad-scale regional climates and local environmental responses to these changes during climate periods where the relative importance of various climate feedbacks cannot be assumed similar to today. This challenge is paralleled by concerns about future local or regional climate changes and their impact on the environment. Modelling paleoclimates is therefore a means to understand past climate and environmental changes better, using physically based tools, as well as a means to evaluate model skill in forecasting the responses to major drivers.

These challenges are at the heart of the Paleoclimate Modeling Intercomparison project (PMIP) and the new set of PMIP4 simulations (Otto-Bliesner et al., 2017, Jungclaus et al., 2017, Kageyama et al., 2017, Haywood et al., 2016) has the ambition to tackle them. Paleoclimate experiments for the Last Glacial Maximum, the mid Holocene and the last millennium were formally included in CMIP during its fifth phase (CMIP5, Taylor et al., 2012), equivalent to the third phase of PMIP (PMIP3, Braconnot et al, 2012). This formal inclusion made it possible to compare the mechanisms causing past and future climate changes in a rigorous way (e.g. Izumi et al., 2015) and to evaluate the models used for projections (e.g. Harrison et al., 2014, Harrison et al., 2015). More than 20 modelling groups took part in PMIP3 and many of the PMIP3 results are prominent in the fifth IPCC assessment report (Masson-Delmotte et al., 2013; Flato et al., 2013). PMIP3 also identified significant knowledge gaps and areas where progress is needed. PMIP4 has been designed to address these issues.

The five periods chosen for PMIP4-CMIP6 (Table 1) were selected because they contribute directly to the CMIP6 objectives, in particular they address the key CMIP6 question "How does the Earth System respond to forcing?" (Eyring et al, 2016) for multiple forcings and climates states different from the current or historical climates. They are characterized by greenhouse gas concentrations, astronomical parameters, ice sheet extents, and volcanic and solar activities different from the current or historical ones (Table 2), consistent with the need to provide a large sample of the climate responses to important forcings. The choice of two new periods, the last interglacial (~127 000 years ago) and the mid Pliocene Warm Period was motivated by the desire to explore the relationships between climate-ice-sheet system and sea level and to expand analyses of climate sensitivity and polar amplification. For each target period, comparison with environmental observations and climate reconstructions enable us to determine whether the modelled responses are realistic, allowing PMIP to address

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Mis en forme : Anglais (Royaume-Uni) the second key CMIP6 question "What are the origins and consequences of systematic model biases?" PMIP simulations and data-model comparisons will show whether the biases in the present-day simulations are found in other climate states. Also, analyses of PMIP simulations will show whether present-day biases have an impact on the magnitude of simulated climate changes. Finally, PMIP is also relevant to the third CMIP6 question "How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?" through examination of these questions for documented past climate states and via the use of the last millennium simulations as a reference state for natural variability.

The detailed justification of the experimental protocols and analysis plans for each period are given in a series of companion papers: Otto-Bliesner et al. (2017) for the *midHolocene* and *lig127ka* experiments, Kageyama et al. (2017) for the *lgm*, Jungclaus et al. (2017) for the *past1000* and Haywood et al. (2016) for the *midPliocene-eoi400* experiment. These papers also explain how the boundary conditions for each period should be implemented and include the description of sensitivity studies using the PMIP4-CMIP6 simulation as a reference. Here we provide an overview of the PMIP4-CMIP6 simulations and highlight the scientific questions that will benefit from the CMIP6 environment. In section 2, we give a summary on the PMIP4-CMIP6 periods and the associated forcings and boundary conditions. The analysis plan is outlined in Section 3. Critical points in the experimental set-up are briefly described in section 4. A short conclusion is given in section 5.

2. The PMIP4 experiments for CMIP6 and associated paleoclimatic and paleoenvironmental data

The choice of the climatic periods for CMIP6 is based on past PMIP experience and is justified by the need to address new scientific questions, while also tracing back model evolution and ability to represent these climate states since the first phase of PMIP (Table 1). The forcings and boundary conditions for each PMIP4-CMIP6 paleoclimate simulation are summarised in Table 2. All the experiments can be run independently and have value for comparison to the CMIP6 DECK (Diagnostic, Evaluation and Characterization of Klima) and historical experiments (Eyring et al., 2016). They are therefore all considered as Tier 1 within CMIP6. It is not mandatory for groups wishing to take part in PMIP4-CMIP6 to run all five PMIP4-CMIP6 experiments. It is however mandatory to run at least one of the two entry cards, i.e. the *midHolocene* or the *lgm*.

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<#>LM, the millennium before the start of the industrial revolution, from 850 to 1849 CE (*past1000*)¶
<#>MH, the mid-Holocene, 6,000 years ago (*midHolocene*)¶
<#>LGM, the Last Glacial Maximum, 21,000 years ago (*lgm*)¶
<#>LIG, the Last Interglacial, 127,000 years ago (*lig127k*)¶
<#>mPWP, the mid-Pliocene Warm Period, 3.2 million years ago (*midPliocene-eoi400*)¶
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Supprimé: , cf. Table 1) and were included in PMIP3-CMIP ... [5]

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2.1 PMIP4-CMIP6 entry cards: the mid-Holocene (*midHolocene*) and last glacial maximum (*lgm*)

The MH and LGM periods are strongly contrasting climate states. The MH provides an opportunity to examine the response to orbitally-induced changes in the seasonal and latitudinal distribution of insolation (Figure 1). It is a period of strongly enhanced northern hemisphere summer monsoons, extra-tropical continental aridity and much warmer summers. The LGM provides an opportunity to examine the impact of changes in ice sheets and continental extent (which increases due to the drop in sea level, Figure 2) and of the decrease in atmospheric greenhouse gases on climate. The LGM is particularly relevant because the forcing and temperature response from the LGM to present was as large as that projected from present to the end of the 21st century (Braconnot et al., 2012).

Evaluation of the PMIP3-CMIP5 MH and LGM experiments has demonstrated that climate models simulate changes in large-scale features of climate that are governed by the energy and water balance reasonably well (Harrison et al., 2014, 2015, Li et al., 2013), including changes in land-sea contrast and high-latitude amplification of temperature changes (Izumi et al., 2013; Izumi et al., 2015). These results confirm that the simulated relationships between large-scale patterns of temperature and precipitation change in future projections are credible. However, the PMIP3-CMIP5 simulations of MH and LGM climates show only moderate skill in predicting reconstructed patterns of climate change overall (Hargreaves et al., 2013; Hargreaves and Annan, 2014; Harrison et al., 2014; Harrison et al., 2015). This arises because of persistent problems in simulating regional climates. For example, state-of-the-art models cannot fully properly reproduce the northward penetration of the African monsoon in response to the MH orbital forcing (Perez-Sanz et al., 2014; Pausata et al., 2016), which was already noted in PMIP1 (Joussaume et al, 1999). While this likely reflects inadequate representation of feedbacks, model biases could also contribute to this mismatch (e.g. Zheng and Braconnot, 2013). Systematic benchmarking of the PMIP3-CMIP5 MH and LGM also show that better performance in paleoclimate simulations is not consistently related to better performance under modern conditions, stressing that the ability to simulate modern climate regimes and processes does not guarantee that a model will be good at simulating climate changes (Harrison et al., 2015).

For PMIP4-CMIP6, we have modified the experimental design of the *midHolocene* and *lgm* experiments with the aim of obtaining more realistic representations of these climates (Table 2, Otto-Bliesner et al., 2017 for *midHolocene* and Kageyama et al., 2017 for *lgm*). One of these modifications is the inclusion of changes in atmospheric dust loading (Figure 3), which can have a large effect on regional climate changes. For

Déplacé vers le haut [4]: All the experiments can be run independently and have value for comparison to the CMIP6 DECK (Diagnostic, Evaluation and Characterization of Klima) and historical experiments (Eyring et al., 2016). They are therefore all considered as Tier 1 within CMIP6

Supprimé: (Table **1**).

Déplacé vers le haut [5]: It is not mandatory for groups wishing to take part in PMIP4-CMIP6 to run all five PMIP4-CMIP6 experiments. It is however mandatory to run at least one of the two entry cards, i.e. the *midHolocene* or the *lgm*.¶

Supprimé: applied (e.g. in the continental reconstructions, ice sheet height and extent, vegetation cover), and in the transient forcings (for instance in the last millennium simulations for solar, volcanic ... [7]

Supprimé: Figure 1: Context of the PMIP4 experiments (fro ... [8]

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Supprimé: (Harrison et al., 2015).

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Déplacé vers le haut [8]: While this likely reflects inadequate

Supprimé: (Harrison et al., 2015). Hence

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Déplacé (insertion) [9]

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Supprimé: Dust has now been implemented in many CMI ... [13]

midHolocene, realistic values of the concentration of atmospheric CO_2 and other trace gases will be also used (Otto-Bliesner et al. 2017). This makes this experiment more realistic than in PMIP3 where it was designed as a simple test to changes in insolation forcing. The PMIP3-CMIP5 *lgm* experiments considered a single ice sheet reconstruction (Abe-Ouchi et al., 2015). However, there is uncertainty about the geometry of the ice sheets at the Last Glacial Maximum. The protocol for the PMIP4-CMIP6 *lgm* simulations accounts for this uncertainty and includes a choice between the old PMIP3 ice sheet (Abe-Ouchi et al., 2015) or one of two new reconstructions: ICE-6G_C (Argus et al., 2014; Peltier et al., 2015) and GLAC-1D (Tarasov et al., 2012; Briggs et al., 2014, Ivanovic et al., 2016). Altogether, the *lgm* experiments will allow testing the impact of these different ice sheet reconstructions (Figure 2) and of the dust forcing, which was not included in the PMIP3 set-up.

2.2 The last millennium (*past1000*)

The millennium prior to the industrial era, 850-1849 CE, provides a well-documented (e.g. PAGES2k-PMIP3 group, 2015) period of multi-decadal to multi-centennial changes in climate, with contrasting periods such as the Medieval Climate Anomaly and the Little Ice Age. This interval was characterised by variations in solar, volcanic and orbital forcings (Figure 1), which acted under climatic background conditions similar to today. This interval provides a context for analysing earlier anthropogenic impacts (e.g. land-use changes) and the current warming due to increased atmospheric greenhouse gas concentrations. It also helps constrain the uncertainty in the future climate response to a sustained anthropogenic forcing.

The PMIP3-CMIP5 *past1000* simulations show relatively good agreement with regional climate reconstructions for the northern hemisphere, but less agreement for southern hemisphere. They also provided an assessment of climate variability on decadal and longer scales and information on predictability under forced and unforced conditions experiments (Fernández-Donado et al., 2013). Single-model ensembles have provided improved understanding of the importance of internal versus forced variability and of the individual forcings when compared to reconstructions at both global and regional scales (Man et al., 2012; Phipps et al., 2013; Schurer et al., 2014; Man et al., 2014; Man and Zhou, 2014; Otto-Bliesner et al., 2016). Other studies focused on the temperature difference between the warmest and coldest centennial or multi-centennial periods and their relation to changes in external forcing, in particular variations in solar irradiance (e.g. Hind and Moberg, 2013).

The PMIP4-CMIP6 *past1000* simulation (Jungclaus et al, 2017) builds on the DECK experiments, in particular the pre-industrial control (*piControl*) simulation as an unforced reference, and the *historical* simulations (Eyring

Supprimé: CO_2 concentration was prescribed to be the same as in the pre-industrial control simulation, because the focus was on testing the impact of the insolation forcing on meridional climate gradients and seasonality. Realistic

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Déplacé vers le haut [10]: experiments considered a single ice sheet reconstruction (Abe-Ouchi et al., 2015). However, there is uncertainty about the geometry of the ice sheets at the Last Glacial Maximum.

Supprimé: used in PMIP4-CMIP6 (Table 2). This will allow the *midHolocene* experiment to be used as the initial state for transient simulations of the late Holocene planned as part of PMIP4, and ensure consistency of forcing between the *midHolocene* PMIP4-CMIP6 snapshot experiment and the transient simulations (Otto-Bliesner et al., 2017). ¶
¶
The PMIP3-CMIP5 LGM

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Déplacé vers le haut [11]: : ICE-6G_C (Argus et al., 2014; Peltier et al., 2015) and GLAC-1D (Tarasov et al., 2012; Briggs et al.,

Supprimé: 2015) or one of two new 21ky BP reconstructions based on somewhat different approaches

Supprimé: 2014, Ivanovic et al., 2016). Groups wishing to use the *lgm* equilibrium experiment to initialise PMIP4 transient simulations of the last deglaciation (Ivanovic et al., 2016) must use either ICE-6G_C or GLAC-1D because these are consistent with the ice sheet and meltwater forcings provided for the PMIP4 transient experiments. The impact of these different ice-sheet forcings will be a focus for sensitivity experiments in PMIP4 (Kageyama et a ... [14]

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et al., 2016). The *past1000* simulations provide initial conditions for *historical* simulations that can be considered superior to the *piControl* state, as they integrate information from the forcing history (e.g. large volcanic eruptions in the early 19th century). It is therefore mandatory to continue the *past1000* simulations into the historical period. The PMIP4-CMIP6 *past1000* protocol will use a new, more comprehensive reconstruction of volcanic forcing (Sigl et al., 2015) and ensures a more continuous transition from the pre-industrial past to the future. The final choices resulted from strong interactions with the groups producing the different forcing fields for the historical simulations (Jungclaus et al, 2017).

2.3 The Last Interglacial (*lig127k*)

The Last Interglacial (ca 130-115 kyr BP) was characterised by a northern hemisphere insolation seasonal cycle even larger than for the mid-Holocene (Otto-Bliesner et al., 2017). This resulted in a strong amplification of high-latitude temperatures and reduced Arctic sea ice. Global sea level was at least 5 m higher than now for at least several thousand years (e.g. Dutton et al., 2015). Both the Greenland and Antarctic ice sheets contributed to this sea level rise, making it an important period for testing our knowledge of climate-ice sheet interactions in warm climates. The availability of quantitative climate reconstructions for the Last Interglacial (e.g. Capron et al., 2014) makes it feasible to evaluate these simulations and assess regional climate changes.

Climate model simulations of the Last Interglacial, reviewed in the IPCC AR5 (Masson-Delmotte et al., 2013), varied in their forcings and were not necessarily made with the same model as the CMIP5 future projections. There are large differences between simulated and reconstructed mean annual surface temperature anomalies compared to present, particularly for Greenland and the Southern Ocean, and in the temperature trends in transient experiments run for the whole interglacial (Bakker et al., 2013; Lunt et al., 2013). Part of this discrepancy stems from the fact that the climate reconstructions were of the local maximum interglacial warming, and this was not globally synchronous, an issue which is addressed in the PMIP4-CMIP6 protocol.

The PMIP4-CMIP6 *lig127k* experiment will help to determine the interplay of warmer atmospheric and oceanic temperatures, changed precipitation, and changed surface mass and energy balance on ice sheet thermodynamics and dynamics. The major changes in the experimental protocol for *lig127k*, compared to the pre-industrial DECK experiment, are changes in the astronomical parameters and greenhouse gas concentrations (Table 2 and Otto-Bliesner et al., 2017). Meaningful analyses of these simulations are now possible because of the concerted effort to synchronise the chronologies of individual records and thus provide a spatial-temporal picture of last

Déplacé vers le haut [14]: the individual forcings when compared to reconstructions at both global and regional scales (Man et al., 2012; Phipps et al., 2013; Schurer et al., 2014; Man et al., 2014; Man and Zhou, 2014; Otto-Bliesner et al.,

Supprimé: show relatively good agreement with regional climate reconstructions for the northern hemisphere, but less agreement with southern hemisphere records. The simulations exhibit more regional coherence than shown by southern hemisphere records, though it is not clear whether this is due to deficiencies in the southern hemisphere records, poor representation of internal variability and/or an overestimation of the forced response in the simulations (PAGES2k-PMIP3 group, 2015).

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¶
The PMIP4-CMIP6 *past1000* simulation (Jungclaus et al, 2017) builds on the DECK experiments, in particular the pre-industrial

Supprimé: Single-model ensembles have provided impro ... [16]

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Supprimé: Masson-Delmotte et al., 2013; Dutton et al.,

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interglacial temperature change (Capron et al., 2014, 2017), and also to document the timing of the contributions of Greenland and Antarctica to the global sea level (Winsor et al., 2012; Steig et al., 2015). Regional responses of tropical hydroclimate and of polar sea ice can be assessed and compared to the *mid-Holocene*. Outputs from the *lig127k* experiment will be used by ISMIP6 to force stand-alone ice sheet experiments (*lastIntergacialforcedism*) in order to quantify the potential sea level change associated with this climate.

2.4 The mid-Pliocene Warm Period (*midPliocene-eoi400*)

The *midPliocene-eoi400* experiment focuses on the last time in Earth history when atmospheric CO_2 concentrations approached current values (~400 ppmv) with a continental configuration similar to today (Table 2, Figure 1, Figure 2). Vegetation reconstructions (Salzmann et al., 2008) indicate that the area of deserts was smaller than today and boreal forests were present in high northern latitude regions covered by tundra today. Climate model simulations from the PlioMIP project (concomitant with PMIP3) produce global mean surface air temperature anomalies ranging from +1.9 °C to +3.6 °C (relative to each model's pre-industrial control) and an enhanced hydrological cycle (Haywood et al., 2013) with strengthened monsoons (Zhang et al., 2013). These simulations also show that meridional temperature gradients were reduced (due to high latitude warming), which has significant implications for the stability of polar ice sheets and sea level in the future (e.g. Miller et al., 2012). Model–data comparisons provide high confidence that mean surface temperature was warmer than pre-industrial (Dowsett et al., 2012; Haywood et al., 2013; Masson-Delmotte et al., 2013). However, as is the case for the Last Interglacial, the PlioMIP simulations were not always derived from the same models as for the CMIP5 future projections.

The PMIP4-CMIP6 *midPliocene-eoi400* experiment (Haywood et al., 2016) is designed to understand the long-term response of the climate system to a near modern concentration of atmospheric CO_2 (long term climate sensitivity or Earth System Sensitivity). It will also be used to address the response of ocean circulation, Arctic sea-ice and modes of climate variability (e.g. El Niño Southern Oscillation), as well as the global response in the hydrological cycle and regional changes in monsoon systems. The simulation has the potential to be informative about required emission reduction scenarios designed to prevent an increase in global annual mean temperatures by more than 2 °C after 2100 CE. Boundary conditions (Table 2) include modifications to global ice distributions (Figure 2), topography/bathymetry, vegetation and CO_2 and are provided by the US Geological Survey Pliocene Research and Synoptic Mapping Project (PRISM4: Dowsett et al., 2016).

Supprimé: The *lig127k* experiment will also be the starting point for a transient experiment covering the interglacial to be run within PMIP4.

Supprimé: mPWP

Supprimé: a specific interglacial, dated ~3.2 Ma before present, during the wider mid-Pliocene Warm Period (mPWP, ca. 3.3 to 3 million years ago). This was

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Supprimé: **3. Experimental set up and model configuration ¶**
The forcings and boundary conditions for each PMIP4-CMIP6 paleoclimate simulation are summarised in Table 2. The complete justification of the experimental protocols and analysis plans are given in a series of companion papers: Otto-Bliesner et al.

2.5 Paleoclimatic and paleoenvironmental data for the PMIP4-CMIP6 periods

The choice of the time periods for the PMIP4-CMIP6 simulations has been made bearing in mind the availability of palaeoenvironmental and/or palaeoclimate reconstructions that can be used for model evaluation and diagnosis. Past environmental and climatic changes are typically documented at specific sites, whether on land, in ocean sediments or in corals, or from ice cores. The evaluation of climate simulations such as the PMIP4-CMIP6 ones requires these paleoclimatic and paleoenvironmental data to be synthesised for specific time periods. A major challenge in building such syntheses is to synchronise the chronologies of the different records. There are many syntheses of information on past climates and environments. Table 3 lists some of the sources of quantitative reconstructions for the PMIP4-CMIP6 time periods, but it is not our goal here to provide an extensive review of these resources. We expect new data sets to become available, which will increase the number of possible model-data comparisons for the PMIP4-CMIP6 periods.

Much of the information on paleoclimates stems from the impact of climatic changes on the environment, such as on fires, dust, marine microfauna and vegetation. Past climatic information is also contained in isotopic ratios of oxygen and carbon, which can be found in ice sheets, speleothems, or in the shells of marine organisms. Ocean circulation can be documented by geochemical tracers in marine sediments from the sea floor (e.g. $\Delta^{14}C$, $\delta^{13}C$, $^{231}Pa/^{230}Th$, ε_{Nd}). The fact that these physical, chemical or biological indicators are indirect records of the state of the climate system and can also be sensitive to other factors (such as atmospheric CO_2 concentrations for vegetation) has to be taken into account in model-data comparisons. Comparisons with climate model output can therefore be performed from different points of view: either the climate model output can be directly compared to reconstructions of past climate variables, or the response of the climatic indicator itself can be simulated from climate model output and compared to the climate indicator. Such "forward" models include dynamical vegetation models, tree ring models, or models computing the growth of foraminifera, for which specific output is needed (cf. section 4.3). Some paleoclimatic indicators such as meteoric water isotopes have to be computed as the climate model is running, but are also examples of this forward modelling approach. Modelling the impacts of past climate changes on the environment is key to understand how climatic signals are transmitted to past climate records. It also provides an opportunity to test the types of models that are used in the assessment of the impacts of future climate changes on the environment.

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Déplacé vers le bas [19]: The climate models taking part in
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Déplacé vers le bas [24]: Natural aerosols show large
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Supprimé: will be provided for the *midHolocene, lig127k* ... [25]
Déplacé vers le bas [25]: Dust anomalies/ratios compared to
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Déplacé vers le bas [28]: Additional dust-related fields (dust
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Déplacé vers le bas [29]: 2005), three dust maps are provided
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Supprimé: 2015, Figure 4) and modelling groups are free ... [28]
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Déplacé vers le bas [31]: Spin-up procedures will differ
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3. Analysing the PMIP4-CMIP6 runs

The community using PMIP simulations is very broad, from climate modellers and palaeoclimatologists to biologists studying recent changes in biodiversity and archaeologists studying potential impacts of past climate changes on human populations. Here, we highlight several topics of analyses that will benefit from the new experimental design and from using the full PMIP4-CMIP6 ensemble.

3.1. Comparisons with paleoclimate and paleoenvironemental reconstructions, benchmarking and beyond

Model-data comparisons for each period will be one of the first tasks conducted after completion of these simulations. One new feature common to all periods is that we will make full use of the fact that modelling groups must also run the *piControl* and *historical* experiments. Indeed, existing paleoclimate reconstructions have used different modern reference states, and this has been shown to have an impact on the magnitude of reconstructed changes (e.g. Hessler et al., 2014). Running both the *piControl* and *historical* simulations was not systematic in previous phases of PMIP, which prevented investigation of the impact of these reference states for model-data comparisons. The new set of simulations will provide a way of quantifying this source of reconstruction uncertainty, as will comparisons with present-day observations and reanalysis data sets (Obs4MIPS, Ferraro et al, 2015).

Comparisons of PMIP4-CMIP6 simulations with available paleoclimatic reconstructions is a unique contribution to CMIP6 in terms of evaluating model biases for climates different from the historical one. An ensemble of metrics has already been developed for the PMIP3-CMIP5 *midHolocene* and *lgm* simulations (e.g. Harrison et al. 2014). These, applied to the PMIP4-CMIP6 *midHolocene* and *lgm* “entry card” simulations, will provide a rigorous assessment of model improvements compared to previous phases of PMIP. Furthermore, for the first time, thanks to the design of the PMIP4-CMIP6 experiments, we will be able to take the impact of uncertainties in the forcings into account in the benchmarking. The benchmarking metrics will also be expanded to other periods and data sets so that systematic biases for different periods and for the present-day can be compared. Benchmarking the ensemble of the PMIP4-CMIP6 simulations, for all the periods, will therefore allow quantifying the climate-state dependence of the model biases, a topic which is highly relevant for a better assessment of potential biases in the projected climates in CMIP6.

Another promising activity will consist in analysing the potential relationships between model biases in different regions and/or in different variables (such as temperature vs. hydrological cycle) across the PMIP ensemble, as

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Table 4: examples of data syntheses for

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Supprimé: Reconstructing paleoclimates and paleoenvironments, as well as building new syntheses of these reconstructions, are very active areas of research.

Déplacé vers le haut [37]: We expect new data sets to become available, which will increase the number of possible model-data comparisons for the PMIP4-CMIP6 periods. ¶

Supprimé: **4.2. Role of forcings and feedbacks¶**

Déplacé vers le bas [38]: Quantifying the role of forcings and feedbacks in creating climates different from today has been a focus of PMIP for many years.

Déplacé vers le bas [39]: polar amplification, land-sea

Supprimé: All the PMIP4-CMIP6 experiments will be run ... [41]

Déplacé vers le bas [40]: Multi-period analyses provide a way

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Déplacé vers le bas [41]: One challenge will be to develop new

Déplacé vers le bas [42]: The PMIP4-CMIP6 ensemble will

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Déplacé vers le bas [43]: For the LGM, there is evidence of a

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Supprimé: Ice sheets represent strong changes in radiative ... [43]

Supprimé: Understanding this oceanic circulation as well ... [44]

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Mis en forme ... [49]

well as for the recent climate. One further objective for the PMIP4-CMIP6 benchmarking will be to develop more process-oriented metrics making use of the fact that paleoclimatic data document different aspects of climate change. There are many aspects of the climate system which are difficult to measure directly, and which are therefore difficult to evaluate using traditional methods. The "emergent constraint" (e.g. Sherwood et al., 2014) concept, which is based on identifying a relationship to a more easily measurable variable, has been successfully used by the carbon-cycle and modern climate communities and holds great potential for the analysis of paleoclimate simulations. This could be particularly valuable to examine the realism of e.g. cloud feedbacks in the simulations or the contribution of seasonal climate changes to hydrological budgets. Using multiple time periods to examine "emergent" constraints will ensure that they are robust across climate states.

3.2. Analysing the response of the climate system to multiple forcings

Multi-period analyses provide a way of determining whether systematic model biases affect the overall response and the strength of feedbacks independent of climate state. One challenge will be to develop new approaches to analyse the PMIP4-CMIP6 ensemble so as to separate the impacts of model resolution, content, or complexity on the simulated climate. Similarly the uncertainties in boundary conditions will be addressed for periods for which alternative forcing is proposed.

Quantifying the role of forcings and feedbacks in creating climates different from today has been a focus of PMIP for many years. Many CMIP6 models will include new processes, such as dust, or improved representations of major radiative feedback processes, such as clouds. This will allow a broader analysis of feedbacks than was possible in PMIP3-CMIP5. We will evaluate the impact of these new processes and improved realisations of key forcings on climates at global, large-scale (e.g. polar amplification, land-sea contrast) as well as regional scales, together with the mechanisms explaining these impacts. A particular emphasis will be put on the modulation of the climate response to a given forcing by the background climate state and how it affects changes in cloud feedbacks, snow and ice sheets (such as in e.g. Yoshimori et al., 2011), vegetation and ocean deep water formation. Identification of similarities between past climates and future climate projections such as the one found for land-sea contrast or polar amplification (Izumi et al., 2013; Masson-Delmotte et al., 2006; Izumi et al., 2015) or for snow and cloud feedbacks for particular seasons (Braconnot and Kageyama, 2015) will be used to provide better understanding of the relationship between patterns and time scales of external forcings and patterns and timing of the climate responses.

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Déplacé vers le bas [45]: These attempts also ignored uncertainties in forcings and boundary conditions. PMIP4-CMIP6 is expected to result in a much larger ensemble of *lgm* experiments. The issue of climate sensitivity (*sensu stricto*) and earth-system sensitivity (PALEOSENS Project Members, 2012) will also be examined through joint analysis of multiple paleoclimate simulations and climate reconstructions from different archives.

Supprimé: **4.4 Relating past and future**

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Attempts

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Supprimé: **Our analyses will capitalise on the DECK *piControl* and *abrupt4xCO2* experiments, as well as on the CFMIP experiments *AMIP4K* and *AMIPminus4K*.**

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The relationship between radiative forcing and global temperature is not straightforward (Crucifix, 2006; Yoshimori et al., 2011), partly because the nature of the forcing that drives the Earth into different climate states preferentially triggers short wave or long wave radiative responses, that have different impacts on the energy or water exchanges, on the feedbacks between different climate system components, or have different large- or regional- scale patterns.

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These analyses should provide new clues to constraint climate sensitivity. Previous attempts using information about the LGM period have been hampered by the fact that there were too few *lgm* experiments to draw statistically-robust conclusions (Crucifix et al., 2008; Hargreaves et al., 2012; Harrison et al., 2014; Hopcroft and Valdes, 2015b). These attempts also ignored uncertainties in forcings and boundary conditions. PMIP4-CMIP6 is expected to result in a much larger ensemble of *lgm* experiments. The issue of climate sensitivity (*sensu stricto*) and earth-system sensitivity (PALEOSENS Project Members, 2012) will also be examined through joint analysis of multiple paleoclimate simulations and climate reconstructions from different archives.

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The PMIP4-CMIP6 ensemble will allow new analyses of the impact of smaller (mPWP) or larger (LGM) ice sheets. The ocean and sea-ice feedbacks will also be analysed. The representation of sea ice and Southern Ocean proved to be problematic in previous simulations of colder (LGM, Roche et al., 2012) and warmer climates (LIG, Bakker et al., 2013, Lunt et al., 2013) and we are eager to analyze improved models for this area which is key for atmosphere-ocean carbon exchanges. For the LGM, there is evidence of a shallower, and yet active overturning circulation in the North Atlantic (e.g. Lynch-Stieglitz et al., 2007, Böhm et al., 2015). Understanding this oceanic circulation for the LGM and the other PMIP4 periods, as well as its links to surface climate is a topic of high importance since the Atlantic Meridional Overturning Circulation could modulate future climate changes at least in regions around the North Atlantic. The PMIP4 multi-period ensemble, for which we require improved simulations in terms of spin-up, will strengthen the analyses for this particular topic compared to previous phases of PMIP (Marzocchi et al., 2017).

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Multi-period analyses will also be useful for understanding the relationship between mean climate state and modes of natural variability (e.g. Liu et al., 2014; Saint-Lu et al., 2015). Analyses of multiple long simulations with different forcings should provide a better understanding of changes in ENSO behaviour (Zheng et al., 2008; An et al., 2014) and help determine whether state-of-the-art climate models underestimate low frequency noise (Laepple and Huybers, 2014). Analyses will focus on how models reproduce the relationship between changes in seasonality and interannual variability (Emile-Geay et al., 2016), the diversity of El-Niño events (Capotondi et al., 2015; Karamperidou et al., 2015; Luan et al., 2015), and the stability of teleconnections within the climate system (e.g. Gallant et al., 2013; Batehup et al., 2015).

Supprimé: Future changes in modes of climate variability, such as El Niño Southern Oscillation (ENSO), are poorly constrained (Christiansen et al., 2013) because model projections are insufficiently long to provide robust statistics for low frequency (multi-decadal and centennial) variations. Robust statistics of ENSO changes have been derived through analysis of high-resolution paleo-records (Emile-Geay et al., 2016). The equilibrium paleoclimate experiments in PMIP4-CMIP6 will provide an opportunity to sample simulations for long enough to obtain robust estimates of ENSO changes (Stevenson et al., 2010) and analyses

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Supprimé: The PMIP Paleovariability Working Group will develop diagnostics for climate variability (Philips et al., 2014) to be applied to all the PMIP4-CMIP6 simulations.

3.3 Interactions with other CMIP6 MIPs and the WCRP Grand Challenges

PMIP has already developed strong links with several other CMIP6 MIPs (Table 4). CFMIP includes an idealized experiments which allow investigations of cloud feedbacks and associated circulation changes in a colder versus a warmer world and this will assist in disentangling the processes at work in the PMIP4 simulations. We have also required CFMIP specific output to be implemented in the PMIP4-CMIP6 simulations so that the same analyses can be carried out for both the PMIP4 and CFMIP simulations and the results in terms of cloud feedbacks in different past and future climates directly compared.

Interactions between PMIP and other CMIP6 MIPs have mutual benefits: PMIP provides simulations of large climate changes that have occurred in the past and evaluation tools which capitalise on extensive data syntheses, while other MIPs will employ diagnostics and analyses which will be useful for analyzing the PMIP4 experiments. We are eager to settle collaborations with the CMIP6 MIPs listed in Table 4 and have ensured that all the outputs necessary for the application of common diagnostics between PMIP and these MIPs will be available (see section 4.3). Links with CFMIP and ISMIP6 mean that PMIP will contribute to the World Climate Research Programme (WCRP) Grand Challenges "Clouds, Circulation and Climate Sensitivity" and "Cryosphere and Sea Level" respectively. PMIP will provide input to the WCRP Grand Challenge on "Regional Climate Information", through a focus on evaluating the mechanisms of regional climate change in the past.

4. Model configuration, experimental set up, documentation and required output.

To achieve the PMIP4 goals and benefit from other simulations in CMIP6, particular care must be put on model versions and the implementation of the experimental protocols. Here we summarize the guidelines that are common to all the experiments, focusing on the requirements to ensure strict consistency between CMIP6 and PMIP4 experiments. These concern model complexity, forcings, and mineral dust, which is a new feature in the PMIP4 experiments. This section also provides guidelines for the documentation and required output. The reader is referred to the PMIP4 companion papers on the specific periods for details in the set-up of each PMIP4-CMIP6 experiment.

4.1 Model version, set-up and common design of all PMIP4-CMIP6 experiments

The climate models taking part in CMIP6 are very diverse: some represent solely the physics of the climate system, some include the carbon cycle and other biogeochemical cycles, and some include interactive natural

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For shorter time scales, the *past1000* simulations and corresponding high temporal resolution data are one of the only means to examine the mechanisms and realism of the relationships between events at the daily scale (e.g. weather extremes) and longer-term climatic changes.¶
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Supprimé: Table 5). CFMIP includes an idealized experiment mimicking the *lgm* simulation: *AMIPminus4K* is an atmosphere-only experiment in which the sea-surface temperatures are uniformly lowered by 4K (a mirror of the *AMIP4K* experiment in which sea-surface temperatures are increased by 4K). These experiments

Supprimé: *lgm* climate. Some MIPs have designed experiments based on PMIP data, including VolMIP for the study of the impact of large past volcanic eruptions and ISMIP6 for the impact of the last interglacial climate on the Greenland ice sheet. Links with CFMIP and ISMIP6 mean that PMIP will also contribute to the World Climate Research Programme (WCRP) Grand Challenges "Clouds, Circulation and Climate Sensitivity" and "Cryosphere and Sea Level" respectively. Furthermore, PMIP will provide input to the WCRP Grand Challenge on "Regional Climate Information", through a focus on evaluating the mechanisms of regional climate change in the past, for example in the Arctic.

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Supprimé: This is the case for AerChemMIP (Collins et al., 2017) for the aerosol forcings, SIMIP (Notz et al., 2016) and OMIP (Griffies et al., 2016) for the sea-ice and ocean components, LS3MIP (van den Hurk et al., 2016) for the land surface, C4MIP (Jones et al., 2016) for the carbon cycle, ISMIP (Nowicki et al., 2016) for ice sheets, and CFMIP (Webb et al., 2017) for the cloud forcing and feedback analyses. The analytical tools developed in RFMIP (Pincus et al., 2016) will be useful for assessing the LGM GHG radiative forcing and those developed in VolMIP (Zanchettin et al., 2016) and LUMIP (Lawrence et al., 2016) will be relevant for the analyses of the impacts of volcanic and land use forcings in the *past1000* simulation. The *past1000* experiment also offers a long time series perturbed by natural forcings and reconstructed land use changes for detection and attribution exercises and it is therefore relevant for DAMIP (Gillett et al., 2016). We have ensured that all the outputs necessary for the application of common diagnostics across PMIP and other CMIP6 MIPs will be available (see section 4.7).

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vegetation and/or interactive dust cycle/aerosols. It is mandatory that the model version used for the PMIP4-CMIP6 experiments is exactly the same as for the other CMIP6 experiments, in particular the DECK and *historical* simulations. The experimental set-up for each simulation is based on the DECK pre-industrial control (*piControl*) experiment (Eyring et al., 2015), i.e. the *piControl* forcings and boundary conditions are modified to obtain the forcings and boundary conditions necessary for each PMIP4-CMIP6 paleoclimate experiment (Table 2). No additional interactive component should be included in the model unless it is already included in the DECK version. Such changes would affect the global energetics (Braconnot and Kageyama, 2015) and therefore prevent rigorous analyses integrating across multiple time periods or between MIPs (section 3).

Because of this, even though environmental records show that natural vegetation patterns during each of the PMIP4-CMIP6 period were different from today, the PMIP4-CMIP6 paleoclimate simulations should use similar model configuration as the DECK and historical simulations. If the DECK and historical simulations use dynamic vegetation, then the PMIP4-CMIP6 paleoclimate simulations should also. If the DECK and historical simulations use prescribed vegetation, then the same vegetation should be prescribed in the PMIP4-CMIP6 paleoclimate simulations. One exception to this is the *midPliocene-eoi400* experiment, where models which prescribe vegetation in the DECK and historical simulations should prescribe the mid-Pliocene vegetation (Haywood et al., 2016). The other exception is for models including interactive dust cycle for the LGM, which should impose vegetation which allows dust emissions over LGM dust emission regions.

Two experiments, *lgm* and *midPliocene-eoi400* require modifying ice sheets (Figure 2), which also implies modifying the coastlines, the ocean bathymetry (if feasible for *midPliocene-eoi400*), the topography and land surface types over the continents and to ensure rivers reach the ocean in order to close the global fresh water budget. The ocean initial salinity should be adjusted for these ice volume changes and modelling groups should ensure that the total mass of the atmosphere remains the same in all experiments.

For each experiment, the greenhouse gases and astronomical parameters should be modified from the DECK *piControl* experiment (Table 2). Spin-up procedures will differ according to the model and type of simulation, but the spin up should be long enough to avoid significant drift in the analysed data. Initial conditions for the spin-up can be taken from an existing simulation. The model should be run until the absolute value of the trend in global mean sea-surface temperature is less than 0.05 K per century and the Atlantic Meridional Overturning

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Circulation (AMOC) is stable. A parallel requirement for carbon-cycle models and/or models with dynamic vegetation is that the 100-year average global carbon uptake or release by the biosphere is <0.01 Pg C per year.

4.2 A new feature of the PMIP simulations: mineral dust

Natural aerosols show large variations on glacial-interglacial time scales, with glacial climates having higher dust loadings than interglacial climates (Kohfeld and Harrison, 2001; Maher et al., 2010). Dust emissions from northern Africa were significantly reduced during the MH (McGee et al., 2013). As is the case with vegetation, the treatment of dust in the *midHolocene, lig127k* and *lgm* simulations should parallel the treatment in the *piControl*. However, some of the models in CMIP6 include representations of interactive dust. For those models, maps of soil erodibility that account for changes in the extension of possible dust sources are provided for the *midHolocene, lig127k* and *lgm* experiments. Dust anomalies/ratios compared to the pre-industrial background should be used, for consistency with the DECK *piControl* simulation. As there have been instances of runaway climate-vegetation-dust feedback, leading to unrealistically cold LGM climates (Hopcroft and Valdes, 2015a), it is advisable to test the atmosphere model behaviour before running the fully coupled *lgm* simulation.

To allow experiments with prescribed dust changes, three-dimensional monthly climatologies of dust atmospheric mass concentrations are provided for the *piControl*, *midHolocene*, and *lgm*. These are based on two different models (Albani et al., 2014, 2015, 2016; Hopcroft et al., 2015, Figure 3) and modelling groups are free to choose between these data sets. Additional dust-related fields (dust emission flux, dust load, dust aerosol optical thickness, short- and long-wave, surface and top of the atmosphere dust radiative forcing) are also available from these simulations. Implementation should follow the same procedure as for the *historical* run. The implementation for *lig127k* experiment should use the same data set as for the *midHolocene* one. Since dust plays an important role in ocean biogeochemistry (e.g. Kohfeld et al, 2005), three dust maps are provided for the *lgm* run. Two of these are consistent with the climatologies of dust atmospheric mass concentrations; the other is primarily derived from paleoenvironmental observations (Lambert et al., 2015, Figure 3). The modelling groups should use consistent data sets for the atmosphere and the ocean biogeochemistry. The Lambert et al. (2015) data set can therefore be used for models which cannot include the changes in atmospheric dust according to the other two data sets.

4.3 Documentation and required model output for the PMIP4-CMIP6 database

Detailed documentation of the PMIP4-CMIP6 simulations is required. This should include:

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Table 5: interactions of PMIP with other CMIP6 MIPs¶
4.7 Implications:

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- a description of the model and its components;
- information about the boundary conditions used, particularly when alternatives are allowed;
- information on the implementation of boundary conditions and forcings. Figures showing the land-sea mask, land-ice mask, and topography as implemented in a given model are useful for the *lgm* and *midPliocene-eoi400* experiments, while figures showing insolation are particularly important for the *midHolocene* and *lig127k* experiments. Check lists for the implementation of simulations are provided in the PMIP4 papers which give detailed information for each experiment;
- information about the initial conditions and spin-up technique used. A measure of the changes in key variables (Table 5) should be provided in order to assess remaining drift.

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Documentation should be provided via the ESDOC website and tools provided by CMIP6 (http://es-doc.org/) to facilitate communication with other CMIP6 MIPs. This documentation should also be provided for the PMIP4 website to facilitate linkages with non-CMIP6 simulations to be carried out in PMIP4. The PMIP4 special issue, shared between *Geoscientific Model Development* and *Climate of the Past*, provides a further opportunity for modelling groups to document specific aspects of their simulations. We also require the groups to document the spin-up phase of the simulations by saving a limited set of variables during this phase (Table 5).

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The data stored in the CMIP6 database should be representative of the equilibrium climates of the MH, LGM, LIG and mPWP periods, and of the transient evolution of climate between 850-1849 CE for the *past1000* simulations. A minimum of 100 years output is required for the equilibrium simulations but, given the increasing interest in analysing multi-decadal variability (e.g. Wittenberg, 2009), modelling groups are encouraged to provide outputs for 500 years or more if possible. Daily values should also be provided and will allow to account for the calendar issue (see Appendix). The list of variables required to analyse the PMIP4-CMIP6 paleoclimate experiments (https://wiki.lsce.ipsl.fr/pmip3/doku.php/pmip3:wg:db:cmip6request) reflects plans for multi-time period analyses and for interactions with other CMIP6 MIPs. We have included relevant variables from the data requests of other MIPs, including the CFMIP-specific diagnostics on cloud forcing, as well as land surface, snow, ocean, sea ice, aerosol, carbon cycle and ice sheet variables from LS3MIP, OMIP, SIMIP, AerChemMIP, C4MIP, and ISMIP6 respectively. Some of these variables are also required to diagnose how climate signals are recorded by paleoclimatic sensors via models of e.g. tree growth (Li et al., 2014), vegetation dynamics (Prentice et al., 2011) or marine planktonic foraminifera (e.g. Lombard et al., 2011; Kageyama et al., 2013). The only set of variables defined specifically for PMIP are those describing oxygen isotopes in the climate system. Isotopes are widely used for paleoclimatic reconstruction and are explicitly simulated in several models. We have asked that average annual cycles of key variables are included in the PMIP4-CMIP6 data request for equilibrium simulations, as these proved exceptionally useful for analyses in PMIP3-CMIP5.

5. Conclusions

The PMIP4-CMIP6 simulations provide a framework to compare current and future anthropogenic climate change with past natural variations of the Earth's climate. PMIP4-CMIP6 is a unique opportunity to simulate past climates with exactly the same models as used for simulations of the future. This approach is only valid if the model versions and implementation of boundary conditions are consistent for all periods, and if these boundary conditions are seamless for overlapping periods.

PMIP4-CMIP6 simulations are important in terms of model evaluation for climate states significantly different from the present and historical climates. We have chosen climatic periods well documented by paleoclimatic and paleoenvironmental records, with climate and environmental changes relevant for the study and projections of future climate changes: the millennium prior to the industrial epoch (*past1000*), 6,000 years ago (*midHolocene*), the last glacial maximum (*lgm*), the last interglacial (*lig127k*) and the mid-Pliocene (*midPliocene-eoi400*). .

The PMIP4-CMIP6 experiments will also constitute reference simulations for projects developed in the broader PMIP4. The corresponding sensitivity experiments, or additional experiments, are embedded in the PMIP4 project and are described in the companion papers to this overview (Haywood et al., 2016, Otto-Bliesner et al., 2017, Jungclaus et al., 2017, Kageyama et al., 2017). They are essential for a deeper understanding of the drivers of past climate changes for the PMIP4-CMIP6 climates or as initial conditions for transient simulations (e.g. Ivanovic et al., 2016, for the last deglaciation, Otto-Bliesner et al., 2017 for the last interglacial and the Holocene), or for examining time periods from deeper with high atmospheric CO_2 concentrations (Lunt et al, 2017). Figure 4 summarises the position of the PMIP4-CMIP6 experiments with respect to the other PMIP4 experiments and projects on the right-hand-side. The left-hand-side shows how the PMIP4-CMIP6 experiments relate to the CMIP6 DECK and some other CMIP6 MIPs. PMIP4-CMIP6 experiments have been designed to be analyzed by both communities.

Déplacé vers le bas [46]: Variations in the shape of the Earth's orbit govern the latitudinal and seasonal distribution of insolation, and also produce variations in the lengths of individual "months" (where months are defined alternatively as either (a) the duration in days for the Earth to complete one-twelfth of its orbit (the "celestial" or "angular" calendar), or (b) a specific number of days, e.g. 31 days in January, 30 days in June (the "conventional" or "modern" calendar). For example, at 6 ka, perihelion occurs in August, aphelion in February and those months were approximately 1.5 days shorter and longer than at present, respectively (

Déplacé vers le bas [47]:). Variations in the lengths of months (or seasons) must therefore be taken into consideration when examining experiment minus control long-term mean differences, because the effect of the changing calendar on the calculation of long-term means can be as large as the potential differences among the means themselves (Joussaume and Braconnot, 1997; Pollard and Reusch, 2002; Timm et al., 2008; Chen et al., 2011).

Déplacé vers le bas [48]: shows the difference between present-day long-term means for October temperature and precipitation, and those calculated using the appropriate celestial month lengths for 6 and 127 ka. Modifications to month length have not usually been taken into account in the model output post-treatment procedures (but see Harrison et al., 2014).

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Déplacé vers le bas [49]: Daily or 6-hourly values are also useful for running regional models. It is important to test the use of regional models for climate model projections at the regional scale. Regional models are also used to produce fine-scale palaeoclimate scenarios for use by the impact community, for example to study past climate impacts on biodiversity via ecological niche modelling. Paleoclimate indicators often respond to climate features not adequately captured with monthly data alone (such as growing season length). Daily weather variables are therefore required for some forward models, as well as to compute bioclimatic variables which are reconstructed e.g. based on pollen data (e.g. Bartlein et al., 2011).¶

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The PMIP community anticipates major benefits from analysis techniques developed by the other CMIP6 MIPs, in particular in terms of learning about the processes of past climate changes in response to forcings (e.g. greenhouse gases, astronomical parameters, ice sheet and sea level changes) as well as the role of feedbacks (e.g. clouds, ocean, sea-ice). PMIP4-CMIP6 has the potential to be mutually beneficial for the paleoclimate and present/future climate scientists to learn about natural large climate changes and the mechanisms at work in the climate system for climates states as different from today as future climate is projected to be.

Supprimé: Figure 5: the PMIP4-CMIP6 experiments in the framework of CMIP6, with associated MIPs, and in the framework of PMIP4, with its working groups.¶
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Data availability

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All data mentioned in the present manuscript can be downloaded following the instructions given in the companion papers giving details on the PMIP4-CMIP6 experimental protocols (Otto-Bliesner et al., 2017, Jungclaus et al., 2017, Kageyama et al., 2017, Haywood et al., 2016).

Acknowledgements

MK and QZ acknowledge funding from the French-Swedish project GIWA. PB, JJ and SPH acknowledge funding from the JPI-Belmont project “PAleao-Constraints on Monsoon Evolution and Dynamics (PACMEDY)” through their respective national funding agencies. SPH also acknowledges funding from the Australian Research Council (DP1201100343) and from the European Research Council for “GC2.0: Unlocking the past for a clearer future”. AMH and AMD acknowledge funding from the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007–2013)/ERC grant agreement no. 278636 and the EPSRC-supported Past Earth Network. RFI is funded by a NERC Independent Research Fellowship [#NE/K008536/1]. SJP’s contribution is supported under the Australian Research Council's Special Research Initiative for the Antarctic Gateway Partnership (Project ID SR140300001). FL acknowledges support from CONICYT projects 15110009, 1151427, ACT1410, and NC120066.

Appendix: justification of the requirement of high frequency output (daily and 6-hourly).

Variations in the shape of the Earth's orbit govern the latitudinal and seasonal distribution of insolation, and also produce variations in the lengths of individual "months" (where months are defined alternatively as either (a) the duration in days for the Earth to complete one-twelfth of its orbit (the "celestial" or "angular" calendar), or (b) a specific number of days, e.g. 31 days in January, 30 days in June (the "conventional" or "modern" calendar). For example, at 6 ka, perihelion occurs in August, aphelion in February and those months were approximately 1.5 days shorter and longer than at present, respectively (Appendix Figure 1). Variations in the lengths of months (or seasons) must therefore be taken into consideration when examining experiment minus control long-term mean differences, because the effect of the changing calendar on the calculation of long-term means can be as large as the potential differences among the means themselves (Joussaume and Braconnot, 1997; Pollard and Reusch, 2002; Timm et al., 2008; Chen et al., 2011). The size of the potential calendar effect or bias is illustrated in Appendix Figure 1, and is even larger for *lig127k*, for which eccentricity is large. This Figure shows the difference between present-day long-term means for October temperature and precipitation, and those calculated using the appropriate celestial month lengths for 6 and 127 ka. Modifications to month length have not usually been taken into account in the model output post-treatment procedures (but see Harrison et al., 2014). An approach to deal with the calendar issue is to use a bias-correction approach, in particular, like that of Pollard and Reusch (2002), with the mean-preserving daily interpolation approach of Epstein (1991). For the PMIP4-CMIP6 simulations we strongly recommend to provide daily data for the calculation of monthly or seasonal means, and so we include those in the PMIP4-CMIP6 data request for some key variables.

Daily or 6-hourly values are also useful for running regional models. It is important to test the use of regional models for climate model projections at the regional scale. Regional models are also used to produce fine-scale palaeoclimate scenarios for use by the impact community, for example to study past climate impacts on biodiversity via ecological niche modelling. Paleoclimate indicators often respond to climate features not adequately captured with monthly data alone (such as growing season length). Daily weather variables are therefore required for some forward models, as well as to compute bioclimatic variables which are reconstructed e.g. based on pollen data (e.g. Bartlein et al., 2011).

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have been major foci throughout PMIP's history: the mid-Holocene and the Last Glacial Maximum (Table 1). These two periods represent reference points

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assessing the sensitivity of the climate system to changes in atmospheric CO_2 concentration and orbitally-induced changes in tropical circulation and the monsoons (Braconnot et al., 2012; Harrison et al., 2015). They are considered as entry cards in the PMIP4-CMIP6 set of experiments, so that a sufficient number of simulations are available to be able to trace

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transient simulations of the millennium prior to the industrial epoch (Schmidt et al., 2011, 2012, Junglaus et al., 2017) allow the study of the mechanisms of decadal to centennial climate variability (natural variability vs. impact of solar, volcanic and anthropogenic

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, cf. Table 1) and were included in PMIP3-CMIP5. In addition, a number of other time periods were included in PMIP3, in particular the mid-Pliocene Warm Period (mPWP, cf. the PlioMIP project, Haywood et al., 2010, 2011), and the last interglacial period (130,000 to 115,000 years before present, Lunt et al., 2013). The latter simulations were used to examine whether climate models could produce a rate of ice-sheet melting in agreement with a global sea level at least 5m higher than now (Masson-Delmotte et al., 2013;

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2015). Discussions on transient simulations of climate behaviour, focusing on the last interglacial period and the last deglaciation (Ivanovic et al., 2016) were also initiated, as were simulations of climates of deeper times, in particular the early Eocene, ~50 million years ago (Lunt et al, 2012; Lunt et al, 2017). Questions on climate sensitivity and polar amplification and on the relationships between climate-ice-sheet system and sea level led us to propose, for PMIP4-CMIP6, two additional periods for which there is good data coverage, the possibility to design simple, but realistic, simulations, and large working groups interested in the analyses and the collaboration with other MIP participating in CMIP6. These additional periods are the last interglacial, 127 000 years ago and the mid Pliocene Warm Period (Table 1).

The true power of PMIP is the connection to the environmental observations and climate reconstructions. Uncertainties in the paleoenvironmental observations, or perhaps more broadly in the climate inferences made from those observations, are a key part of PMIP analyses, as is the structural uncertainty across the model responses. Both of these factors have been part of the PMIP approach from the beginning. Improved reconstructions, increased complexity and realism of climate simulations require putting more emphasis on the understanding of impacts of the uncertainties on the drivers themselves. For each of the selected periods, this encompasses time-uncertainty in the reconstructions (e.g. are all data synchronous? what date should be used to compute the astronomical parameters to compare with available data?) as well as structural uncertainty in the

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applied (e.g. in the continental reconstructions, ice sheet height and extent, vegetation cover), and in the transient forcings (for instance in the last millennium simulations for solar, volcanic aerosol or land use/land cover change). Differences between plausible reconstructions of boundary conditions and forcings can impact the assessment of model skill. In these cases, we have included alternative forcings and boundary conditions for the PMIP4-CMIP6 experiment or to be used in PMIP4 sensitivity experiments (Jungclaus et al., 2017; Otto-Bliesner et al., 2017; Kageyama et al., 2017; Haywood et al., 2016).

More background is provided for each of the PMIP4-CMIP periods in next sections.

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Figure 1: Context of the PMIP4 experiments (from left to right: mPWP, mid-Pliocene Warm Period; LIG, last interglacial; LGM, last glacial maximum; MH, mid-Holocene; LM, last millennium; H, CMIP6 historical simulation): (a)-(d) insolation anomalies (differences from 1950 CE), for July at 65°N, calculated using the programs of Laskar et al. (2004, panel (a)) and Berger (1978, panels (b)-(d)); (e) $\delta^{18}O$ (magenta, Lisiecki and Raymo, 2005, scale at left), and sea level (blue line, Rohling et al., 2014; blue shading, a density plot of eleven mid-Pliocene sea level estimates (Dowsett and Cronin 1990; Wardlaw and Quinn, 1991; Krantz, 1991; Raymo et al., 2009; Dwyer and Chandler, 2009; Naish and Wilson, 2009; Masson-Delmotte et al., 2013; Rohling et al., 2014; Dowsett et al., 2016) scale at right); (f) and (g) $\delta^{18}O$ (magenta, Lisiecki and Raymo, 2005, $\delta^{18}O$ scale at left), and sea level (blue dots, with light-blue 2.5, 25, 75 and 97.5 percentile bootstrap confidence intervals, Spratt and Lisiecki, 2015; blue rectangle, LIG high-stand range, Dutton et al., 2015; dark blue lines, Lambeck et al., 2014, sea-level scale at right on panel (g)), (h) sea level (Kopp, et al., 2016, scale at right); (i) CO_2 for the interval 3.0-3.3 Ma shown as a density plot of eight mid-Pliocene estimates (Raymo et al., 1996; Stap et al., 2016; Pagani et al., 2010; Seki et al., 2010; Tripati et al., 2009; Bartoli et al., 2011; Seki et al., 2010; Kurschner et al., 1996); (j) and (k) CO_2 measurements (Bereiter et al., 2015, scale at left); (l) CO_2 measurements (Schmidt et al, 2011, scale at right); (m) and (n) CH_4 measurements (Loulergue et al., 2008, scale at left); (o) CH_4 measurements (Schmidt et al, 2011, scale at right); (p) volcanic radiative forcing (Schmidt et al., 2012, scale at right); (q) total solar irradiance (Schmidt et al., 2012, scale at right).

Table 1: Characteristics, purpose and CMIP6 priority of the five PMIP4-CMIP6 experiments

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during which the northern hemisphere was characterised by

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They also simulate the scaling of precipitation changes with respect to temperature changes at the hemispheric scale realistically (Li et al., 2013).

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(e.g. Mauri et al., 2014; Perez-Sanz et al., 2014; Harrison et al., 2015). State

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, emphasizing the importance of testing models against the paleoclimate record to increase confidence in projections of future climate (Braconnot et al., 2012; Hargreaves and Annan, 2014; Schmidt et al., 2014

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Dust has now been implemented in many CMIP6 models, either by using models with an interactive representation of dust or by prescribing atmospheric dust content. In PMIP3, the

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2014, Ivanovic et al., 2016). Groups wishing to use the *lgm* equilibrium experiment to initialise PMIP4 transient simulations of the last deglaciation (Ivanovic et al., 2016) must use either ICE-6G_C or GLAC-1D because these are consistent with the ice sheet and meltwater forcings provided for the PMIP4 transient experiments. The impact of these different ice-sheet forcings will be a focus for sensitivity experiments in PMIP4 (Kageyama et al., 2017). There are uncertainties regarding other boundary conditions for the *midHolocene* and *lgm* experiments, including dust and vegetation (section 3.4.1), and these will also be investigated as part of the analysis of the entry-card simulations

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(Table 1). The importance of forced variability on multi-decadal to centennial time scales was highlighted by comparing spectra from *past1000* simulations with those from control

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Single-model ensembles have provided improved understanding of the importance of internal versus forced variability and

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using the same forcing as for the standard CMIP6 historical simulations.

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It is expected that more groups will be able to provide ensembles of past1000 runs and higher-resolution simulations, which will allow the analysis of a greater range of regional processes, such as the role of storm-tracks and blocking on regional precipitation.

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These papers also explain how the boundary conditions for each period have been designed and constitute key references for the experimental protocol for each of the PMIP4-CMIP6 simulations. Here we provide guidelines that are common to all of the experiments, focusing on the implementation of the boundary conditions where there is a need to ensure consistency between CMIP6 and PMIP4 experiments.

3.1 Model version and set-up

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Except for the *past1000* simulation, all the other PMIP4-CMIP6 simulations are equilibrium experiments, in which the boundary conditions and forcings are constant from one year to another.

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2016), i.e. the *piControl* forcings and boundary conditions are modified to obtain the forcings and boundary conditions necessary for each PMIP4-CMIP6 paleoclimate experiment (Table 2). No additional interactive component (such as vegetation or dust) should be included in the model unless it is already included in the DECK version. Such changes would affect the global energetics (Braconnot and Kageyama, 2015) and therefore prevent rigorous analyses integrating across multiple time periods or between MIPs (sections 4.2 and 4.3).

Table 2: summary of changes in boundary conditions w.r.t. *piControl* for each PMIP4-CMIP6 experiment

3.2 Summary of the forcings and boundary conditions: greenhouse gases, insolation, ice sheets

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should be modified from the DECK *piControl* experiment according to Table 2. Astronomical parameters have to be adjusted for all experiments but *midPliocene-eoi400.*

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The details of the implementation of the ice sheets can be found in Haywood et al. (2016) for *midPliocene-eoi400* and Kageyama et al. (2017) for *lgm*.

Figure 2: Changes in boundary conditions related to changes in ice sheets for the *midPliocene-eoi400* (top) and *lgm* (middle: ICE-6G_C and bottom: GLAC-1D) experiments. Coastlines for paleo-period shown as brown contours. Ice sheet boundaries for each period shown as red contour. Bright shading: changes in altitude over regions covered by ice sheets during the considered paleo-period. Faded shading: changes in altitude over ice-free regions.

3.3 Vegetation and land use

Paleoenvironmental records show that natural vegetation patterns during each of the PMIP4-CMIP6 period were different from today. However, in order to ensure comparability between past, present and future climate simulations, the PMIP4-CMIP6 paleoclimate simulations should follow the same protocol as the DECK and historical simulations.

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that allows dust emissions over LGM dust emission regions.

Simulations to examine the impact of vegetation changes are of interest and can be evaluated using paleoclimate data. These can be made using prescribed vegetation changes, by running a model such as BIOME4 (https://pmip2.lsce.ipsl.fr/) off line to compute vegetation patterns compatible with a past climate state, or by running additional simulations with a non-standard version of the model with dynamic vegetation. Sensitivity experiments such as these will be encouraged within PMIP4 but are not part of the PMIP4-CMIP6 experiments.

For the *past1000* simulation, land-use changes have to be implemented in the same manner as for the *historical* simulation, using the land-use forcing provided by the Land Use Model Intercomparison Project (Lawrence et al., 2016) and the CMIP6 Land Use Harmonization dataset LUH2 (https://cmip.ucar.edu/lumip; for details see Jungclaus et al., 2017). This data set provides a seamless transition between the pre-industrial millennium and the historical period. It is derived from the HYDE3.2 (Klein Goldewijk, 2016) estimates of the area of cropland, managed pasture, rangeland, urban, and irrigated land. Different crop types are treated separately and estimates of wood harvest are also provided. LUH2 includes improved updates of shifting cultivation rates, management information and new estimates of wood consumption.

3.4 Natural aerosols

3.4.1 Mineral Dust

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will be provided for the *midHolocene, lig127k* and *lgm* experiments. The maps are the same for the interglacial experiments.

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model behaviour with an atmosphere-only model before running the entire *lgm* simulation.

To allow experiments with prescribed dust changes, three-dimensional monthly climatologies of dust atmospheric mass concentrations will be provided for the *piControl*, *midHolocene*, and *lgm*.

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These are based on two different models (Albani et al.,

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These are based on two different models (Albani et al.,

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2015, Figure 4) and modelling groups are free to choose between these data sets.

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. Since dust plays an important role in ocean biogeochemistry (e.g. Kohfeld et al.,

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(2015) data set can therefore be used for models that cannot include the changes in atmospheric dust according to the other two data sets.

Figure 3: Maps of dust deposition (g m-2 a-1) simulated with the Community Earth System Model for a. PI (Albani et al., 2016), b. MH (Albani et al., 2015), and c. LGM (Albani et al., 2014). Maps of dust deposition (g m-2 a-1) for the LGM d. simulated with the Hadley Centre Global Environment Model 2-Atmosphere (Hopcroft et al, 2015), and e. reconstructed from a global interpolation of paleodust data (Lambert et al., 2015).

3.4.2 Volcanoes and stratospheric aerosols

The *past1000* experiment is the only one that requires imposing changes in volcanic aerosols. Modelling groups using interactive aerosol modules and sulphur injections in their historical simulations should follow the same method for the *past1000* experiment and use sulphur injection estimates by Toohey and Sigl. (2017) directly. For the other models, estimates of aerosol radiative properties as a function of latitude, height, and wavelength should be calculated using the Easy Volcanic Aerosol (EVA) module (Toohey et al., 2016). There are uncertainties associated with this approach. Additional sensitivity studies allowing the assessment of the impacts of these uncertainties on the *past1000* simulations will be made as part of the PMIP4 past1000 Tier 2 experiments (see Jungclaus et al., 2017). The sulphur injection time series and the EVA software package are provided via the PMIP4 web page (https://pmip4.lsce.ipsl.fr/doku.php/exp_design:lm).

3.5 Solar irradiance

For the *past1000* experiment, new reconstructions of TSI and SSI are provided that are based on recent estimates of cosmogenic isotopes and improved irradiance models (see Jungclaus et al., 2017 for details). The forcing prescribed for the Tier 1 past1000 experiment is constructed using a ^{14}C based reconstruction (Usoskin et al., 2016) of yearly sunspot numbers and an updated version of the Vieira et al. (2011) irradiance model. To achieve a smooth transition to the industrial period for historical experiments (1850 – 2015 CE) that start from the end of

the *past1000* simulations, the forcing is scaled to match the CMIP6 historical forcing (Matthes et al., 2017). Alternative forcing reconstructions, reflecting uncertainty in the cosmogenic isotopes and the methods used in solar irradiance models, are provided as a basis for additional Tier 2 experiments (Jungclaus et al., 2017).
3.6 Spin-up and duration of experiments

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In previous phases of PMIP, we recommended that the model should be run until the absolute value of the trend in global mean sea-surface temperature is less than 0.05 K per century and the Atlantic Meridional Overturning Circulation (AMOC) is stable.

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We require the groups to document this spin-up by saving a limited set of variables during this phase (Table 3).

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3.7 Documentation

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(*midHolocene*: Otto-Bliesner et al., 2017; *lgm*: Kageyama et al., 2017; *past1000*: Jungclaus et al., 2017; *lig127k*: Otto-Bliesner et al., 2017; *midPliocene-eoi400*: Haywood et al., 2016);

information about the initial conditions and spin-up technique used (cf. section 3.6). A measure of the changes in key variables (Table 3

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4. Overview of analyses plan and links to the required output

The five PMIP4-CMIP6 experiments naturally address the key CMIP6 question "How does the Earth System respond to forcing?" (Eyring et al, 2016), for multiple forcings and in climates states very different from the current or historical climates. For each target period, comparison with environmental observations and climate reconstructions enable us to determine whether the modelled responses are realistic. PMIP also addresses key CMIP6 question 2 "What are the origins and consequences of systematic model biases?"

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More importantly, analyses of PMIP simulations will show whether present-day biases have an impact on the magnitude of simulated climate changes. Finally, PMIP is also relevant to CMIP6 question 3 “How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?” through examination of these questions for documented past climate states and via the use of the last millennium simulations as reference state for natural variability.

The community using PMIP simulations is very broad, from climate modellers and palaeoclimatologists to biologists studying changes in biodiversity and archaeologists studying potential impacts of past climate changes on human populations. Because of this, we do not aim to give a comprehensive plan of PMIP analyses, but instead here we focus on topics closely related to the CMIP6 key questions. Each PMIP4-CMIP6 period has been selected for specific reasons (Table 1). Here, we list several analyses which are important for single periods as well as for the full PMIP4-CMIP6 ensemble, starting first by presenting examples of paleoclimate reconstructions available for comparison to the PMIP4-CMIP6 simulations. .

4.1 Paleoclimatic and paleoenvironmental reconstructions, model-data comparisons.

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4.1 Paleoclimatic and paleoenvironmental reconstructions, model-data comparisons.

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Compared to the PMIP3-CMIP5 models, many CMIP6 models will include new processes, such as dust, or improved representations of major radiative feedback processes, such as clouds. Improvements to the design of the *past1000*, *midHolocene* and *lgm* experiments are also proposed (section 2). We will evaluate the impact of these changes on the PMIP4-CMIP6 climates at global, large-scale (e.g.

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All the PMIP4-CMIP6 experiments will be run with the same model version, facilitating analyses across the five time periods to examine potential relationships between forcings of different nature and amplitude and the climate responses, and compare the processes involved in these responses (e.g. Izumi et al., 2013). For example, there are temperature thresholds that determine whether snow and ice can be present, and temperature thresholds also play a part in determining the distribution of specific vegetation types. Thus, a given change in climate could have different effects on snow/ice or vegetation feedback depending on the base climate state. Density thresholds also play a part in controlling the oceanic overturning circulation, again leading to the possibility that ocean changes may be modulated by background state (Swingedouw et al. 2009).

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They will allow us to determine, for example, whether the persistent failure to reproduce the observed magnitude of change in monsoon precipitation and the relatively small impact of vegetation feedback during the MH is related to biases or base climate. Similarly, they will help to quantify whether simulated changes in ocean circulation at the LGM are affected by systematic model biases or threshold behaviour. Model-data comparisons (cf. Section 4.1) will be used to assess the realism of the simulated climate change and to detect key mechanisms affecting model behaviour independently of the base climate state.

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Ice sheets represent strong changes in radiative forcing, as well as a direct forcing on atmosphere circulation.

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Understanding this oceanic circulation as well as its links to surface climate is a topic of high importance since the Atlantic Meridional Overturning Circulation could modulate future climate changes at least in regions around the North Atlantic (IPCC 2013).

4.3 Benchmarking the PMIP4-CMIP6 simulations

The compatibility of past, historical and future climate simulations will allow benchmarking based on syntheses of paleoenvironmental data and paleoclimate reconstructions (Section 4.1) to be applied to same models used for future projections. We

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, since the *piControl* and *historical* simulations provide two alternative reference states for paleoclimate simulations. Existing

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data sets (Section 4.1, Table 4) and from the development of new data syntheses. Large-scale features, such as polar amplification, land-sea contrast, and the scaling between precipitation and temperature changes, as well as more regional features such as the monsoons and mid-continental

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data sets (Section 4.1, Table 4) and from the development of new data syntheses. Large-scale features, such as polar amplification, land-sea contrast, and the scaling between precipitation and temperature changes, as well as more regional features such as the monsoons and mid-continental

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2014) will be expanded to include more process-oriented metrics. Benchmarking results from the

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will be compared to benchmark metrics from previous generations of PMIP to

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will be compared to benchmark metrics from previous generations of PMIP to

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will be compared to benchmark metrics from previous generations of PMIP to

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Improved model-data comparisons should also provide new possibilities to link regional climate reconstructions to the Earth's global energetic and climate sensitivity. Additional constraints can be obtained by using perturbed-physics experiments, in which different versions of the same model are run using different values of key parameters (Annan et al., 2005: Yoshimori et al., 2011). The 'perturbed forcing' approach (Bounceur et al., 2015; Araya-Melo, 2015), using sensitivity experiments carried out in PMIP4, could provide a way to chart the sensitivity of the climate system in a multi-dimensional space of forcing conditions.

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4.5 Changes in mean climate vs. changes in climate variability

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The most straightforward way for dealing with the calendar effect is to save and use daily data for the calculation of monthly or seasonal means, and so we include those in the PMIP4-CMIP6 data request for some key variables. A second approach, less desirable, but probably adequate for our purposes, is to use a bias-correction approach, in particular, like that of Pollard and Reusch (2002), with the mean-preserving daily interpolation approach of Epstein (1991).

Figure 4: The calendar effect: (a) month-length anomalies, 140 ka to present, with the PMIP4 experiment times indicated by vertical lines. The month-length anomalies were calculated using the formulation in Kutzbach and Gallimore (1988). (b and c) The calendar effect on October temperature at 6 and 127 ka, calculated using Climate Forecast System Reanalysis near-surface air temperature (https://www.earthsystemcog.org/projects/obs4mips/), 1981-2010 long-term means, and assuming the long-term mean differences in temperature are zero everywhere. (e and f) The calendar effect on October precipitation at 6 and 127 ka, calculated using the CPC Merged Analysis of Precipitation (CMAP) enhanced precipitation (http://www.esrl.noaa.gov/psd/data/gridded/ data.cmap.html), 1981-2010 long-term means, and again assuming that the long-term mean differences in temperature are zero everywhere. Calendar effects were calculated by interpolating present-day monthly temperature or precipitation to a daily time step as in Pollard and Reusch, 2002 (but using a mean-preserving algorithm for pseudo-daily interpolation for monthly values; Epstein, 1991), and then recalculating the monthly means using the appropriate paleo calendar (Bartlein and Shafer, 2016). Note that the 6 and 127 ka map patterns for both variables, while broadly similar, are not simply rescaled versions of one another.

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