Response to GMD Editors' comments on "The PMIP4 contribution to CMIP6 - Part 2: Two Interglacials, Scientific Objective and Experimental Design for Holocene and Last Interglacial Simulations" by Otto-Bliesner et al.

Thank you for your patience on our resubmission of our manuscript addressing the Editors' comments. Indeed, the revisions to the comments were not major though it took a bit of time to ensure that the three PMIP4 papers describing the Last Millennium, Interglacials, and Last Glacial Maximum similarly handled the description of the "Tiers", documentation, and data distribution. Working together, Masa, Johann, and I have coordinated our responses to the concerns of the Editors and have revised our papers to be more consistent.

For clarity, we reproduce the Topical Editor and other Editors' comments in *blue/italic* and provide answers in black. Changes to the manuscript are presented in **bold face**.

First, addressing Topical Editor comments:

1. *The second response to reviewer #3 does not seem to reflect on the question, is that a copy/paste mistake?*

Not sure what response is being referred to. Our responses to Reviewer #3, parts a-d seem appropriate. Please advise further.

2. *In the Abstract and beginning of the manuscript you are relating all the time to "Tier 1" simulations. However, these are only defined on page 4 of the current version of the manuscript. Please reword to avoid this. This also connects to the general comment sent earlier through Julia Hargreaves.*

The reference to "Tier 1" in the abstract has been deleted. We now include a new second paragraph to the Introduction (lines 80+ in the tracked changes version) describing the Tier structure. See response to #6 below for more details and new text.

3. *Page 8, line 306 "Antarctic ice-sheets is" singular/plural form?*

Corrected to be singular form.

4. *I do not understand the sentence on page 11, first line "Albedo ...forcing"*

The sentence is indeed confusing. As such, we have decided to delete this sentence.

5. *I have the same particular comments than Julia Hargreaves on the ESGF distribution and standards in your paragraph 6. Also the same issue in specifying the conditions for checking equilibrium which are vague and difficult to find in the present manuscript.*

See responses to #7-10 below.

Second, addressing the general comments by the Editors of the three PMIP4 papers:

6. *Some papers mention the entry cards for CMIP, but others do not. Some bring in the "Tier" nomenclature without defining it, while the LGM discusses "sensitivity" experiments, leaving it uncertain as to how these fit into the CMIP system.*

   ** All papers should explain the entry card system and contain full and consistent information on the documentation requirement for the runs. Many groups will do all the Tier 1 runs, so it really will be very confusing if the documentation requirements are different! All the papers should make sure to define CMIP concepts such as "Tier 1".*

We have now categorized all experiments in the PMIP4 papers as Tier 1, Tier 2 and Tier 3. The concept of Tier is introduced in the CMIP6 overview paper (Eyring et al., 2016), with Tier 1 having the highest priority. Within PMIP4, the Tier 1 experiments are those, which are Tier 1 for CMIP6 as well. They are also reference experiments for Tier 2 and Tier 3 experiments described for each period in the PMIP4 GMD manuscripts, which will be made clearer in the revised versions (especially for the LGM sensitivity experiments, which will be categorized as Tier 2). In the PMIP4-CMIP6 overview paper, we introduce the concept of PMIP4 entry card, capitalizing on PMIP's previous experiments. These (the *midHolocene* and *lgm* experiments) are special PMIP4-CMIP6 Tier 1 experiments. We consider that at least one of these experiments must be performed by the modelling groups to be part of PMIP4-CMIP6, because they will allow us to monitor the progress from the previous phases of PMIP and CMIP. This is explained in the overview paper, but will be recalled in the PMIP4 papers. We want to make it clear that the Tier 2 and 3 experiments absolutely require the corresponding Tier 1 experiment for their analysis, so the groups must perform the Tier 1 experiment first.

In the Interglacial manuscript we have included a new second paragraph to the Introduction:

This paper is part of a suite of five manuscripts documenting the PMIP4 contributions to CMIP6. Kageyama et al. (2016) provide an overview on the five selected time periods and the experiments. More specific information is given in the contributions for the last millennium (*past1000*) by Jungclaus et al. (2016), for the last glacial maximum (*lgm*) by Kageyama et al. (2017), for the mid-Pliocene warm period (*midPliocene-eoi400*) by Haywood et al. (2016), and the present manuscript mid-Holocene (*midHolocene*) and the previous interglacial (*lig127k*). PMIP4 has adopted the CMIP6 categorization where the highest-priority experiments are classified as Tier 1, whereas additional sensitivity experiments or dedicated studies are Tier 2 or Tier 3. The standard experiments for the five periods are all ranked Tier 1. Tier 2 and 3 experiments absolutely require the corresponding Tier 1 experiment for their analysis, so the groups must perform the Tier 1 experiment first. Modelling groups are not obliged to run all PMIP4-CMIP6 experiments. It is mandatory, however, for all participating groups to run at least one of the experiments that were run in previous phases of PMIP (i.e., *midHolocene* or *lgm*).

7. *The documentation requirement seems to be different in all the papers (and the LGM is actually inconsistent with the overview paper). The documentation requirement is really presented as part of the protocol, so should be included in each of the individual papers.*

The overview paper will insist on the importance of documenting the simulations. The specificities for each simulation are detailed in each paper, since they depend on the forcings for each experiment. This includes the documentation on spin-up and equilibrium as detailed below.

We have streamlined the documentation requirements and each manuscript now contains a section "Documentation". The specifications are, of course, different for the different time periods and experiments.

2.6 Setup and documentation of simulations

To provide initial conditions for the simulations, it is recommended that a spin-up simulation is performed departing from the CMIP6 *piControl* experiment. The length of this spin-up simulation will be model- and resource- dependent. However, it should be long enough to minimize at least surface climate trends.

The modelling groups are responsible for a comprehensive documentation of the model system and the experiments. Documentation should be provided via the ESDOC website and tools provided by CMIP6 (http://es-doc.org/) to facilitate communication with other CMIP6 projects. A PMIP4 special issue in GMD and Climate of the Past has been opened where the groups are encouraged to publish these documentations.

The documentation should include:

- **The model version and specifications, like interactive vegetation or interactive aerosol modules etc.**
- **A link to the DECK experiments performed with this model version.**
- **Specification of the forcing data sets used and their implementation in the model. The provision of figures and tables giving monthly-latitude insolation anomalies and daily incoming solar radiation at the top of the atmosphere (TOA) for one year should be provided because this allows the implementation of the most critical forcing to be checked.**
- **Information about the initial conditions and spin-up technique used.**
- **We request providing information on drift in key variables for a few hundred years at the end of the spin-up and the beginning of the actual experiment. These variables are:**
  - globally and annually averaged SSTs
  - deep ocean temperatures (global and annual average over depths below 2500m)
  - deep ocean salinity (global and annual average over depths below 2500m)
  - top of atmosphere energy budget (global and annual average)

- surface energy budget (global and annual average)
- northern sea-ice (annual average over northern hemisphere)
- southern sea-ice (annual average over southern hemisphere)
- northern surface air temperature (annual average over northern hemisphere)
- southern surface air temperature (annual average over southern hemisphere)
- Atlantic Meridional Overturning Circulation (maximum overturning stream function in the North Atlantic basin between 0 and 80°N below 500m depth)
- carbon budget (if relevant).

8. *We are all confused about what the comment that groups are responsible for finding their own ESGF space for Tier2-3 experiments means in practice, and note that there is no indication as to whether the LGM sensitivity experiments should be uploaded or not.*

   ** Please clarify what, in practice, this group responsibility means. Will modellers be able to upload Tier 2 and 3 experiments to ESGF or not, and how are the LGM sensitivity runs to be made available?*

On the PMIP side, we are taking all necessary measures so that the PMIP Tier-2 and Tier-3 output can be uploaded and published on the ESGF distributed network. However, LSCE, who is coordinating the database, cannot provide the disk space for all modelling groups as it did until PMIP2, and for some of the groups in PMIP3. This is what we meant by the statements in the papers. Modelling groups participating to PMIP will have to coordinate with their national ESGF node to upload their data on ESGF, as they will do for their PMIP4-CMIP6 Tier-1 data. We have clarified this in Section 6 of our paper.

Data from PMIP4-only Tier 2 and 3 simulations must be processed following the same standards as Tier 1 for data processing (e.g. CMOR standards) and should be distributed via the PMIP4 ESGF or the CMIP6 ESGF Tier 2 and Tier 3. Modeling groups producing these simulations are responsible to secure suitable space on ESGF nodes. These experiments will follow the same naming, variable convention and format, and documentation requests as Tier 1 PMIP4-CMIP6 experiment so as to be compliant with ESGF database requirements.

9. *Are all boundary conditions to be uploaded to ESGF? This is promised in the LGM paper, but not in the others.*

   ** Please make it clear whether all boundary conditions will be uploaded to ESGF. It would be best if they were, as the current situation where everything is available on the PMIP website is sub-optimal (it seems to me OK for modellers doing the runs now, but it is not future-proof: web addresses change!).*

We have put a link in the ESGF/Input4MIPs reference document providing the connection to the PMIP4 web site. This way it is also done for other CMIP6 experiments (see the reference document entries for FAFMIP, OMIP, VolMIP etc.). However, owing to our priority to make the data sets available as fast as possible, we didn't have resources to make the data sets fully

Input4MIPs compliant. We will work with the providers of the data sets towards a distribution via ESGF.

We have included this information in the text:

The forcing and boundary condition data sets described in this paper are available in the PMIP4 repository https://pmip4.lsce.ipsl.fr/doku.php/exp_design:index. After final acceptance of this manuscript, they will be made available also through Input4MIPs (https://esgf-node.llnl.gov/projects/input4mips/, see the living document "Input4MIPs summary" there on the progress of this process).

10. *The LGM experiment requires 100 years of equilibrated run to be stored on ESGF, and defines which variables are to be used by participating groups to ensure sufficient equilibrium is attained before the other experiments are started. There is less detail on this in the other papers.*

    ** Please can all experiments require the 100 years of equilibrated run on ESGF. If possible, please define a common metric for assessing equilibrium for all the runs. If there are good reasons why different metrics should be used for the different experiments, please provide an explanation and guidance for the modellers.*

For the Interglacial experiments, we have defined the spinup and metrics for assessing equilibrium of the experiments. See new text for Section2.6 included in response #7 above.

We also now better define what data should be uploaded to the ESGF in revised Section 6

The Tier 1 *midHolocene* and *lig127k* simulations are part of the CMIP6 experiment family and data will be distributed through the official CMIP6 channels via the Earth System Grid Federation (ESGF, https://earthsystemcog.org/projects/wip/CMIP6DataRequest). A minimum of 100 years of output is required to be uploaded for each simulation (usually the final 100 years of the simulation). However, given the increasing interest in analyzing multi-decadal variability (e.g. Wittenberg, 2009) and the availability of reconstructions of ENSO (El Niño-Southern Oscillation) and other modes of variability (see Section 3), modeling groups are encouraged to provide outputs for at least 500 years if possible.

In addition, the difference in orbital configuration between 127 ka, 6 ka and preindustrial means that there are differences in month and season length that should be accounted for in calculating seasonal changes (Kutzbach and Gallimore, 1988). To be able to account for this effect when comparing the simulations to the paleoclimate reconstructions, daily outputs of at least surface 2-meter temperature (tas), precipitation (pr) and 10-meter winds (uas) should be archived. If not possible, a less accurate but probably adequate approach, would be to use a program that provides an approximate estimate of monthly means on the fixed-angular celestial calendar from fixed-day calendar.

Data from PMIP4-only Tier 2 and 3 simulations must be processed following the same standards as Tier 1 for data processing (e.g. CMOR standards) and should be distributed via the PMIP4 ESGF or the CMIP6 ESGF Tier 2 and Tier 3. Modeling groups producing these simulations are responsible to secure suitable space on ESGF nodes. These experiments will follow the same naming, variable convention and format, and documentation requests as Tier 1 PMIP4-CMIP6 experiment so as to be compliant with ESGF database requirements.

The list of variables requested for the PMIP4-CMIP6 paleoclimate experiments can be found here: http://clipc-services.ceda.ac.uk/dreq/u/PMIP.html. This request is presently processed by the CMIP6 Working Group for Coupled Modeling Infrastructure Panel (WIP) into tables, which define the variables included in the data request to the modelling groups for data to be contributed to the archive. The most up-to-date list including all variables requested for CMIP6 can be found at the WIP site:

proj.badc.rl.ac.uk/svn/exarch/CMIP6dreq/tags/latest/dreqPy/docs/CMIP6_MIP_tables.xlsx

The last two columns in each row list MIPs associated with each variable. The first column in this pair lists the MIPs, which are requesting the variable in one or more experiments. The second column lists the MIPs proposing experiments in which this variable is requested.

As supplementary to this manuscript we provide version 1.00.05 (April 2017) of the table in Appendix A. We note, however, that this document is still in development and inconsistencies may still exist.

The only variables defined specifically in PMIP are those describing oxygen isotopes for model systems that calculate these data interactively (Kageyama et al., 2016).

The PMIP4 contribution to CMIP6 - Part 2: Two Interglacials, Scientific Objective and Experimental Design for Holocene and Last Interglacial Simulations

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Abstract. Two interglacial epochs are included in the suite of Paleoclimate Modeling Intercomparison Project (PMIP4) simulations in the Coupled Model Intercomparison Project (CMIP6). The experimental protocols for simulations of the mid-Holocene (*midHolocene,* 6000 years before present) and the Last Interglacial (*lig127k*, 127,000 years before present) are described here. These equilibrium simulations are designed to examine the impact of changes in orbital forcing at times when atmospheric greenhouse gas levels were similar to those of the preindustrial period and the continental configurations were almost identical to modern. These simulations test our understanding of the interplay between radiative forcing and atmospheric circulation, and the connections among large-scale and regional climate changes giving rise to phenomena such as land-sea contrast and high-latitude amplification in temperature changes, and responses of the monsoons, as compared to today. They also provide an opportunity, through carefully designed additional sensitivity experiments, to quantify the strength of atmosphere, ocean, cryosphere, and land-surface feedbacks. Sensitivity experiments are proposed to investigate the role of freshwater forcing in triggering abrupt climate changes within interglacial epochs. These feedback experiments naturally lead to a focus on climate evolution during interglacial periods, which will be examined through transient experiments. Analyses of the sensitivity simulations will also focus on interactions between extratropical and tropical circulation, and the relationship between changes in mean climate state and climate variability on annual to multi-decadal timescales. The comparative abundance of paleoenvironmental data and of quantitative climate reconstructions for the Holocene and Last Interglacial make these two epochs ideal candidates for systematic evaluation of model performance, and such comparisons will shed new light on the importance of external feedbacks (e.g., vegetation, dust) and the ability of state-of-the-art models to simulate climate changes realistically.

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Keywords: paleoclimate simulations, transient climate evolution, climate-system feedbacks, interglacial, model evaluation

1 Introduction

The modeling of paleoclimate, using physically based tools, has long been used to understand and explain past environmental and climate changes (Kutzbach and Street-Perrott, 1985), and is increasingly seen as a strong out-of-sample test of the models that are used for the projection of future climate changes (Braconnot et al., 2012; Harrison et al., 2014; Harrison et al., 2015; Schmidt et al., 2014). The Paleoclimate Modelling Intercomparison Project (PMIP) has served to coordinate paleoclimate experiments and data-model comparisons for several decades (Braconnot et al., 2012; Braconnot et al., 2007a; Braconnot et al., 2007b; Joussaume and Taylor, 1995; Joussaume et al., 1999), and now spearheads the paleoclimate contribution to the current phase of the Coupled Model Intercomparison Project (CMIP6, Eyring et al., 2016).

This paper is part of a suite of five manuscripts documenting the PMIP4 contributions to CMIP6. Kageyama et al. (2016) provide an overview on the five selected time periods and the experiments. More specific information is given in the contributions for the last millennium (*past1000*) by Jungclaus et al. (2016), for the last glacial maximum (*lgm*) by Kageyama et al. (2017), for the mid-Pliocene warm period (*midPliocene-eoi400*) by Haywood et al.

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(2016), and the present manuscript mid-Holocene (*midHolocene*) and the previous interglacial (*lig127k*). PMIP4 has adopted the CMIP6 categorization where the highest-priority experiments are classified as Tier 1, whereas additional sensitivity experiments or dedicated studies are Tier 2 or Tier 3. The standard experiments for the five periods are all ranked Tier 1. Tier 2 and 3 experiments absolutely require the corresponding Tier 1 experiment for their analysis, so the groups must perform the Tier 1 experiment first. Modelling groups are not obliged to run all PMIP4-CMIP6 experiments. It is mandatory, however, for all participating groups to run at least one of the experiments that were run in previous phases of PMIP (i.e., *midHolocene* or *lgm*).

The two experiments described here focus on comparing the most recent interglacial epochs and specifically the current interglacial (the Holocene) and the previous interglacial (the Last Interglacial, LIG) periods (Fig. 1). These two experiments are of interest because they examine the response of the climate system to relatively simple changes in forcing compared to the present. The main difference in forcing from present was in the latitudinal and seasonal distribution of incoming solar radiation (insolation) caused by known changes in the Earth's orbit; greenhouse gas (GHG) concentrations were similar to those of the preindustrial period and the continental configurations were also very similar to modern. Differences in orbital configuration between the two interglacial periods (Berger, 1978) mean that the insolation changes are stronger in the LIG than in the Holocene, but the observational basis for evaluating model simulations is more extensive in the Holocene than the LIG because of preservation issues. Taken together, these two interglacial periods are good test cases of our mechanistic understanding of the interplay between radiative forcing and atmospheric circulation, and opportunities to examine connections among large-scale and regional climate changes which give rise to phenomena such as land-sea contrast and high-latitude amplification of temperature changes, the regulation of atmospheric CO_2 and biogeochemical cycles, and the waxing and waning of the monsoons.

The Tier 1 interglacial experiments for CMIP6 are time-slice (or equilibrium) experiments at 6000 and 127,000 years before present (where present is defined as 1950), hereafter referred to as 6 ka (*midHolocene*) and 127 ka (*lig127k*). The mid-Holocene interval has been the focus for model simulations, model-model comparisons, paleodata synthesis, and model-data comparison since the beginning of PMIP, and this work has contributed to model evaluation and understanding of climate change in the last three major assessments of the Intergovernmental Panel on Climate Change (Flato et al., 2013; Folland et al., 2001; Hegerl et al., 2007; Jansen et al., 2007; Masson-Delmotte et al., 2013). The changes in insolation are characterized by enhanced seasonal contrast in the northern hemisphere (NH) (and reduced seasonal contrast in the southern hemisphere, SH), giving rise to warmer NH summers and a significant enhancement of the NH monsoons (COHMAP Members, 1988; Hely et al., 2014; Lezine et al., 2011; Saraswat et al., 2013; Tierney et al., 2017). Systematic benchmarking against pollen-based reconstructions of climate variables and lake-level-based water-balance reconstructions (Braconnot et al., 2012; Braconnot et al., 2007b; Coe and Harrison, 2002; Harrison et al., 2014; Harrison et al., 2015; Harrison et al., 1998) have highlighted that climate models persistently underestimate changes in the monsoon precipitation and produce too much continental drying (Harrison et al., 2015).

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Given the long history of coordinated model experiments for 6 ka, this period allows us to assess whether there is an improvement in the ability of models to reproduce a climate state different from the modern one. For this reason, the Tier 1 *midHolocene* experiment is one of two possible ‘entry cards’ for PMIP simulations in CMIP6 (Table 1): all modeling groups contributing to PMIP4-CMIP6 must perform either the *midHolocene* experiment or a simulation of the Last Glacial Maximum (Kageyama et al., 2016).

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Although the LIG (129 ka to 116 ka) was discussed in the First Assessment Report of the IPCC (Folland et al., 1990), it gained more prominence in the IPCC Fourth and Fifth Assessment (AR4 and AR5) because of reconstructions highlighting that global mean sea level was at least 5 m higher (but probably no more than 10 m higher) than present for several thousand years (Dutton et al., 2015a; Jansen et al., 2007; Masson-Delmotte et al., 2013). Thus the LIG is recognized as an important period for testing our knowledge of climate-ice sheet interactions in warm climate states. However, the ensemble of LIG simulations examined in the AR5 (Masson-Delmotte et al., 2013) was not wholly consistent: the orbital forcing and GHG concentrations varied between the simulations. While it has been suggested that differences in regional temperatures between models might reflect differences in cryosphere feedback strength (Yin and Berger, 2012; Otto-Bliesner et al., 2013) or differences in the simulation of the Atlantic Meridional Overturning Circulation (AMOC) (Bakker et al., 2013; Masson-Delmotte et al., 2013), differences between models could also have arisen because of differences in the experimental protocols. Furthermore, the LIG simulations were mostly made with older and/or lower-resolution versions of the models than were used for future projections, making it more difficult to use the results to assess model reliability (Lunt et al., 2013). The Tier 1 *lig127k* experiment (Table 1) is designed to address the climate responses to stronger orbital forcing than the *midHolocene* experiment using the same state-of-the-art models and following a common experimental protocol. It will provide a basis to address the linkages between ice sheets and climate change in collaboration with the Ice Sheet Model Intercomparison Project for CMIP6 (ISMIP6) (Nowicki et al., 2016).

The *midHolocene* and *lig127k* experiments are starting points for examining interglacial climates. A number of other experiments are proposed in the current phase of PMIP (PMIP4) to facilitate diagnosis of these Tier 1 experiments The Tier 2 simulations will include sensitivity experiments to examine the impact of uncertainties in boundary conditions and the role of feedbacks in modulating the response to orbital forcing. Ocean, vegetation, and dust feedbacks, and the synergies between them, have been a focus in previous phases of PMIP (Braconnot et al., 1999; Dallmeyer et al., 2010; Otto et al., 2009; Wohlfahrt et al., 2004) and this allows us to design simple experimental protocols to compare the strength of these feedbacks in different climate models. Simulations with prescribed but adjusted vegetation cover will be a major focus for both the Holocene and LIG in PMIP4, and comparison of these simulations with ESM simulations that include dynamic vegetation will allow exploration of the magnitude of land-surface biases in these latter models. Changes in vegetation and land-surface hydrology are an important control on dust emissions (Tegen et al., 2002; Engelstädter et al., 2003), which can affect the strength of the West African Monsoon (Konare et al. 2008, Pausata et al. 2016). The examination of the dust feedback will be a new focus in PMIP4. In addition, the LIG provides an ideal opportunity to examine the role of cryosphere feedbacks through

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sensitivity experiments, which will be a focus of additional experiments associated with both the Holocene and the LIG. One such feedback is the release of freshwater into the ocean and the role of such freshwater forcing in generating more abrupt climate changes than would be expected for the smoothly varying changes in insolation forcing during an interglacial (Goelzer et al., 2016a; Luan et al., 2015; Stone et al., 2016). Understanding the role of feedbacks in general on the generation of abrupt climate changes, and the need to understand the relationship between mean climate changes and short-term (annual to multi-decadal) climate variability, leads naturally to a desire to simulate the transient behavior of the climate system – and such transient experiments are proposed for both the Holocene and LIG time periods. New results have highlighted the possibility to use reconstruction of past interannual variability from corals and mollusc shells to assess the Holocene simulated changes in variability at the scale of the tropical Pacific Ocean (Emile-Geay et al. 2016). Groups are also encouraged to run their models with an active land and ocean carbon cycle to assess terrestrial and ocean carbon storage and differences between the two interglacial periods.

The aim of this paper is to present and explain the experimental designs both for the PMIP4-CMIP6 Tier 1 interglacial experiments, and for associated Tier 2 and Tier 3 sensitivity and transient experiments. Section 2 describes and discusses the PMIP4-CMIP6 *midHolocene* Tier 1/entry card and *lig127k* Tier 1 simulations. Section 3 describes Tier 2 and Tier 3 PMIP4 sensitivity studies that can be carried out to diagnose these Tier 1 simulations. Section 4 briefly describes the paleodata resources, which can be used to evaluate the simulations.

2 Experimental design for the Tier 1 PMIP4-CMIP6 *midHolocene* and *lig127k* simulations

The core or Tier 1 experiments for the Holocene and the LIG are the *midHolocene* and *lig127k* simulations. The CMIP DECK (Diagnostic, Evaluation and Characterization of Klima) *piControl* for 1850 C.E and the CMIP6 *historical* experiment (see Eyring et al. 2016 for description of these experiments) are the reference simulations to which the paleo-experiments will be compared. Thus, the paleo-experiments must use the same model components and follow the same protocols for implementing external forcings as are used in the *piControl* and *historical* simulations. The *midHolocene* simulation is one of the PMIP entry cards in the PMIP4-CMIP6 experiments, which means that groups who run the *lig127k* simulation must also run either the *midHolocene* or the *lgm* (Last Glacial Maximum) experiment (Kageyama et al., 2016). The boundary conditions for the *midHolocene*, *lig127k,* and *piControl* experiments are given in Table 1, and more detailed information is given below.

2.1 Orbital configuration, solar constant, and insolation anomalies

Earth's orbital parameters (eccentricity, longitude of perihelion, and obliquity) should be prescribed following Berger and Loutre (1991). These parameters affect the seasonal and latitudinal distribution and magnitude of solar energy received at the top of the atmosphere and, in the case of obliquity, the annual mean insolation at any given latitude (Berger and Loutre, 1991). The DECK *piControl* simulations are to use the orbital parameters appropriate for 1850 C.E (Table 1) (Eyring et al., 2016), when perihelion occurs close to the boreal winter solstice. The exact date slightly varies depending on the internal model calendar and the number of days used to define a year. Because of this and the fact that the length of the seasons varies as a function of precession and eccentricity (Joussaume and Braconnot, 1997), the vernal equinox must be set to noon on March 21th in all the simulations (*piControl, midHolocene,* and *lig127k*). The orbit at 6 ka was characterized by an eccentricity of 0.018682, similar to 1850 C.E. (Table 1). Obliquity was larger (24.105°) and perihelion at 6 ka occurred near the boreal autumn equinox. The orbit at 127 ka was characterized by larger eccentricity than at 1850 C.E., with perihelion occurring close to the boreal summer solstice (Fig. 2). The tilt of the Earth's axis was maximal at 131 ka and remained higher than in 1850 C.E. through 125 ka; obliquity at 127 ka was 24.04° (Table 1). The different orbital configurations for the *midHolocene* and *lig127k* result in different seasonal and latitudinal distribution of top-of-atmosphere insolation compared to the DECK *piControl* (Fig. 3). Both time periods show large positive insolation anomalies during boreal summer. July-August anomalies between 40 and 50°N reach about 55-60 $\mathrm{W\ m^{-2}}$ at 127 ka and 25 $\mathrm{W\ m^{-2}}$ at 6 ka. The higher obliquity at 127 ka and 6 ka contributes to a small but positive annual insolation anomaly compared to preindustrial at high latitudes in both hemispheres and a slight insolation reduction in the tropics in the annual mean. The global difference in insolation forcing between the interglacial experiments and the preindustrial is negligible.

The solar constant prescribed for the *midHolocene* and *lig127k* simulations is the same as in the DECK *piControl* simulation, which is fixed at the mean value for the first two solar cycles of the historical simulation (i.e. 1850-1871) (Eyring et al., 2016). This value (1360.7 $\mathrm{W\ m^{-2}}$) is lower than the value for the solar constant used by some models in PMIP3 (1365 $\mathrm{W\ m^{-2}}$) and this leads to a global reduction of incoming solar radiation compared to the PMIP3 experiments (Fig. 4). The slight differences in orbital parameters between the 1850 C.E. reference periods to be used for PMIP4-CMIP6 and the 1950 C.E. reference used for PMIP3 leads to seasonal differences in forcing with a slight decrease in boreal spring and increase in boreal autumn. The combination of the two factors leads to an overall reduction: the largest reduction occurs in boreal spring and is about 1.6 $\mathrm{W\ m^{-2}}$ between 10°S and 40°N.

2.2 Greenhouse gases

Ice-core records from Antarctica and Greenland provide measurements of the well-mixed GHGs: CO_2, CH_4, and N_2O (Fig. 1). These measurements are given as mole fractions in dry air and are noted as parts per million (ppm) or parts per billion (ppb) respectively. For simplicity, we use the term 'concentration' for these GHG-levels. By 6 ka and 127 ka, the concentrations of atmospheric CO_2 and CH_4 had increased from their respective levels during the previous glacial periods, the Last Glacial Maximum and the penultimate glaciation, to values comparable to preindustrial levels.

midHolocene. In PMIP4-CMIP6, we use a revised version of an earlier trace gas reconstruction (Joos and Spahni, 2008). The CO_2 concentration for the mid-Holocene is derived from ice-core measurements from Dome C (Monnin et al., 2001; Monnin et al., 2004) and dated using the AICC2012 age scale (Veres et al., 2013). A smoothing spline (Bruno and Joos, 1997; Enting, 1987) with a nominal cut-off period of 3000 years was used to produce a continuous CO_2 record. This yields a CO_2 concentration of 264.4 ppm at 6 ka. Methane has been measured in ice from Antarctic ice cores EPICA Dome C (Flückiger et al., 2002), EPICA Dronning Maud Land (EPICA Community Members,

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2006) and Talos Dome (Buiron et al., 2011). For Greenland, methane data are from GRIP (Blunier et al., 1995; Chappellaz et al., 1997; Spahni et al., 2003), GISP2 (Brook, 2009), and GISP2D (Mitchell et al., 2013). Both are splined with a nominal cut-off period of 200 years. This results in a concentration of 574 ppb for the Antarctic ice cores, representative for high latitude Southern Hemisphere air, and of 620 ppb for the Greenland ice cores, representative for the high latitude Northern Hemisphere air, and an estimated global mean value of 597 ppb. The N_2O data around 6 ka are from a compilation of published data from EPICA Dome C (Flückiger et al., 2002; Spahni et al., 2005) and new, unpublished data measured at University of Bern using ice from Greenland (NGRIP) and Talos Dome (TALDICE). The data are splined with a nominal cut-off period of 700 yr and the resulting N_2O concentration at 6 ka is 262 ppb.

The realistic GHG concentrations used for the *midHolocene* PMIP4-CMIP6 experiment are different from those used in the PMIP3 experiments (Braconnot et al. 2012). The PMIP3 experiments were designed simply to examine the effects of changes in orbital forcing, and the CO_2 concentrations were therefore kept the same as the value typically used in pre-industrial experiments (280 ppm) although other GHGs were prescribed from ice-core measurements. The use of realistic values for all the GHGs in the PMIP4-CMIP6 *midHolocene* experiment may improve comparisons with paleoclimate reconstructions and will ensure that the *midHolocene* experiment is consistent with planned transient Holocene simulations (see Section 3). However, the reduction in CO_2 concentration from 280 to 264.4 ppm will reduce GHG forcing by about 0.3 W m^{-2} (Myhre et al., 1998), which translates to a difference in global mean surface air temperature of -0.24°C when applying an equilibrium climate sensitivity of 3°C for a nominal doubling of CO_2. Simulations with the IPSL model (Dufresne and co-authors, 2013) show that this change in the experimental protocol between PMIP3 and PMIP4-CMIP6 yields a global mean cooling of 0.24 ± 0.04°C, as expected, with regional differences of up to 0.5°C in parts of Eurasia and in South Africa (Fig. 5). Although these differences are small overall, they will need to be accounted for in comparisons between the PMIP4-CMIP6 *midHolocene* simulations and previous generations of PMIP 6 ka simulations.

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lig127k. The LIG GHG concentrations are available solely from Antarctic ice cores. CO_2 concentrations can only be derived from Antarctic ice, because of potential in-situ CO_2 production in the Greenland ice sheet (Tschumi and Stauffer, 2000). We also do not have any reliable CH_4 and N_2O concentrations from Greenland in the LIG due to melt layers in the ice, as Greenland temperatures were significantly warmer at that time compared to modern (Fig. 1) (NEEM Community Members 2013). For the *lig127k* simulation (Table 1), we adopt mean values for 127.5-126.5 ka on the AICC2012 age scale (Bazin et al., 2013) from EPICA Dome C (Bereiter et al., 2015; Schneider et al., 2013) for CO_2, from EPICA Dome C and EPICA Dronning Maud Land (Loulergue et al., 2008; Schilt et al., 2010a) for CH_4, as well as from EPICA Dome C and Talos Dome (Schilt et al., 2010a; Schilt et al., 2010b) for N_2O. The atmospheric CO_2 and N_2O concentrations of 275 ppm and 255 ppb, respectively, can be regarded as globally representative, while the mean ice core CH_4 concentration (662 ppb) is representative for high-latitude Southern Hemisphere air. A global mean atmospheric CH_4 concentration of 685 ppb is adopted for 127 ka, thereby assuming the same difference (23 ppb) between the global mean atmospheric CH_4 and Antarctic ice core CH_4 values as for the mid-Holocene.

2.3 Paleogeography and ice sheets

***midHolocene*.** Several lines of evidence indicate that the ice sheets had their modern characteristics by the mid-Holocene, except in a few places such as the Baffin Islands (Carlson et al., 2008b; Clark et al., 2000). While the presence of a relict of the Laurentide ice sheet may be the origin of model-data mismatches in the climate of eastern North America (Wohlfahrt et al., 2004), the effect is local and small. Cosmogenic surface exposure ages and threshold lake records (Carlson et al., 2014; Larsen et al., 2015; Sinclair et al., 2016) also suggest that by 6 ka, the Greenland ice sheet was similar in extent to the present. The ice sheet distribution and elevations, land-sea mask, continental topography and oceanic bathymetry should all be prescribed as the same as in *piControl* in the *midHolocene* simulation (Table 1).

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***lig127k*.** Evidence for the evolution of the ice sheets during the LIG comes mainly from proximal marine records (Carlson and Winsor, 2012). The deposition of a detrital carbonate layer in the Labrador Sea, dated to around 128 ka based on geomagnetic secular variation (Winsor et al., 2012), suggests that ice had retreated from Hudson Bay and is taken to indicate the final demise of the Laurentide ice sheet (Carlson, 2008; Nicholl et al., 2012). The disappearance of the Eurasian ice sheet is more difficult to constrain because either the proximal marine records lack benthic $\delta^{18}O$ data, or the benthic $\delta^{18}O$ data show trends that are different from those of open ocean records during the LIG (Bauch, 2013). The cessation of deposition of ice-rafted debris (IRD) from the Eurasian ice sheet has been dated to between 128-126 ka using $\delta^{18}O$ (Risebrobakken et al., 2006). However, sea-level data (Dutton et al., 2015b) suggests that this ice sheet disappeared earlier and was likely gone by ~127 ka. Proximal marine records of the Greenland ice sheet document a gradual retreat during the LIG, with minimum extent around 120 ka (Carlson et al., 2008a; Colville et al., 2011; Stoner et al., 1995; Winsor et al., 2012). However, Greenland-sourced IRD reached a minimum similar to the Holocene before ~127 ka (Colville et al., 2011; Winsor et al., 2012).

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The extent of the Antarctic ice sheet is not directly constrained by data proximal to the ice sheet at 127 ka. Given higher-than-present sea levels, the gradual retreat of the Greenland ice sheet, and the lack of other NH ice sheets, it seems likely that the Antarctic ice sheet was smaller than present by ~127 ka (Colville et al., 2011; Dutton et al., 2015a; Dutton et al., 2015b; Mercer, 1978). The existence of ~250 ka Mt. Erebus ash in the ANDRILL site in Ross Sea could indicate a smaller-than-present West Antarctic ice sheet (WAIS) sometime after ~250 ka (McKay et al., 2012). The ice-core record from Mount Moulton, West Antarctica could be consistent with deglaciation of much of West Antarctica during the LIG, and likely at 130-126 ka (Steig et al., 2015). Standalone ice sheet model simulations forced by ocean warming suggest the West Antarctic ice sheet to be a major contributor to LIG global mean sea level rise, with contributions also coming from the marine-based portions of the East Antarctic ice sheet (DeConto and Pollard, 2016). Contributions are 6.0-7.5 m of equivalent sea-level rise, which would explain global mean sea level being at least +6 m by ~127 ka (Dutton et al., 2015b). However, because of the difficulty in

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implementing ice-to-ocean changes for the WAIS and the uncertainties associated with dating the changes in the other ice sheets, the paleogeography of the *lig127k* simulation will be prescribed the same as in the DECK *piControl* simulation (Table 1). In view of the greater uncertainty associated with the prescription of ice sheets in the *lig127k* experiment, this aspect of the boundary conditions will be a major focus of sensitivity experiments (see Section 3).

2.4 Vegetation

There is abundant evidence for changes in vegetation distribution during the mid-Holocene and the LIG (Goni et al., 2005; Harrison and Bartlein, 2012; Hely et al., 2014; LIGA Members, 1991; Prentice et al., 2000). However, there is insufficient data coverage for many regions to be able to produce reliable global vegetation maps. Furthermore, given the very different levels of complexity in the treatment of vegetation properties, phenology and dynamics in the current generation of climate models, paleo-observations do not provide sufficient information to constrain their behavior in a comparable way. The treatment of natural vegetation in the *midHolocene* and *lig127k* simulations should therefore be the same as in the DECK *piControl* simulation. That is, depending on what is done in the DECK *piControl* simulation, vegetation should either be prescribed to be the same as in that simulation, or prescribed but with interactive phenology, or predicted dynamically (Table 1). Uncertainties related to the treatment of vegetation in the different simulations will be analyzed through sensitivity experiments (see section 3).

2.5 Aerosols: tropospheric dust and stratospheric volcanic

Natural aerosols show large variations on glacial-interglacial time scales, with low aerosol loadings during interglacials compared to glacials, and during the peak of the interglacials compared to present day (Albani et al., 2015; deMenocal et al., 2000; Kohfeld and Harrison, 2000; McGee et al., 2013). Atmospheric dust affects radiative forcing at a regional scale and can therefore affect precipitation and surface hydrology (Miller et al., 2004; Yoshioka et al., 2007) including the monsoons (Konare et al., 2008; Pausata et al., 2016; Vinoj et al., 2014) as well as moderating snow albedo feedbacks when sufficient dust is deposited (Krinner et al., 2006). While model simulations that are observationally constrained by a global compilation of dust records suggest that the global dust budget was dominated by NH dynamics during the *midHolocene* as it is today, the total loading as well as regional patterns of dust loading were different (Albani et al., 2015). This motivates the inclusion of changes in dust loading in the *midHolocene* and *lig127k* simulations (Table 1, Figure 6).

As in the case of vegetation, the implementation of changes in atmospheric aerosol in the *midHolocene* and *lig127k* simulations should follow the treatment used for the DECK *piControl* and *historical* simulations. Models with an interactive representation of dust should prescribe changes in soil erodibility or dust emissions to account for the changes in dust sources during the interglacials. Although the maps provided by PMIP for this purpose are for mid-Holocene conditions and from the only model simulation available (Albani et al., 2015), they should be used for both the *midHolocene* and *lig127k* simulations. For each model configuration, if atmospheric dust loading is prescribed in the DECK *piControl* and *historical* simulations, the *midHolocene* and *lig127k* simulations should use the three-dimensional monthly climatology of atmospheric dust mass concentrations or aerosol optical depths

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available from the same data-constrained simulations as the soil erodibility maps. Also available are datasets of the dust shortwave and longwave direct radiative forcing. If atmospheric dust loading is not represented in the DECK *piControl* and *historical* simulations, it should not be included in the *midHolocene* and *lig127k* simulations. The impact of dust on the radiation balance is sensitive to the optical properties prescribed (Perlwitz et al., 2001); it is uncertain how optical properties might change during interglacials (Potenza et al., 2016; Royer et al., 1983). Uncertainties in the protocol and in the interplay between dust and vegetation will be a focus of the analyses.

There is no observationally-constrained estimate of the volcanic stratospheric aerosol for either the mid-Holocene or the LIG. The background volcanic stratospheric aerosol used in the CMIP6 DECK *piControl* should be used for the *midHolocene* and *lig127k* simulations. Other aerosols included in the DECK *piControl* should similarly be included in the *midHolocene* and *lig127k* simulations.

2.6 Setup and documentation of simulations

To provide initial conditions for the simulations, it is recommended that a spin-up simulation is performed departing from the CMIP6 *piControl* experiment. The length of this spin-up simulation will be model- and resource-dependent. However, it should be long enough to minimize at least surface climate trends.

The modelling groups are responsible for a comprehensive documentation of the model system and the experiments. Documentation should be provided via the ESDOC website and tools provided by CMIP6 (http://es-doc.org/) to facilitate communication with other CMIP6 projects. A PMIP4 special issue in GMD and Climate of the Past has been opened where the groups are encouraged to publish these documentations.

The documentation should include:

- The model version and specifications, like interactive vegetation or interactive aerosol modules etc.
- A link to the DECK experiments performed with this model version.
- Specification of the forcing data sets used and their implementation in the model. The provision of figures and tables giving monthly-latitude insolation anomalies and daily incoming solar radiation at the top of the atmosphere (TOA) for one year should be provided because this allows the implementation of the most critical forcing to be checked.
- Information about the initial conditions and spin-up technique used.
- We request providing information on drift in key variables for a few hundred years at the end of the spin-up and the beginning of the actual experiment. These variables are:
  - globally and annually averaged SSTs
  - deep ocean temperatures (global and annual average over depths below 2500m)
  - deep ocean salinity (global and annual average over depths below 2500m)
  - top of atmosphere energy budget (global and annual average)
  - surface energy budget (global and annual average)
  - northern sea-ice (annual average over northern hemisphere)

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- southern sea-ice (annual average over southern hemisphere)
- northern surface air temperature (annual average over northern hemisphere)
- southern surface air temperature (annual average over southern hemisphere)
- Atlantic Meridional Overturning Circulation (maximum overturning stream function in the North Atlantic basin between 0 and 80°N below 500m depth)
- carbon budget (if relevant)

3 PMIP4-CMIP6 Tier 2 and Tier 3 Simulations

The selection of only two intervals, *midHolocene* and *lig127k*, for PMIP4-CMIP6 interglacial experiments is designed to maximize both the multi-model ensemble size and opportunities for model evaluation, since both periods have been the focus for data synthesis. However, this means that the experiments do not sample the diversity in the transient forcings and responses during the LIG and the Holocene. Although transient simulations for these two periods are included in the suite of PMIP4 simulations (see 3.5), there is utility in examining other interglacial climates using equilibrium experiments parallel to the *midHolocene* and *lig127k* simulations, particularly in order to provide additional samples of the response of the system to insolation forcing. Additional Tier 2 experiments – the end of the LIG (116 ka) and the early Holocene (9.5 ka) (see 3.1) – are proposed to address this.

Uncertainties in the boundary and initial conditions for the mid-Holocene and LIG mean that the PMIP4-CMIP6 *midHolocene* and *lig127k* simulations may not capture important feedbacks accurately. The major sources of uncertainty in the boundary conditions are the prescription of modern vegetation cover by some models, and the prescription of modern ice sheets in the *lig127k* simulation. Both sources of uncertainty can be addressed through Tier 2 sensitivity experiments (see 3.2, 3.3). The equilibrium experiments also do not address climate changes forced by the non-linear behavior of ice sheet-ocean coupling, or the possibility that such feedbacks could give rise to abrupt changes in climate superimposed on the more slowly-varying insolation forcing during the Holocene and the LIG. This will be addressed through Tier 2 idealized simulations of specific freshwater-forcing events, specifically the Heinrich 11 event at the beginning of the LIG and the 8.2 ka event during the Holocene (see 3.4). Understanding the interplay among different components of the Earth system in determining the long-term evolution of LIG and Holocene climate is the major goal of the proposed Tier 3 transient experiments (Section 3.5) to be carried out during PMIP4.

Further information and access to datasets is available on PMIP4 web site and will be updated during the course of the project (https://pmip4.lsce.ipsl.fr/doku.php/exp_design:index)

3.1 Equilibrium response to alternative states of orbital forcing

hol9.5k The maximum expression of Holocene orbitally-induced differences in TOA insolation forcing from present occurred during the early part of the Holocene, but the climate at this time was still affected by the presence of a relict of the Laurentide ice sheet (Carlson et al., 2008b). As a result, summer temperatures in mid- to high latitudes

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were cooler than during the mid-Holocene (Carlson et al., 2008b; Renssen et al., 2012; Renssen et al., 2009). The presence of the ice sheet delayed the response to insolation forcing in monsoon regions (Lezine et al., 2011; Marzin et al., 2013). It has also been suggested that the remnant ice-sheet may have counteracted the reduction of ENSO variability in response to orbital forcing in the early Holocene (Carre et al., 2014; Luan et al., 2015). Protocols for early Holocene experiments were developed in previous phases of PMIP (PMIP2, PMIP3), and provide the basis for proposed PMIP4 simulation for 9.5 ka. Since the phase of precession at 9.5 ka is similar to that of 127 ka, this experiment provides a basis for examination of the similarities in seasonal changes between the two interglacials (Braconnot et al., 2008). Following the experimental protocol for the *midHolocene* simulation, orbital parameters should be changed following Berger and Loutre (1991). The extent and topography of the ice sheet should be prescribed using either ICE-6G or GLAC-1D, as proposed by the PMIP deglaciation working group (Ivanovic et al., 2016). GHG concentrations can also be prescribed from the last deglaciation experiment (Table 2).

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lig116k Continental ice sheet growth and associated sea level lowering started at ~116 ka, marking the end of the LIG (Stirling et al., 1998). Simulations with climate models that include feedbacks among the atmosphere, ocean, land, and sea ice are able to simulate sufficient cooling to initiate ice sheet growth when forced with the 116 ka orbital conditions reducing NH summer insolation (Herrington and Poulsen, 2012; Jochum et al., 2012). However, the result is sensitive to the atmospheric CO_2 concentration used. To test the ability of the CMIP6 and PMIP4 models to simulate glacial inception, we propose a sensitivity experiment using orbital parameters for 116 ka (*lig116k*). The CO_2 concentration should be prescribed as 273 ppm (Bereiter et al., 2015; Schneider et al., 2013). All other forcings and boundary conditions will remain the same as the *lig127k* simulation (Table 2).

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3.2 Sensitivity to Prescribed Vegetation

Except in the case of models with dynamic vegetation, the *midHolocene* and *lig127k* simulations will be run with prescribed preindustrial vegetation cover because of the lack of a comprehensive and reliable global data set of vegetation for the two periods. However, pollen and macro-fossil evidence show that boreal forest extended farther north than today in the mid-Holocene (Bigelow and al., 2003; Prentice et al., 2000; Binney et al., 2017) and, except in Alaska and central Canada, extended to the Arctic coast during the LIG (Edwards et al., 2003; LIGA, 1991; Lozhkin and Anderson, 1995). Pollen and other biogeographical/geomorphological and paleohydrological evidence also indicate northward extension of vegetation into modern-day desert areas, particularly in northern Africa, both in the mid-Holocene (Drake et al., 2011; Hely et al., 2014; Larrasoana et al., 2013; Lezine et al., 2011; Prentice et al., 2000; Tierney et al., 2017) and during the maximum phase of the LIG (Castaneda et al., 2009; Hooghiemstra et al., 1992). Given the impact of increased woody cover on albedo and evapotranspiration, these vegetation changes should have profound impacts on the surface energy and water budgets and may help to explain mismatches between simulated and reconstructed high-latitude (Muschitiello et al., 2015) and monsoon climates (Braconnot et al., 1999; Claussen and Gayler, 1997; Pausata et al., 2016) in both time periods.

We propose sensitivity experiments for the *midHolocene* and *lig127k* to explore the feedbacks between vegetation and climate. Vegetation cover in the NH high-latitudes should be changed from tundra to boreal forest and the Sahara desert replaced by evergreen shrub to 25°N and savanna/steppe poleward of 25°N. Ideally, these regional changes should be made separately in order to diagnose the interaction between high-latitude and low-latitude climates, and a third experiment could be made implementing both changes. In each experiment, all other boundary conditions should be implemented as in the baseline *midHolocene* and *lig127k* simulations (Table 2).

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Sensitivity experiments will also be required to characterize the uncertainties related to the prescription of dust fields in the midHolocene and LIG simulations, but it is difficult to anticipate the form of such experiments until the Tier 1 experiments are diagnosed. A first step could be to investigate the vegetation feedback on emission in simulations with interactive dust exploiting the vegetation sensitivity analyses.

3.3 Sensitivity to Prescribed Ice Sheets

The *midHolocene* and *lig127k* simulations will be run with prescribed modern ice sheets and paleogeography. However, it is highly likely that the Antarctic ice sheet was smaller than present by ~127 ka, most probably because of the disappearance of the WAIS, and that the Greenland ice sheet was reduced in extent compared to present. Given that only about 3-4 m sea level rise are covered by contributions from ocean thermal expansion (McKay et al., 2011), land based glaciers (Marzeion et al., 2012), and melting of the Greenland Ice Sheet (NEEM Community Members, 2013; Masson-Delmotte et al., 2013), the remaining sea level rise is most likely to be linked to a mass loss from the Antarctic ice sheet. We propose a sensitivity experiment *lig127k-ais* to test the impact of a smaller-than-present Antarctic ice sheet, using a reduced ice-sheet configuration obtained from off-line simulations with their own models or the model results such as those from DeConto and Pollard (2016) or Sutter et al. (2016). These authors used a dynamic ice sheet model, forced with climate model output and calibrated to reproduce LIG sea-level estimates, to simulate the Antarctic ice sheet at 128 ka. All other boundary conditions should be implemented as in the baseline *lig127k* simulation. An additional sensitivity simulation *lig127k-gris* to complement the *lig127k* simulations is proposed in which the Greenland ice sheet is configured to its minimum LIG extent are also of interest, using configurations obtained from off-line simulations, for example from ISMIP6.

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3.4 Freshwater Forcing

Sensitivity to the H11 meltwater event during the early LIG. Heinrich layers in the North Atlantic, containing high concentrations of IRD, record multiple examples of prolonged iceberg discharge during the past 500 ka (Hemming, 2004; Marino et al., 2015; McManus et al., 1999). Heinrich event 11 (H11) is a well-documented example that occurred from ~135-128 ka (Marino et al., 2015). The associated freshwater flux has been estimated as peaking at ~0.3 Sv at ~132.5 ka and tapering off thereafter (Marino et al., 2015), and is broadly consistent with an estimate of 0.19 Sv at 130 ka based on coral records (Carlson, 2008). There is also evidence of a rapid sea level rise associated with this meltwater pulse, estimated at ~70 m or 28±8 m ka^{-1} (~0.32±0.09 Sv) during the deglacial transition (Grant et al., 2012). Model simulations have shown that the freshwater forcing of H11, including its cessation, may be important for explaining the evolution of climate through the early part of the LIG (Goelzer et al., 2016a, 2016b;

Holden et al., 2010; Loutre et al., 2014; Stone et al., 2016). We propose a sensitivity experiment (*lig127k-H11)* to examine the impact of the H11 event. The insolation anomalies at 130 ka are similar to those at 127 ka. Therefore the experiment can be made by adding a persistent flux of 0.2 Sv to the North Atlantic between 50 and 70°N for 1000 years, with all other boundary conditions implemented as in the baseline *lig127k* simulation (Table 2).

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Sensitivity to the 8.2 ka freshwater event during the early Holocene. While the climate impact of the 8.2 ka event is well documented, the magnitude of the freshwater forcing and its duration are less well constrained. There are generally thought to be two components to the freshwater forcing in the early Holocene, a background flux from the Laurentide ice sheet (Hillaire-Marcel et al., 2007; Licciardi et al., 1999) and catastrophic flux from the drainage of Lake Agassiz (Barber et al., 1999; Clarke et al., 2004; Teller et al., 2002). Lake Agassiz appears to have drained in several flood events of relatively short duration, but with an estimated total discharge into the Labrador Sea of ca 151,400 km^3 (Andrews et al., 1999; Andrews et al., 1995; Clarke et al., 2009; Clarke et al., 2004; Ellison et al., 2006; Hillaire-Marcel et al., 2007; Kerwin, 1996; Lajeunesse and St-Onge, 2008; Lewis et al., 2012; Roy et al., 2011). The background flux is smaller (ca 0.13 Sv) but persistent for several hundred years (Carlson et al., 2009; Carlson et al., 2008b; Clarke et al., 2009; Hillaire-Marcel et al., 2007). The proposed sensitivity experiment (*hol8.2k)* can use the orbital, ice sheet, and GHG boundary conditions of the 9.5 ka experiment. The 'Lake + Ice_100 yrs' scenario of Wagner et al (2013) is more consistent with ice dynamics and the data of Carlson et al (2009) than the shorter '1-yr flood scenarios (Morrill et al., 2013) and should be adopted for this sensitivity experiment. That is, modeling groups should impose a single input of 2.5 Sv for one year followed by a background freshwater flux of 0.13 Sv for 99 years (Table 2). This freshwater flux is added to the Labrador Sea, but modeling groups can choose whether to add it uniformly over the whole of the Labrador Sea or only over part of the area.

These simulations should be run a minimum of 100 years after then end of the pulse and if possible even longer, preferably until the Atlantic Meridional Overturning Circulation (AMOC) has recovered to its initial state.

3.5 Transient Holocene and LIG simulations

Transient simulations provide an opportunity to examine the time-dependent evolution of climate in response to forcings and feedbacks. Transient simulations of the last deglaciation are a major focus in PMIP4 (Ivanovic et al., 2016). These simulations will be run for the period 21 to 9 ka with time-varying orbital forcing, greenhouse gases, ice sheets and other geographical changes. The later part of this experiment is obviously of interest for comparison with the early Holocene experiments. However, we are also proposing transient simulations focusing on the Holocene and the LIG.

Using the PMIP-CMIP6 *midHolocene* simulation as a starting point, we propose a transient simulation of the last 6000 years (*past6k)*. In this simulation, both orbital parameters and GHGs will be changed following Berger and Loutre (1991) and ice-core measurements (as described in Section 2.2). Changes in paleotopography over the past 6 ka are small and, for simplicity and consistency with the *midHolocene* simulation, we propose using modern values throughout. Vegetation and aerosols will also be fixed at preindustrial values, except for groups running fully dynamic vegetation and/or aerosol models where the initial state of these components will be derived from their *midHolocene* simulation. Alternatively, some groups may start the Holocene transient simulation from the end of the last deglaciation experiment at 9 ka, incorporating changes in the evolution of ice sheets and paleotopography consistent with that experiment. A proposed LIG transient simulation (*lig127to121k)* will be run from 127 to 121 ka, using appropriate changes in orbital forcing but with all other boundary conditions specified as in the *lig127k* simulation. These simulations as well as simulations planned by some modeling groups with climate-ice sheet models will be important as input for addressing the role of coupling between climate and the ice sheets.

4 Paleoenvironmental data and climate reconstructions for comparison to model simulations

The ability to evaluate the realism of the Tier 1 PMIP4-CMIP6 simulations and the various sensitivity experiments is central to PMIP. Some paleoenvironmental observations can be used for direct comparison with model outputs, including e.g. simulated water balance against lake-level reconstructions (e.g., Coe and Harrison, 2002) or simulated vegetation patterns against pollen-based vegetation reconstructions (e.g., Perez Sanz et al., 2014). Such qualitative comparisons are often adequate to evaluate simulations when, as is the case with regional climate changes in the mid-Holocene and LIG, the changes are large and regionally coherent (Harrison and Bartlein, 2012). There are also quantitative reconstructions of climate variables from a wide variety of archives. There are uncertainties associated with such reconstructions (Harrison et al., 2016), both statistical and resulting from an incomplete understanding of the climate controls on specific types of records, and these uncertainties need to be taken into account in comparisons with simulations. However, an increasing number of process-based models can be used to translate climate model outputs into explicit simulations of specific paleo-records (Emile-Geay and Tingley, 2016; Li et al., 2014; Thompson et al., 2011), allowing uncertainties in process understanding to be made explicit. Drawing on ongoing work for the LGM and the use of ocean biochemistry, tracer and isotopic modeling, efforts will be made to isolate key features of the ocean reconstructions that should be reproduced by climate models.

The major analytical focus for the Holocene experiments is on systematic benchmarking (Harrison et al., 2015) of the *midHolocene* simulation, analysis of feedbacks, and elucidation of the relationship between mean climate state and interannual to centennial variability. Analysis of the *midHolocene* simulation and associated sensitivity experiments benefits from the fact that there has been a major focus on data synthesis for this time period (Bartlein et al., 2011; Bigelow and al., 2003; Daniau et al., 2012; Emile-Geay et al., 2016; Hessler et al., 2014; Kohfeld and Harrison, 2000; Leduc et al., 2010; Marchant et al., 2009; Marlon et al., 2013; Pickett et al., 2004; Prentice et al., 2000). Thus the number of records and spatial coverage of quantitative reconstructions are relatively extensive (Bartlein et al., 2011; Hessler et al., 2014). There are gaps in coverage from continental regions, particularly in the SH, but this situation is likely to improve in the near future (Flantua et al., 2015; Herbert and Harrison, 2016). Knowledge of ocean conditions during the mid-Holocene is poor and likely to remain so, in part because of incomplete understanding of the causes of differences between sea-surface temperature reconstructions based on different biological groups and in part because the signal-to-noise ratio in the reconstructions is small due to other methodological uncertainties (Hessler et al., 2014; Jonkers and Kucera, 2015; Rosell-Mele and Prahl, 2013). There are several sources of information about short-term climate variability during the Holocene, including tree-ring records, spelothems, corals and molluscs. However, there are major gaps in data coverage from the tropical oceans that challenge our understanding of ENSO variability; the distribution of speleothem records is limited to karst areas; and few tropical trees show clear-cut seasonality in growth. More comprehensive syntheses of these data are needed, and there are major challenges in combining the different data sources to yield large-scale reconstructions of climate variability. It will also be necessary to develop appropriate methods to use these data for comparison with simulations, focusing on temporal statistics and teleconnection patterns (Emile-Geay et al., 2016; Emile-Geay and Tingley, 2016).

There are many individual records documenting the evolution of climate through the Holocene, including quantitative climate reconstructions (Wanner et al., 2008). Synthetic products have either focused on reconstructions of global temperature changes (Clark et al., 2012; Marcott et al., 2013; Shakun et al., 2012), or are available as geographically explicit data sets only for a limited number of climate variables in a few regions such as North America or Europe (Davis et al., 2003; Gajewski, 2015; Mauri et al., 2014; Viau and Gajewski, 2009; Viau et al., 2006). The only exception to this is the Global Lake Status Data Base (Kohfeld and Harrison, 2000), which provides qualitative estimates of the change in lake water balance through time globally. The reliability of global temperature estimates depends on the representativeness of the data included; this point has been made abundantly clear from comparisons of records of hemispheric temperature changes during the last millennium (Fernandez-Donado et al., 2013; Moberg, 2013). Currently available reconstructions of global temperature changes during the Holocene are heavily biased towards marine records, making it imperative that the reliability of these records is assessed using continental reconstructions (Davis et al., 2015; Liu et al., 2014). The lack of geographically explicit reconstructions for tropical regions and the SH would limit analysis of the Holocene transient simulations, but efforts are underway to improve this situation.

The LIG is the most suitable of the pre-Holocene interglacial periods as a focus in PMIP4-CMIP6 because of the relative wealth of data compared to earlier interglacial periods. However, there is an order of magnitude less information than for the Holocene, and there are larger uncertainties in dating of specific events. This means that the LIG data-model comparisons will focus on large-scale features, such as the strength of the high-latitude amplification of warming and the role of snow and sea-ice feedbacks in this warming. There will also be a major focus on the tropical water cycle. These analyses will exploit available datasets for the LIG which mostly document surface sea and air temperatures across the globe (Anderson et al., 2006; Brewer et al., 2008; Capron et al., 2014; Hoffman et al., 2017; McKay et al., 2011; Turney and Jones, 2010) although recent efforts also synthesize reconstructions of sea ice changes (Esper and Gersonde, 2014; Sime et al., 2013), of the deep ocean circulation (Oliver et al., 2010), and to a lesser extent the tropical hydrological cycle (Govin et al., 2014). In addition, several existing maps are reporting vegetation changes in the NH high latitudes (Bennike et al., 2001) and changes in lake area in the Sahara (Petit-Maire, 1999).

There are also syntheses of quantitative climate reconstructions for the LIG (Turney and Jones, 2010; McKay et al., 2011; Capron et al., 2014; Hoffman et al., 2017), which have been used for model evaluation (e.g. Lunt et al., 2013; Otto-Bliesner et al., 2013). A critical evaluation of these LIG data syntheses is available in Capron et al. (2017), and we summarize here key aspects of the comparison. The major limitation in using the data syntheses by Turney and Jones (2010) and McKay et al. (2011) for analysis of the *lig127k* simulations and associated sensitivity experiments is that they are compilations of information about the maximum warmth during the LIG. Given that warming was not synchronous globally (Bauch and Erlenkeuser, 2008; Cortese et al., 2007; NEEM Community Members, 2013; Govin et al., 2012; Masson-Delmotte et al., 2010; Mor et al., 2012; Winsor et al., 2012), these syntheses do not represent a specific time slice. A more recent compilation by Capron et al. (2014) has used harmonized chronologies for ice and marine records to produce records of the change in high-latitude temperature compared to present for four 2000-year long time slabs, and this approach has been expanded to include the fifth time slab (128-126 ka) for comparison with the *lig127k* simulation (Capron et al., 2017). Following a similar strategy, Hoffman et al. (2017) propose the first global marine compilation with harmonized chronologies for the LIG, with time slabs available at 129 and 125 ka, but not 127 ka (note that a high-latitude subset of the Hoffman et al. (2017) compilation at 127 ka is available in Capron et al., 2017). However, even though these compilations are based on harmonized chronologies, dating uncertainties during the LIG can still be several thousand years depending on the type of archive and the dating methods (Govin et al., 2015). Furthermore, the different response scales of different components of the climate system means that records from the 128-126 ka time slab may still bear the imprint of the previous deglaciation (Fig. 1) (Capron et al., 2017). In any case, and as with the early Holocene experiments, the *lig127k* simulation will not solely reflect the insolation forcing. It is therefore recommended that data-model comparisons focus on using the temporal evolution of climate, as captured in the available Capron et al. (2014) and the Hoffman et al. (2017) time-series, to assess the plausibility of the *lig127k* simulation.

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The public-access reconstruction data sets currently available for the mid-Holocene and LIG serve different functions and address different aspects of the climate system. Modeling groups running mid-Holocene and LIG simulations, or sensitivity experiments, are encouraged to use multiple reconstruction data sets for a full diagnosis of the simulations. Many of these data sets provide measures of the uncertainty of the reconstructions and data-model comparisons should be designed to take these uncertainties into account.

5 Conclusions

The PMIP4-CMIP6 *midHolocene* and *lig127k* simulations provide an opportunity to examine the impact of two different changes in radiative forcing on climate at times when other forcings were relatively similar to present. Together with planned sensitivity experiments, this focus on the two interglacials will allow us to explore the role of feedbacks in the climate system and to quantify their contribution to large-scale phenomena relevant to future projections such as land-sea contrast and high-latitude amplification of temperature changes. They will also allow us to address the implications of changes in forcing and feedbacks for the tropical circulation and monsoons – again an issue that is relevant to interpreting future projections. Given that both periods have been foci for model-model and data-model comparisons during previous phases of PMIP, a major focus during CMIP6 will be on evaluating the realism of the *midHolocene* and *lig127k* simulations using a wide range of paleoenvironmental data and paleoclimate reconstructions. This evaluation will be a direct out-of-sample test of the reliability of state-of-the-art models to simulate climate changes, and particularly the climate warming.

Neither one of these interglacial simulations is a perfect analogue for the future, and each interglacial has distinct differences in forcings and in the initial state of the climate system. In a sense this is advantageous because it allows us to investigate the response of the system under different conditions. Sensitivity studies allow us to assess which results may be directly transferrable to future climate projections. In the case of the *midHolocene* simulations, we have the advantageous ability to assess Earth's response to elevated boreal summer insolation alone with which we can compare model results against a plethora of observations. Estimated boreal summer warming this period is roughly equivalent to the summer warming simulated for the mid to late 21st century. In the case of the *lig127k* simulations, we have another advantageous end member where boreal summer insolation was even greater than the middle Holocene and that forced eventually higher-than present sea levels. Higher temperatures in the polar regions, particularly during the summer months, directly influence sea ice and the ice sheets. The data evidence provides a means of evaluating if we are capturing this sensitivity correctly in models being used for projections of future climate change. Consequently, this provides a potential imperfect analogue for the end of this century and beyond. For example, Blaschek et al. (2015) found that the influence of freshwater forcing due to Greenland ice sheet melting is the same, regardless of the background climate. In other cases, the response may be more strongly dependent upon the initial state, such as the response of polar amplification in Greenland, which was found to be sensitive to the prescribed ice-sheet elevation (Masson-Delmotte et al., 2006).

PMIP4 will collaborate with other CMIP6 projects (Kagayema et al., 2016, Table 3). The output from the *lig127k* simulation, for example, will be used to force standalone ice sheet experiments (*ism-lig127k-std*) in ISMIP6. This will complement the suite of standalone ISMIP6 ice sheet experiments (Nowicki et al., 2016; http://www.climate-cryosphere.org/activities/targeted/ismip6) for the recent past and future and will add to increase our understanding of the ice-sheet sensitivity to climate changes. The PMIP4-CMIP6 *midHolocene* and *lig127k* simulations, and associated sensitivity experiments, are also relevant to analyses of sea-ice feedbacks to climate in SIMIP (Notz et al., 2016) and to assessments of the role of dust forcing by AerChemMIP (Collins et al., 2017). Beyond CMIP6, the planned PMIP4-CMIP6 interglacial simulations are relevant to the Grand Challenges set by the World Climate Research Programme (WCRP). Both the *midHolocene* and the *lig127k* simulations are relevant to the Grand Challenge "Clouds, Circulation and Climate Sensitivity", which has a major focus on the controls on the monsoon circulation. Also, the *lig127k* simulation is particularly relevant to the Grand Challenge "Melting Ice and Global Consequences", which addresses the stability of the ice sheets. Those simulations carried out with biogeochemical cycles enabled are relevant to the Grand Challenge "Carbon Feedbacks in the Climate System".

6 Data availability and distribution

The forcing and boundary condition data sets described in this paper are available in the PMIP4 repository https://pmip4.lsce.ipsl.fr/doku.php/exp_design:index. After final acceptance of this manuscript, they will be made available also through Input4MIPs (https://esgf-node.llnl.gov/projects/input4mips/, see the living document “Input4MIPs summary” there on the progress of this process).

The Tier 1 *midHolocene* and *lig127k* simulations are part of the CMIP6 experiment family and data will be distributed through the official CMIP6 channels via the Earth System Grid Federation (ESGF, https://earthsystemcog.org/projects/wip/CMIP6DataRequest). A minimum of 100 years of output is required to be uploaded for each simulation (usually the final 100 years of the simulation). However, given the increasing interest in analyzing multi-decadal variability (e.g. Wittenberg, 2009) and the availability of reconstructions of ENSO (El Niño-Southern Oscillation) and other modes of variability (see Section 3), modeling groups are encouraged to provide outputs for at least 500 years if possible.

In addition, the difference in orbital configuration between 127 ka, 6 ka and preindustrial means that there are differences in month and season length that should be accounted for in calculating seasonal changes (Kutzbach and Gallimore, 1988). To be able to account for this effect when comparing the simulations to the paleoclimate reconstructions, daily outputs of at least surface 2-meter temperature (tas), precipitation (pr) and 10-meter winds (uas) should be archived. If not possible, a less accurate but probably adequate approach, would be to use a program that provides an approximate estimate of monthly means on the fixed-angular celestial calendar from fixed-day calendar.

Data from PMIP4-only Tier 2 and 3 simulations must be processed following the same standards as Tier 1 for data processing (e.g. CMOR standards) and should be distributed via the PMIP4 ESGF or the CMIP6 ESGF Tier 2 and Tier 3 databases. Modeling groups producing these simulations are responsible to secure suitable space on ESGF nodes. These experiments will follow the same naming, variable convention and format, and documentation requests as Tier 1 PMIP4-CMIP6 experiment so as to be compliant with ESGF database requirements.

The list of variables requested for the PMIP4-CMIP6 paleoclimate experiments can be found here: http://clipc-services.ceda.ac.uk/dreq/u/PMIP.html. This request is presently processed by the CMIP6 Working Group for Coupled Modeling Infrastructure Panel (WIP) into tables, which define the variables included in the data request to the modelling groups for data to be contributed to the archive. The most up-to-date list including all variables requested for CMIP6 can be found at the WIP site:

proj.badc.rl.ac.uk/svn/exarch/CMIP6dreq/tags/latest/dreqPy/docs/CMIP6_MIP_tables.xlsx

The last two columns in each row list MIPs associated with each variable. The first column in this pair lists the MIPs, which are requesting the variable in one or more experiments. The second column lists the MIPs proposing experiments in which this variable is requested.

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As supplementary to this manuscript we provide version 1.00.05 (April 2017) of the table in Appendix A. We note, however, that this document is still in development and inconsistencies may still exist.

The only variables defined specifically in PMIP are those describing oxygen isotopes for model systems that calculate these data interactively (Kageyama et al., 2016).

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Table 1. Forcings and boundary conditions. More details can be found in the Section numbers indicated in parentheses.

	1850 C.E. (DECK *piControl*)[1]	**6ka (*midHolocene*)[2]**	**127ka (*lig127k*)[2]**
Orbital parameters (2.1)	CMIP DECK *piControl*		
Eccentricity	0.016764	0.018682	0.039378
Obliquity (degrees)	23.459	24.105	24.040
Perihelion - 180	100.33	0.87	275.41
Vernal equinox	Fixed to noon on March 21	Fixed to noon on March 21	Fixed to noon on March 21
Greenhouse gases (2.2)			
Carbon dioxide (ppm)	284.3	264.4	275
Methane (ppb)	808.2	597	685
Nitrous oxide (ppb)	273.0	262	255
Other GHG gases	CMIP DECK *piControl*	0	0
Solar constant (Wm^{-2}) (2.1)	TSI: 1360.747	Same as *piControl*	Same as *piControl*
Paleogeography (2.3)	Modern	Same as *piControl*	Same as *piControl*
Ice sheets (2.3)	Modern	Same as *piControl*	Same as *piControl*
Vegetation (2.4)	CMIP DECK *piControl*	Prescribed or interactive as in *piControl*	Prescribed or interactive as in *piControl*
Aerosols (2.5) Dust, Volcanic, etc.	CMIP DECK *piControl*	Prescribed or interactive as in *piControl*	Prescribed or interactive as in *piControl*

[1] More information on the CMIP DECK *piControl* and CMIP6 *historical* protocols can be found in the Geoscientific Model Development Special Issue on the Coupled Model Intercomparison Project Phase 6 (CMIP6) Experimental Design and Organization and at http://www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6

[2] Datasets for *midHolocene* and *lig127k* are available on the PMIP4 web page: https://pmip4.lsce.ipsl.fr/doku.php/exp_design:index

Table 2. Summary of PMIP4 Tier 2 and Tier3 sensitivity simulations complementing PMIP4/CMIP6 Tier 1 interglacial experiments. More details can be found in the Section numbers indicated in parentheses.

PMIP4-CMIP6 sensitivity experiments: Tier 2 simulations		
Experiments	Holocene	Last Interglacial
Orbital forcing and trace gases (3.1)	*hol9.5k*: Early Holocene • Orbital: 9.5 ka[1] • Ice sheet: ICE-6G or GLAC-1D reconstruction[3] • GHG: same as for the deglaciation experiment[3]	*lig116k*: Glacial inception • Orbital: 116 ka[2] • CO$_2$: 273 ppm • Other forcings and boundary conditions: as for *lig127k*
Sensitivity to vegetation (3.2)	*midHolocene-veg* • prescribed boreal forests in Arctic and shrub/savanna over Sahara (together and in turn)	*lig127k-veg* • prescribed boreal forests in Arctic and shrub/savanna over Sahara (together and in turn)
Sensitivity to Ice-Sheet (3.3)		*lig127k-ais* and *lig127k-gris* • Antarctic ice sheet at its minimum LIG extent • Greenland ice sheet at its minimum LIG extent
Test to freshwater flux (3.4)	*hol8.2k:* 8.2 ka event • Meltwater flux of 2.5 Sv for one year added to the Labrador Sea followed by 0.13 Sv for 99 years • Other forcings and boundary conditions: as for *hol9.5k* • Initial state*: hol9.5k* simulation	*lig127k-H11*: Heinrich 11 meltwater event • Meltwater flux of 0.2 Sv to the North Atlantic between 50 and 70°N for 1000 years • Other forcings and boundary conditions: as for *lig127k* • Initial state: *lig127k* simulation
PMIP4-CMIP6 sensitivity experiments: Tier 3 simulations		
Transient simulations (3.5) (Note : Exploratory and flexible set up)	*past6k*: transient Holocene • Transient evolution in Earth's orbit and trace gases • Other boundary conditions (land use, solar, volcanism) may be considered by some groups • Initial state: *midHolocene*	*lig127to121k*: transient LIG • Transient evolution in Earth's orbit and trace gases • Other boundary conditions (ice sheets) may be considered by some groups • Initial state: *lig127k*

[1] Orbital parameters for 9.5ka: eccentricity = 0.0193, obliquity = 24.23, perihelion-180 = 303

[2] Orbital parameters for 116ka: eccentricity = 0.0414, obliquity = 22.49, perihelion-180 = 94.17

[3] Ivanovic et al., 2016; available on the PMIP4 web page

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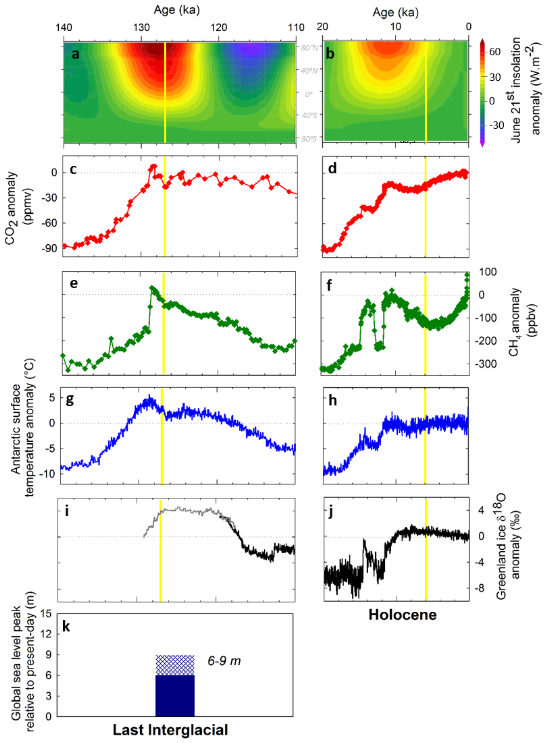


Figure 1: Forcing and climatic records across the Last Interglacial (LIG, left) and the Holocene (right). Records are displayed in panels **A)** to **J)** as anomalies relative to their average value of the last 1000 years. **A** and **B**) 21st June insolation across latitudes; **C** and **D)** Atmospheric CO$_2$ concentration (Siegenthaler et al., 2005; Schneider et al., 2013; Monnin et al., 2001 Monnin et al., 2004); **E** and **F)** Atmospheric CH$_4$ concentration Loulergue et al., 2008); **G** and **H)** Antarctic surface air temperature reconstruction (Jouzel et al., 2007); **I** and **J)** Greenland ice δ^{18}O: from NEEM ice core (NEEM-community-members, 2013) in dark grey and from NGRIP ice core NorthGRIP-community-members, 2004) in black. Note that NEEM ice δ^{18}O is shifted by +2‰. **K**) LIG maximum global mean sea level (GMSL) relative to present-day, uncertainties in the amplitude are indicated by the shading (see Dutton et al., 2015a for a review). Time of maximum varies between reconstructions. No significant sea level variations are reported throughout the Holocene compared to present-day. NGRIP ice δ^{18}O is displayed on the GICC05 annual layer-counted timescale (Svensson et al., 2008) over the last 20 ka and on the AICC2012 chronology (Bazin et al. 2013, Veres et al. 2013)d across the 119-110 ka time interval. All other ice core records are displayed on the AICC2012 chronology, which is coherent, by construction with the GICC05 time scale over the last 60 ka (Bazin et al., 2013, Veres et al., 2013,). Vertical yellow lines indicate 127 and 6 ka, the time intervals chosen to run the coordinated PMIP4-CMIP6 *lig127k* and *midHolocene* simulations.

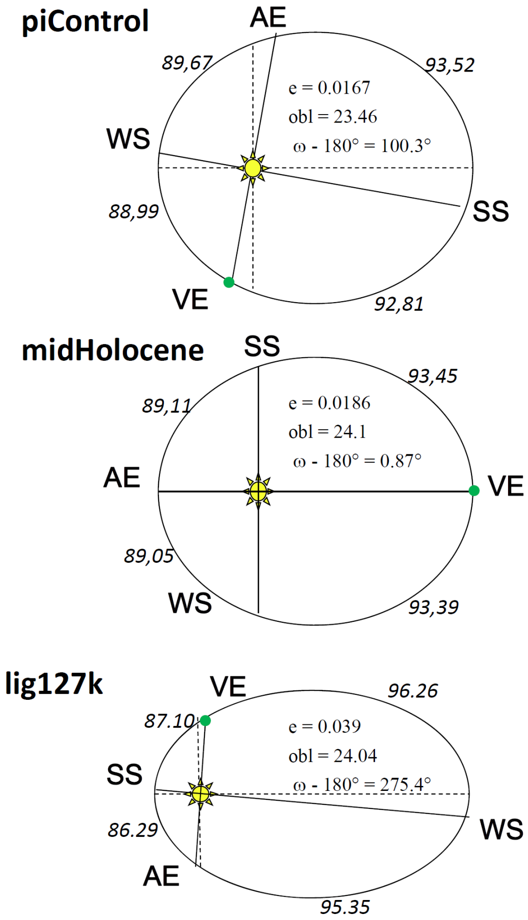
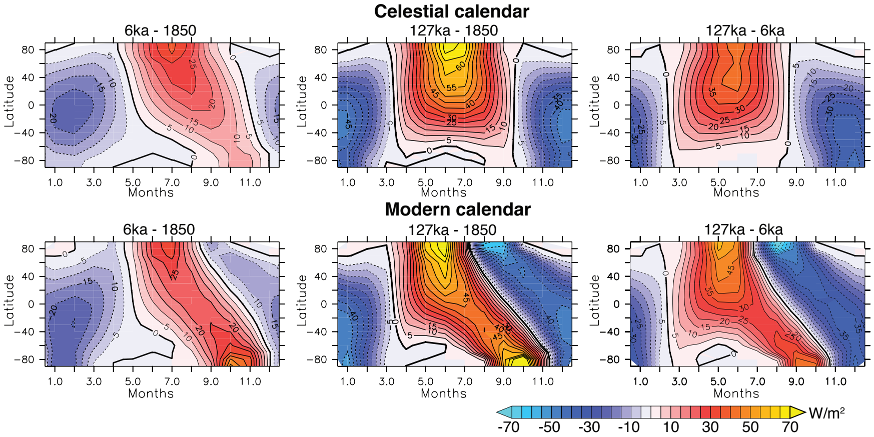


Figure 2. Orbital configurations for *piControl, midHolocene, and lig127k* experiments. Note that aspect ratio between the two axes of the ellipse has been magnified to better highlight the differences between the periods. However, the change in ratio between the different periods is proportional to the real values. In these graphs VE stands for vernal equinox, SS for summer solstice, AE for autumnal equinox, and WS for winter solstice. The numbers along the ellipse are the number of days between solstices and equinoxes.



1405 **Figure 3. Latitude-month insolation anomalies (6ka-1850, 127ka-1850, 127ka-6ka)** computed using either the celestial calendar (top) or the modern calendar (bottom), with vernal equinox on March 21 at noon, to compute monthly averages (W m^{-2}).

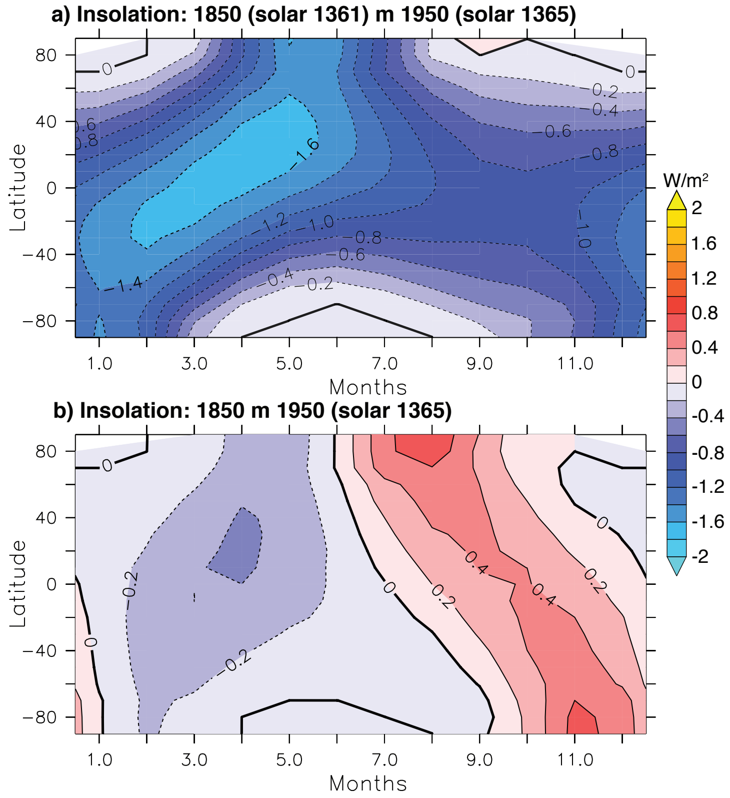


Figure 4. **Difference in incoming solar radiation at the top of the atmosphere (W m^{-2}) between PMIP4 and PMIP3 protocols**, a) considering the changes in Earth's orbital parameters between 1850 and 1950 and the reduction of the solar constant from 1365 to 1360.7 between these two PMIP phases and b) only the changes in Earth's orbital parameters.

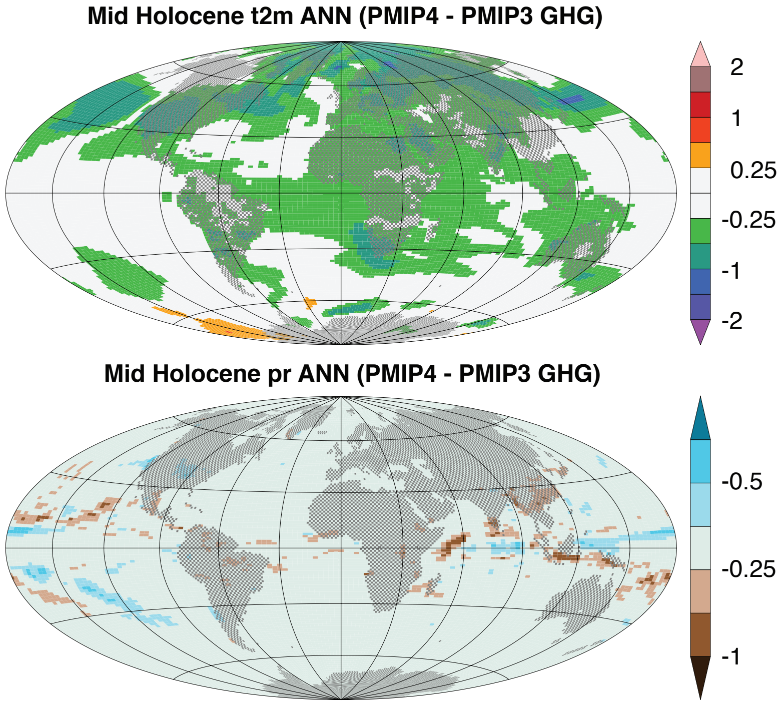


Figure 5. Impact of the changes in trace gases specified for 6 ka between PMIP3 and PMIP4 on surface air temperature (°C) and precipitation (mm d^{-1}) as estimated with the IPSLCM5A model. Only significant values are plotted in colors. 1420

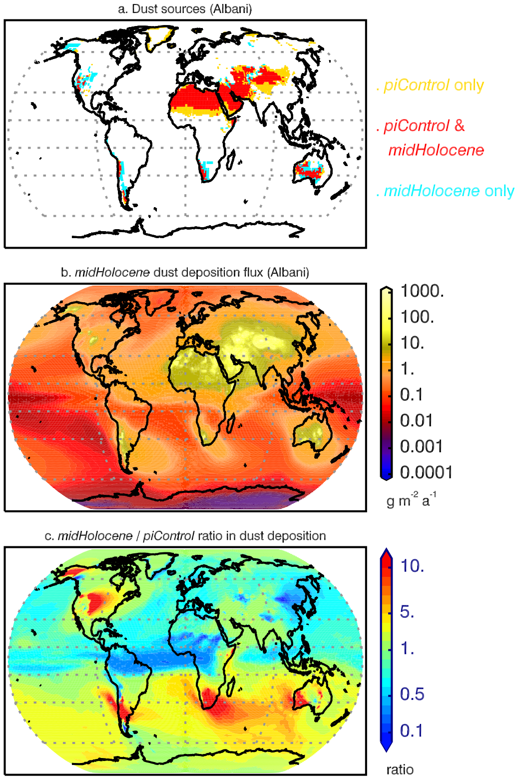


Figure 6. Maps of dust from observationally-constrained simulations with the Community Climate System Model for the *midHolocene* (Albani et al., 2015). a. Active sources for dust emissions for the *midHolocene* and the *piControl* (Albani et al., 2016). b. Dust deposition (g m^{-2} a^{-1}) in the *midHolocene*. c. Ratio of *midHolocene* / *piControl* dust deposition.

Appendix A: Variable request

This list represents what is currently available from the official CMIP6 source (http://proj.badc.rl.ac.uk/svn/exarch/CMIP6dreq/tags/latest/dreqPy/docs/CMIP6_MIP_tables.xlsx).

For updates, users should refer to the website with the PMIP data request (https://pmip4.lsce.ipsl.fr/doku.php/database:pmip4request#the_pmip4_request).

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Spin-up procedures differ for different models, but the model must be run for long enough to avoid long-term drift in the global energetics and major climate variables, including intermediate ocean temperatures. A minimum of 500 years for the total length of simulation is required, assuming an initialization from modern ocean conditions. The outputs stored in the CMIP6 database should be representative of the equilibrium climates of the *midHolocene* and *lig127k* time periods. A minimum of 100 years of output is required to be uploaded for each simulation (usually the final 100 years of the simulation). However, given the increasing interest in analyzing multi-decadal variability (e.g. Wittenberg, 2009) and the availability of reconstructions of ENSO (El Niño-Southern Oscillation) and other modes of variability (see Section 3), modeling groups are encouraged to provide outputs for at least 500 years if possible.

The required detailed documentation of the PMIP4-CMIP6 simulations can be found in Kageyama et al., 2016. Documentation should be provided via the ESDOC website and tools provided by CMIP6 (http://es-doc.org/) to facilitate communication with other CMIP6 projects. This documentation should be mirrored on the PMIP4 website to facilitate linkages with non-CMIP6 simulations to be carried out in PMIP4. For the *midHolocene* and *lig127k*, the documentation should include:

- A description of the model and its components;
- Information on the implementation of the forcings. The provision of figures and tables giving monthly-latitude insolation anomalies and daily incoming solar radiation at the top of the atmosphere (TOA) for one year should be provided because this allows the implementation of the most critical forcing to be checked. Information about the implementation of aerosols should also be provided. Any differences from the protocols in Table 1 need to be documented;
- Information about the initial conditions and spin-up technique used, as well as any information about model tuning that could affect albedo, climate thresholds or climate variability. A measure of the changes and drifts in key variables (e.g., globally averaged 2m temperatures, sea-surface temperatures, bottom ocean temperatures, and top-of-the-atmosphere radiative fluxes) should be provided.