

This document includes responses (in blue) to all the Reviewer comments.

Response to Interactive comments by Anonymous Referee #1 [RC1]

However, it seems to me that in the current setup there are perhaps too many sensitivity experiments proposed, with too many options, with the likely result that in the end a proper model inter-comparison becomes difficult since very few groups in fact performed the same sensitivity experiments. The authors have certainly carefully considered the issue and thus the proposed simulations are possibly the optimal solution, however, it seems to me that the topic is of such importance that a general reviewer comment is justified.

*We agree. With so many sensitivity expts there is the possibility of too few modeling groups doing the same experiments. We have limited the lig116k glacial inception to the reconstructed value of CO2 and kept only the prescribed boreal forest and shrub savanna experiments to test the sensitivities to more idealized vegetation configurations. We also now suggest that the hol8.2k experiment can start from the hol9.5k simulation.*

Therefore I strongly suggest to discuss the topic: What are the differences between early Holocene / Last Interglacial and future climate change? Which lessons from these past periods can be used to inform us about the future? Which systems and their sensitivity are influenced by the difference in the forcing and which ones are for instance solely driven by higher temperatures and can thus be seen as direct analogues? Do the authors have data available to provide some examples? Or have studies been done to investigate this? Possible examples that come to mind are Masson-Delmotte et al. (2006, DOI: 0.1007/s00382-005-0081-9c) and Blaschek et al. (2015, DOI: 10.1007/s00382-014-2279-1).

*We have added a short discussion to the Conclusions. Neither time period can be suggested as a true paleo-analogue for the future because of the seasonal nature of the orbital forcing. That said, higher temperatures in the polar regions, particularly during the summer months and for the Last Interglacial, 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.*

The manuscript describes quite extensively the proxy-based paleoclimate datasets that are available for the early Holocene and the Last Interglacial (section 4). However, it does not seem to come to any conclusions. Is this part solely meant to provide an overview? If so, is this the correct journal and manuscript to do so? Or do the authors mean to provide some guidance for future model-data inter-comparisons? In which case the conclusions of this section should be made more clear.

*The goal here was to summarise the data sets that are available for different types of model evaluation for the MH and LIG, and thus we explicitly draw attention to the state-of-the-art syntheses of data on e.g. hydrology, vegetation, climate reconstruction, climate variability etc in this section. We feel that it is important to do this in the current paper (a) to make it clear that model evaluation of the experiments is feasible, and (b) so that modelers are aware of the available data sets and their limitations. However, we agree that it would be useful to add something at the end of this section in conclusion. So we have added the following:*

*“The public-access data sets currently available for the MH and LIG serve different functions and address different aspects of the climate system. Modeling groups running MH and LIG simulations, or sensitivity experiments, are encouraged to work with data experts, using multiple 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.”*

Minor and technical comments:

Lines 87-88: The second part of this sentence describes the possible results of these forcings, but since this paragraph solely describes the forcings themselves, it could be better to move this part to later in the manuscript.

*Moved to next paragraph.*

Lines 87-88: Provide references for the warmer NH summers and enhanced NH monsoons.

*References have been added.*

Lines 106-107: Different model biases and the issue of model complexity are discussed here. How do the presented experimental designs overcome these issues? Please shortly discuss, perhaps later in the manuscript.

*Deleted sentence.*

Lines 181-183: It would be easier for the reader if the order in which the two periods are described is always the same, either first early Holocene and then Last Interglacial or the other way around.

*Order switched here to be consistent with discussion of other forcings*

Line 197: What is meant with 'surface', really surface or something like 2m- temperature, reference temperature?

Line 198: Are these surface winds?

*We have moved this paragraph and discussion to the Section 6 on Data Availability and made consistent with the text in the revised version of the CMIP6-PMIP4 Overview paper in GMDD*

Line 284: Perhaps 130-126 ka for consistency.

*Revised as suggested.*

Lines 344-348: Consider mentioning again that daily output is needed to calculate output on angular calendar months vs a fixed calendar months. Is the second part of this paragraph clear to the reader? Do they know what 'output needed to force regional area-limited models' is?

*We have made consistent with the text in the revised version of the CMIP6-PMIP4 Overview paper in GMDD. This text now appears in Section 6 on Data Availability of our paper. A supplementary information table has been added to the paper and also a link to the PMIP4 web site.*

Lines 344-363: Are these paragraphs needed or can the manuscript simply refer to the website where all this information can be found?

*We have not shortened this section on the advice of GMD Chief Editor J. Hargreaves. We have added a list of variables to be saved in the SI.*

Line 383: What feedbacks is this sentence referring to?

*Albedo and freshwater*

Line 404: 'can' or 'should' be prescribed from the last deglaciation experiment? It seems to me that these are the details that could in the end result in a model inter-comparison in which all simulations are slightly different from one another.

*Should*

Lines 409-412: Is the CO<sub>2</sub> concentration for 116ka so uncertain?

*The Tier 2 experiment will use the EPICA Dome C data published by Schneider et al., 2013 CP (that is also publishing  $\delta^{13}\text{-CO}_2$  for the same depth intervals) which is the currently best CO<sub>2</sub> data set for the Eemian. For the 116 ka BP, the nearest data point at 115909 ka BP (on AICC12) has 273 ppm in CO<sub>2</sub>.*

Lines 426-440: Make it more clear which of these sensitivity experiments are proposed for both the Holocene and the Last Interglacial and which ones only for the Holocene (in line with Table 2).

*Revised as suggested.*

Line 445: remove first 'is'.

*Paragraph deleted.*

Line 445: year of reference to Hoelzmann is missing.

*Paragraph deleted.*

Lines 446-449: This part is rather vague. Are sensitivity experiments in this direction foreseen in PMIP4 or not?

*Paragraph deleted.*

Line 470: This line seems to suggest that the 'coral records' do not provide evidence of sea level rise. Please rephrase.

*Clarified*

Line 471: Can this value also be given in Sv for easier comparison?

*Done*

Line 484: 0.13Sv doesn't seem small at all, is this typo?

*Revised to be clearer*

Line 489: I understand that the 8.2ka-event happened close to 8.5ka, but is it really necessary to introduce yet another simulation? Can't one simply use either 9.5 or 6ka in line with the other experiments?

*We agree. This proposed experiment now starts from a 9.5 ka simulation.*

Lines 489-492: This is somewhat unclear to me. Should the 2.5Sv pulse be introduced in year 500? Should both fluxes cease after this or should the background flux continue?

*We agree that as first written the experimental protocol was unclear. Revised to be clearer.*

Lines 492-493: Does 'evidence for the recovery' mean that some upward trend should be visible or that it should again be close to the initial state? Why not give a more concrete number like a minimum of 100yrs after the end of the pulse?

*We agree. Sentence revised.*

Lines 479-493: It seems that this experimental design is similar to experiments that have been performed previously (Wagner et al., 2013, DOI: 10.1007/s00382-013-1706-z and Morrill et al., 2013, DOI: 10.5194/cp-9-955-2013), please refer to these manuscripts and discuss how and why those simulations differed from the design that is proposed here.

*We have revised the experimental design for the freshwater inputs to be the 'Lake + Ice\_100 yrs' scenario of Wagner et al. (2013). As they suggest this design is more consistent with ice dynamics and the data of Carlson et al. (2009) than the shorter 1-yr flood scenarios described in Morrill et al., 2013.*

Lines 509-512: Why not start from 127ka? Should groups perform a 128ka equilibrium simulation as initial condition for the transient 128-122ka simulation? According to table 2 one should use 127ka as initial condition, but will this not lead to some spurious jump in the climate?

*The orbital and GHG forcings are similar for 128 ka and 127 ka but agree that a more consistent experimental protocol is to start from 127 ka. Ending date also revised to 121 ka to be of similar length as midHolocene transient simulation.*

Line 540: Should this be 'small' rather than 'large'?

*Yes, small is correct. We corrected.*

Line 572: Bakker et al. 2013 does not include LIG proxy-based climate reconstruction data. Perhaps Bakker et al., 2014 (DOI: 10.1016/j.quascirev.2014.06.031) is meant?

*We originally included this because it uses climate reconstructions to evaluate the simulations, including simulation of sea ice and high-latitude temperatures. We have now taken the reference out. Bakker et al (2014) is also a data-model comparison paper, rather than a primary source for reconstructions.*

Lines 622-623: A number of datasets that are mentioned throughout the manuscript are not available on the website, when will they be?

*Datasets are now available on the website*



Table 1: For 'Other GHG gases' 6ka and 127ka say '0', is that different from 'CMIP DECK piControl'?

*Yes, there are no CFCs included in the midHolocene and lig127k simulations.*

What does 'SSI<sub>ap</sub> if needed' mean?

*Deleted. Refers to the global level of geomagnetic activity, and are used as inputs to parameterisations of magnetospheric particle precipitation.*

Table 2: part of experiment 3.1 could also be considered as part of 3.3 (sensitivity to ice sheets).

*Yes, but we have decided to keep separate.*

The hol8.2 ka event simulation is somewhat confusing, should it be 8.2 or 8.5 ka orbital?

*We now suggest that the hol8.2k experiment should start from the hol9.5k simulation. Except for the freshwater forcing, all other forcings and boundary conditions remain the same as the hol9.5k simulation.*

Why is a freshwater forcing coming from the Antarctic Ice Sheet not taken into account?

*The early last interglacial freshwater forcing associated with the H11 event is likely to have come from the melting of the MIS6 NH ice sheets. Reconstructions from marine data support this.*

Figure 1: Is the horizontal placement of the global sea-level peak in panel k suggesting the timing of the Last Interglacial high-stand?

*No. We will clarify this in the legend.*

Figures 3 and 4: Color bars are missing and quality is rather low.

*Redrafted to improve quality. Color bars added.*

Response to Interactive comments by Julie Brigham-Grette [RC2]

My major complaint is that the modeling design does not really get at sea ice. Its mentioned a few times. It would seem absolutely necessary that different sea ice configurations are included the same way that different (or prescribed) ice sheet geographies are included. For 6k (with nearly ice free summers from 9 to 6ka? (Funder et al) and for 127k (possible ice free summers at peak interglacial?; no sea ice south of Bering Strait, several papers) sea ice variability or 2-3 different modeled geographies might be considered.

*All the sensitivity simulations proposed are to use the same coupled atmosphere-ocean-sea ice models as the midHolocene and lig127k CMIP6 or PMIP4 simulations to assess missing forcings/boundary conditions that affect the coupled climate state. Although AMIP simulations with different scenarios of seasonal sea ice extent could be of interest, we do not include here.*

The paper is well written and easy to follow however I had to read parts of the Eyring et al paper 2016 in this journal to find some of the terminology. I am not a modeler, yet I am among those in the community who would like to read about modeling project plans, but might not immediately

understand what the “CMIP DECK” is. The paper does an impressive job listing summaries and paleodata compilations that might be used for input however it is not exhaustive.

This paper should move forward to publication with only a few picky edits:

Line 110: I suggest for non-modelers that you add a footnote about what an “entry card” is? I understand this refers to a specific list of requirements.

*As indicated in subsequent text: “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).*

Line 129: define ISMIP6 – Ice Sheet Model Intercomparison 6 contribution to CMIP.

*Defined.*

Line 153: typo, Mollusc shells, not mullusc shells.

*Corrected*

Line 164: write out the meaning of DECK – Diagnostic, Evaluation and Characterization of Klima. One should not have to read the Eyring et al. 2016 paper to get all of the acronyms

*We have revised as suggested.*

.Line 429: move the Lozhkin and Anderson reference. So it reads: . . . vegetation and climate in which vegetation cover in the high-latitudes is changed from tundra to boreal forest (experiment a) (Lozhkin and Anderson, 1995) and the Sahara desert is replaced by evergreen shrub to 25°N and savanna/. . .

*Paragraph deleted.*

Line 445: Add year to the Hoelzmann et al reference.

*Paragraph deleted.*

Line 465 and section 3.4: Should/Could H11 be added to figure 1? Line 490: The location of the freshwater flux is extremely important and there might be reasons for the freshwater to hug the coast rather than be flooded over the entire Labrador sea. So this might also be part of the experimental design?

*We have removed all gray lines from Figure 1. We propose starting the H11 experiment from the 127ka simulation. True, this is an idealization but more feasible than adding an additional time slice simulation for some time between 132-130ka. This should give the first-order approximation of the climate state at 130ka. Again to make this simulation feasible for many modeling groups, we have suggested for this Tier 2 simulation to just add the freshwater across the North Atlantic. Although the European ice sheet is reconstructed to be larger in MIS6 than MIS2, the partitioning of the H11 freshwater between the European and Laurentide ice sheets is not clear.*

Line 1158: Fig. 1 caption. Add Veres et al, 2013 to the sentence containing AICC2012. Or perhaps better yet, cite the editors of the AICC2012 volume.

*Veres et al, 2013 moved as suggested.*

Lines 1175 and 1180: Add color bars to figure 3 and 4 because the print on the lines in the figure are very tiny.

*Done.*

Response to Interactive comments by Anonymous Referee #3 [RC3]

I tend to disagree with Referee 1 that the paper should include some speculations on lessons learnt from the interglacial simulations for possible future climate change. The story of future climate change is about the response of our climate system to unprecedented strong variation in external forcing, while the mid-Holocene and the early Eemian pose the challenge of explaining climate change in the presence of weak variation in external forcing. In any case, simulating the subtleties of past climate variability is a prerequisite for gaining confidence in understanding the dynamics of our climate system – which the authors clearly state.

Before publication, I would appreciate, if the authors could consider the following issues.

a) The authors correctly highlight uncertainties arising from prescribing or simulating Holocene and Eemian vegetation patterns. The authors recommend using the reconstruction by Hoelzmann et al. (1998) for Holocene North Africa. Is this still the best reconstruction? What about the reconstructions mentioned in the papers cited by the authors or by Lézine et al. (2011), Larrasoana et al. (2013), : : ? Perhaps there are good reasons to still use Hoelzmann's et al data. But this should be critically reassessed.

*We agree with Reviewer #1 that there are perhaps too many sensitivity experiments proposed, with too many options. With so many sensitivity expts there is the possibility of too few modeling groups doing the same experiments. We have kept only the prescribed boreal forest and shrub savanna experiments to test the sensitivities to more idealized vegetation, consistent with reconstructions, among models and for comparing these two time periods.*

b) In the same line: What about lakes? Lakes potentially matter in the mid-Holocene Sahara (e.g., Krinner et al., GRL, 2012). Perhaps also for lakes, the reconstruction by Hoelzmann et al. would be useful.

*We agree that lakes could potentially impact the monsoon climate, and there were a number of papers showing this prior to the Krinner et al (2012) paper. Indeed, the Hoelzmann et al (1998) data set was explicitly constructed to allow such sensitivity experiments to be made, see Broström, A., Coe, M., Harrison, S.P., Gallimore, R., Kutzbach, J.E., Foley, J., Prentice, I.C. and Behling, P., 1998. Land surface feedbacks and palaeomonsoons in northern Africa. Geophysical Research Letters 25: 3615-3618. However, previous work suggests that the vegetation changes appear to be the most important element of the land-surface feedback – and given limited resources, our focus in PMIP and in this paper is therefore on designing common experiments to examine the sensitivity to vegetation.*

c) SST biases in the coupled atmosphere – ocean models presumably contribute to an

underestimate of Interglacial Monsoon strengths. Hence some SST sensitivity experiments (e.g., strong vs weak gradient between tropical and extratropical SST differences between pre-industrial and mid-Holocene / LIG climate) might be worth considering.

*All the sensitivity simulations proposed are to use the same coupled atmosphere-ocean-sea ice models as the midHolocene and lig127k CMIP6 or PMIP4 simulations to assess missing forcings/boundary conditions that affect the coupled climate state. Although AMIP simulations with different gradients of SST or scenarios of seasonal sea ice extent could be of interest, we do not include here.*

d) Likewise, sensitivity experiments with respect to changes in Arctic sea-ice could be instructive to explore the role of high latitude climate system feedbacks (cf. the papers cited by the authors). *See comment above.*

Minor issues:

i) The term Tier 1 (explained in line 132) should be defined earlier.

*Defined.*

ii) Fig. 6: I do not understand what Figure 6a refers to. Is it just the geographic location of dust sources, or the difference in locations – irrespective of their strength? Please use a superscript in the dimension  $\text{g/m}^2/\text{a}$ .

*Revised.*

iii) Fig. 5: What is the meaning of the different shades of grey on the continents? In the upper figure, the color grey also appears on the temperature scale (temperature difference between 1.5 and 2 K)?!

*We agree that the color scales are confusing in this figure. This figure has been redrafted.*

iv) Line 754 ff: Something went wrong with the citation of the Dahl Jensen and : : : and : : : and .

*Corrected.*

References to papers cited (and not included in the manuscript):

Krinner, G., Lézine, A. M., Braconnot, P., Sepulchre, P., Ramstein, G., Grenier, C., & Gouttevin, I. (2012). A reassessment of lake and wetland feedbacks on the North African Holocene climate. *Geophysical Research Letters*, 39. doi:10.1029/2012gl050992.

Larrasoana JC, Roberts AP, Rohling EJ (2013) Dynamics of Green Sahara Periods and Their Role in Hominin Evolution. *PLoS ONE* 8(10): e76514. doi:10.1371/journal.pone.0076514

Lézine, A. M., Zheng, W., Braconnot, P., & Krinner, G. (2011). Late Holocene plant and climate evolution at Lake Yoa, northern Chad: pollen data and climate simulations. *Climate of the Past*, 7 (4), 1351-1362.

*Now included.*

Additional note from referee #1 [RC4]

As a follow-up on the interactive comment from referee #3, I would like to add some clarifying words.

Past interglacials, especially the early Last Interglacial, are often regarded as analogues for future climate change. Whether this is justified or not is an open question and I'm not asking the authors to provide any proof in favour or against this idea. However, it seems to me that the authors have made a well-considered choice not to mention the Last Interglacial (or the Early Holocene for that matter) in this context and it

Would be highly interesting for the larger community, especially considering the wealth of knowledge on the topic held within the long list of authors, if these considerations would be part of the manuscript

*See response to Referee 1 point 2. We have added some discussion to the Conclusions.*

# 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 Tier 1 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 CMIP6 Tier 2 and Tier 3 sensitivity experiments of PMIP4, 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.

**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). Five paleoclimate experiments are included in CMIP6 Tier 1 (Kageyama et al., 2016): two of these experiments 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

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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<sub>2</sub> 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 (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).

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., 2017).

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

**Moved down [1]:** 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.

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135 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.,  
140 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  
145 experiments will be made in the current phase of PMIP (PMIP4) to facilitate diagnosis of these “Tier 1” experiments  
(Tier 1 experiments are those CMIP6 experiments are those of highest priority for PMIP4 and that enough modeling  
groups (at least eight) are willing to perform; Tier 2 simulations are sensitivity studies in the framework of PMIP4,  
but not CMIP6). 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,  
150 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 realistic 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  
155 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 sensitivity experiments, which will be a focus of additional experiments associated with both the Holocene  
160 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  
165 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  
170 interglacial periods.

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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 W m<sup>-2</sup> at 127 ka and 25 W m<sup>-2</sup> 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.

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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 ( $1360.7 \text{ W m}^{-2}$ ) is lower than the value for the solar constant used by some models in PMIP3 ( $1365 \text{ W m}^{-2}$ ) 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  $1.6 \text{ W m}^{-2}$  between  $10^{\circ}\text{S}$  and  $40^{\circ}\text{N}$ .

2.2 Greenhouse gases

Ice-core records from Antarctica and Greenland provide measurements of the well-mixed GHGs:  $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$  (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  $\text{CO}_2$  and  $\text{CH}_4$  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  $\text{CO}_2$  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  $\text{CO}_2$  record. This yields a  $\text{CO}_2$  concentration of 264.4 ppm at 6 ka. Methane was measured in ice from Antarctic ice cores EPICA Dome C (Flückiger et al., 2002), EPICA Dronning Maud Land (EPICA Community Members, 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  $\text{N}_2\text{O}$  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  $\text{N}_2\text{O}$  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  $\text{CO}_2$  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

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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<sub>2</sub> concentration from 280 to 264.4 ppm will reduce GHG forcing by about 0.3 W m<sup>-2</sup> (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<sub>2</sub>. 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, but that there are 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.

**lig127k.** The LIG GHG concentrations are available solely from Antarctic ice cores. CO<sub>2</sub> concentrations can only be derived from Antarctic ice, because of potential in-situ CO<sub>2</sub> production in the Greenland ice sheet (Tschumi and Stauffer, 2000). We also do not have any reliable CH<sub>4</sub> and N<sub>2</sub>O 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<sub>2</sub>, from EPICA Dome C and EPICA Dronning Maud Land (Loulergue et al., 2008; Schilt et al., 2010a) for CH<sub>4</sub>, as well as from EPICA Dome C and Talos Dome (Schilt et al., 2010a; Schilt et al., 2010b) for N<sub>2</sub>O. The atmospheric CO<sub>2</sub> and N<sub>2</sub>O concentrations of 275 ppm and 255 ppb, respectively, can be regarded as globally representative, while the mean ice core CH<sub>4</sub> concentration (662 ppb) is representative for high-latitude Southern Hemisphere air. A global mean atmospheric CH<sub>4</sub> concentration of 685 ppb is adopted for 127 ka, thereby assuming the same difference (23 ppb) between the global mean atmospheric CH<sub>4</sub> and Antarctic ice core CH<sub>4</sub> 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. Uncertainties in the reconstructions of this relict ice sheet would have a larger impact on the simulations, and thus 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).

**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

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disappearance of the Eurasian ice sheet is more difficult to constrain because either the proximal marine records lack benthic  $\delta^{18}\text{O}$  data, or the benthic  $\delta^{18}\text{O}$  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 was dated to between 128-126 ka using  $\delta^{18}\text{O}$  (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).

The extent of the Antarctic ice sheets 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 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

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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; Vиноj 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), it 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 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

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

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375 of variability (see Section 3), modeling groups are encouraged to provide outputs for at least 500 years if possible.

380 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.

### 3 PMIP4-CMIP6 Tier 2 and Tier 3 Simulations

395 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.

405 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).

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Albedo and freshwater feedbacks could give rise to more abrupt responses to orbital forcing. 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.

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

### 3.1 Equilibrium response to alternative states of orbital forcing

*hol9.5k*. The maximum expression of 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 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 127k, 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.

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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<sub>2</sub> 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<sub>2</sub> 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.

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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.](#)

[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](#)

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**Deleted:** (experiment c). A more realistic simulation of the influence of mid-Holocene vegetation changes in the Sahara (experiment d) could be made using the gridded data set of land-surface conditions provided by Hoelzmann et al. (Hoelzmann et al., 1998), which gives proportions of specific vegetation types (steppe, savanna, xerophytic woods/scrub, tropical deciduous forest, and tropical montane evergreen forest), open water (lakes), and wetlands on a 1° grid. This data set could also be used for a LIG sensitivity experiment, on the assumption that this provides a minimum estimate of the changes during that time (see e.g. Drake et al., 2011). The maps provided by Bigelow et al. (2003) provide more nuanced vegetation changes in high-latitude vegetation (experiment e), since they distinguish cold deciduous boreal forests from evergreen boreal forests and tundra.

**Deleted:** Several modelling groups will be running simulations with models including dynamic vegetation, and this makes it possible to test the impact of the mid-Holocene vegetation changes on modern climate. For groups using dynamic vegetation, an additional sensitivity test is proposed in which the *piControl* simulation is run with the dynamic vegetation component is switched off and vegetation is prescribed using the Hoelzmann et al. vegetation map.

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~~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  $28 \pm 8 \text{ m ka}^{-1}$  (~~~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.

**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<sup>3</sup> (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.~~ This freshwater flux is added to the Labrador Sea, but modeling groups can chose whether to add it uniformly over the whole of the Labrador Sea or only over part of the area.

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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.

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630 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 et al., 2003; Danian et al., 2012; Emile-Geay et al., 2016; Hessler et al., 2014; Kohfeld and  
635 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  
640 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 Prah, 2013). There  
are several sources of information about short-term climate variability during the Holocene, including tree-ring  
records, speleothems, corals and molluscs. However, there are major gaps in data coverage from the tropical oceans  
645 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  
650 Tingley, 2016).

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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  
655 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  
660 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  
665 to improve this situation.

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670 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  
675 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  
680 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. (in  
685 revision), 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  
690 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., in revision). Following a similar  
strategy, Hoffman et al. (2017) propose the first global marine compilation with harmonized chronologies for the  
695 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., in revision). 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  
700 the imprint of the previous deglaciation (Fig. 1) (Capron et al., in revision). 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*  
705 simulation.

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720 The public-access 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 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

725 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.

735 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 21<sup>st</sup> 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).

750 PMIP4 will collaborate with other CMIP6 projects (Kagayama 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; [\*\*Moved down \[4\]:\*\* 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 21<sup>st</sup> 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 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.](http://www.climate-</a></p></div><div data-bbox=)

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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](https://pmip4.lsce.ipsl.fr/doku.php/exp_design_index). 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>). Data from PMIP4-only Tier 2 simulations must be processed following the same standards as Tier 1 for data processing (e.g. CMOR standards) and should be distributed via ESGF. Modeling groups producing these simulations are responsible to secure suitable space on ESGF nodes.

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](http://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).

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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.

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This work is a contribution to the PAGES/PMIP QUIGS Working Group and PALSEA2 (INQUA IFG/PAGES WG). This is LSCE publication number 6047.

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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 <i>piControl</i> ) <sup>1</sup> | 6ka ( <i>midHolocene</i> ) <sup>2</sup>          | 127ka ( <i>lig127k</i> ) <sup>2</sup>            |
|--|---|--|--|
| Orbital parameters (2.1)                 | CMIP DECK <i>piControl</i>                      |  |  |
| Eccentricity                             | 0.016764  | 0.018682   | 0.039378   |
| Obliquity (degrees)                      | 23.459  | 24.105   | 24.040   |
| Perihelion - 180                         | 100.3   | 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 <i>piControl</i>                      | 0  | 0  |
| Solar constant (Wm <sup>-2</sup> ) (2.1) | TSI: 1360.747                                   | Same as <i>piControl</i>                         | Same as <i>piControl</i>                         |
| Paleogeography (2.3)                     | Modern  | Same as <i>piControl</i>                         | Same as <i>piControl</i>                         |
| Ice sheets (2.3)                         | Modern  | Same as <i>piControl</i>                         | Same as <i>piControl</i>                         |
| Vegetation (2.4)                         | CMIP DECK <i>piControl</i>                      | Prescribed or interactive as in <i>piControl</i> | Prescribed or interactive as in <i>piControl</i> |
| Aerosols (2.5)<br>Dust, Volcanic, etc.   | CMIP DECK <i>piControl</i>                      | Prescribed or interactive as in <i>piControl</i> | Prescribed or interactive as in <i>piControl</i> |

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<sup>1</sup> 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>

<sup>2</sup> Datasets for *midHolocene* and *lig127k* are available on the PMIP4 web page: [https://pmip4.lsce.ipsl.fr/doku.php/exp\\_design:index](https://pmip4.lsce.ipsl.fr/doku.php/exp_design:index)

**Table 2. Summary of PMIP4 Tier 2 and Tier 3 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)                                   | <i>hol9.5k</i> : Early Holocene <ul style="list-style-type: none"> <li>Orbital: 9.5 ka</li> <li>Ice sheet: ICE-6G or GLAC-1D reconstruction<sup>1</sup></li> <li>GHG: same as for the deglaciation experiment<sup>1</sup></li> </ul>  | <i>lig116k</i> : Glacial inception <ul style="list-style-type: none"> <li>Orbital: 116 ka</li> <li>CO<sub>2</sub>: 273 ppm</li> <li>Other forcings and boundary conditions: as for <i>lig127k</i></li> </ul>  |
| Sensitivity to vegetation (3.2)   | <i>midHolocene_veg</i> <ul style="list-style-type: none"> <li>prescribed boreal forests in Arctic and shrub/savanna over Sahara (together and in turn)</li> </ul>   | <i>lig127k_veg</i> <ul style="list-style-type: none"> <li>prescribed boreal forests in Arctic and shrub/savanna over Sahara (together and in turn)</li> </ul>   |
| Sensitivity to Ice-Sheet (3.3)  |   | <i>lig127k_ais</i> and <i>lig127k_gris</i> <ul style="list-style-type: none"> <li>Antarctic ice sheet at its minimum LIG extent</li> <li>Greenland ice sheet at its minimum LIG extent</li> </ul>   |
| Test to freshwater flux (3.4)   | <i>hol8.2k</i> : 8.2 ka event <ul style="list-style-type: none"> <li>Meltwater flux of 2.5 Sv for one year added to the Labrador Sea followed by 0.13 Sv for 99 years</li> <li>Other forcings and boundary conditions: as for <i>hol9.5k</i></li> <li>Initial state: <i>hol9.5k</i> simulation</li> </ul> | <i>lig127k_H11</i> : Heinrich 11 meltwater event <ul style="list-style-type: none"> <li>Meltwater flux of 0.2 Sv to the North Atlantic between 50 and 70°N for 1000 years</li> <li>Other forcings and boundary conditions: as for <i>lig127k</i></li> <li>Initial state: <i>lig127k</i> simulation</li> </ul> |
| PMIP4-CMIP6 sensitivity experiments: Tier 3 simulations                 |   |   |
| Transient simulations (3.5)<br>(Note : Exploratory and flexible set up) | <i>past6k</i> : transient Holocene <ul style="list-style-type: none"> <li>Transient evolution in Earth's orbit and trace gases</li> <li>Other boundary conditions (land use, solar, volcanism) may be considered by some groups</li> <li>Initial state: <i>midHolocene</i></li> </ul>                     | <i>lig127k_to121k</i> : transient LIG <ul style="list-style-type: none"> <li>Transient evolution in Earth's orbit and trace gases</li> <li>Other boundary conditions (ice sheets) may be considered by some groups</li> <li>Initial state: <i>lig127k</i></li> </ul>  |

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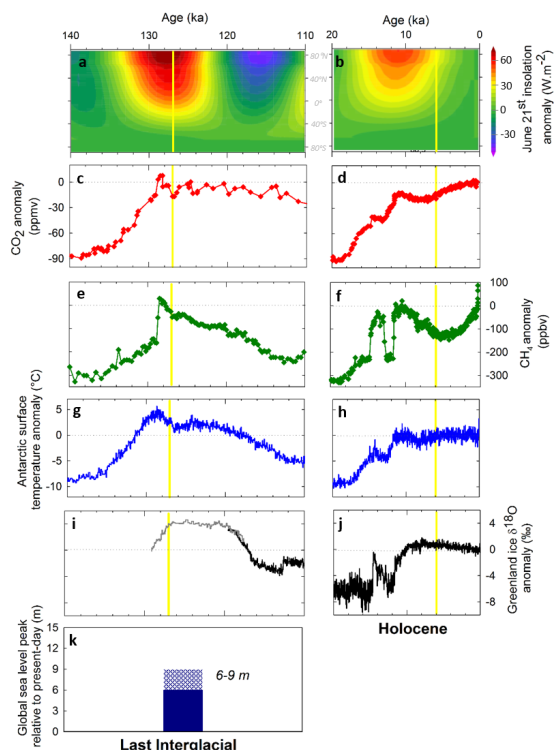
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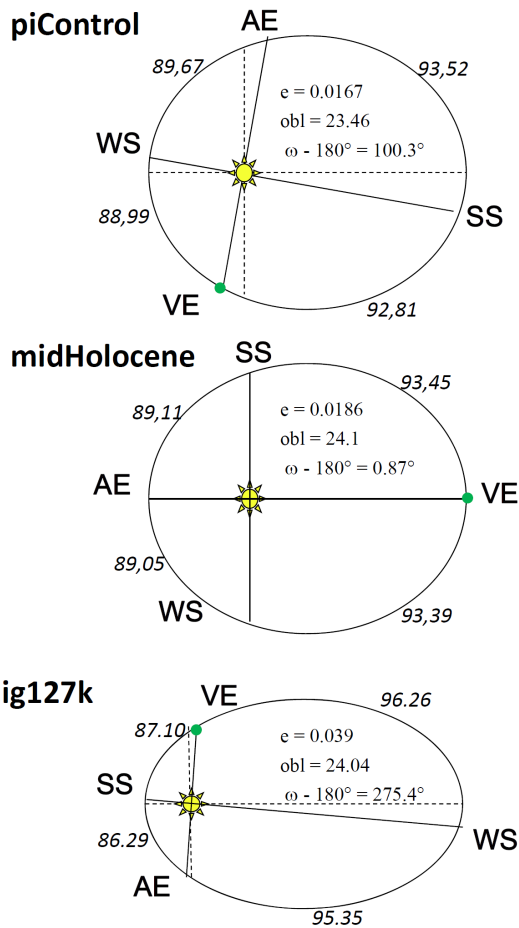
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<sup>1</sup>Ivanovic et al., 2016; available on the PMIP4 web page



**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**) 21<sup>st</sup> June insolation across latitudes; **C** and **D**) Atmospheric CO<sub>2</sub> concentration (Siegenthaler et al., 2005; Schneider et al., 2013; Monnin et al., 2001 Monnin et al., 2004); **E** and **F**) Atmospheric CH<sub>4</sub> concentration Loulergue et al., 2008); **G** and **H**) Antarctic surface air temperature reconstruction (Jouzel et al., 2007); **I** and **J**) Greenland ice δ<sup>18</sup>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<sup>18</sup>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<sup>18</sup>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.

**Deleted: 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)  $21^{st}$  June insolation across latitudes; C and D) Atmospheric  $CO_2$  concentration (Siegenthaler et al. 2005; Schneider et al. 2013 CP, Monnin et al. 2004); E and F) Atmospheric  $CH_4$  concentration (Louergue et al. 2008); G and H) Antarctic surface air temperature reconstruction (Jouzel et al. 2007); I and J) Greenland ice  $\delta^{18}O$ : from NEEM ice core (NEEM community members 2012) in dark grey and from NGRIP ice core (NGRIP project members 2004) in black. Note that NEEM ice  $\delta^{18}O$  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. 2015 for a review). No significant sea level variations are reported throughout the Holocene compared to present-day. NGRIP ice  $\delta^{18}O$  is displayed on the GICC05 annual layer-counted timescale (Svensson et al. 2008) over the last 20 ka and on the AICC2012 chronology 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. 2012, Veres et al. 2012). Vertical yellow lines indicate 127 and 6 ka, the time intervals chosen to run the coordinated PMIP4-CMIP6 *lig127k* and *midHolocene* simulations. Vertical grey lines represent the 116, 9.5, 8.5 and 8.2 ka time intervals for which additional sensitivity simulations will be run within PMIP4.



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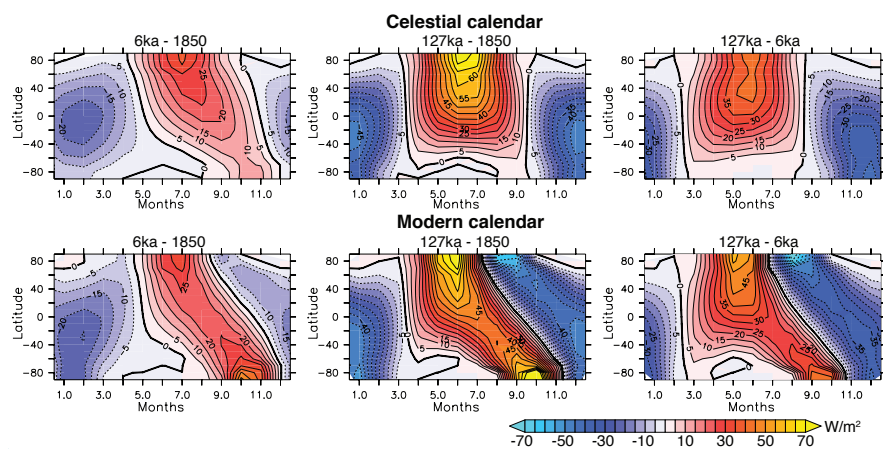
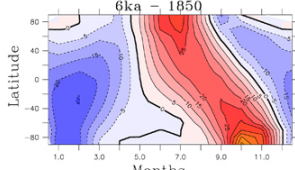
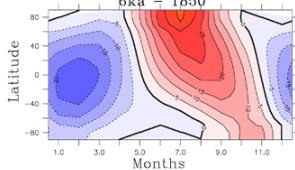


Figure 3. Latitude-month insolation anomalies (6ka-1850, 127ka-1850, 127ka-6ka) computed using either the celestial calendar (top) or the modern calendar (bottom), with vernal equinox on March 21 at noon, to compute monthly averages ( $\text{W m}^{-2}$ ).

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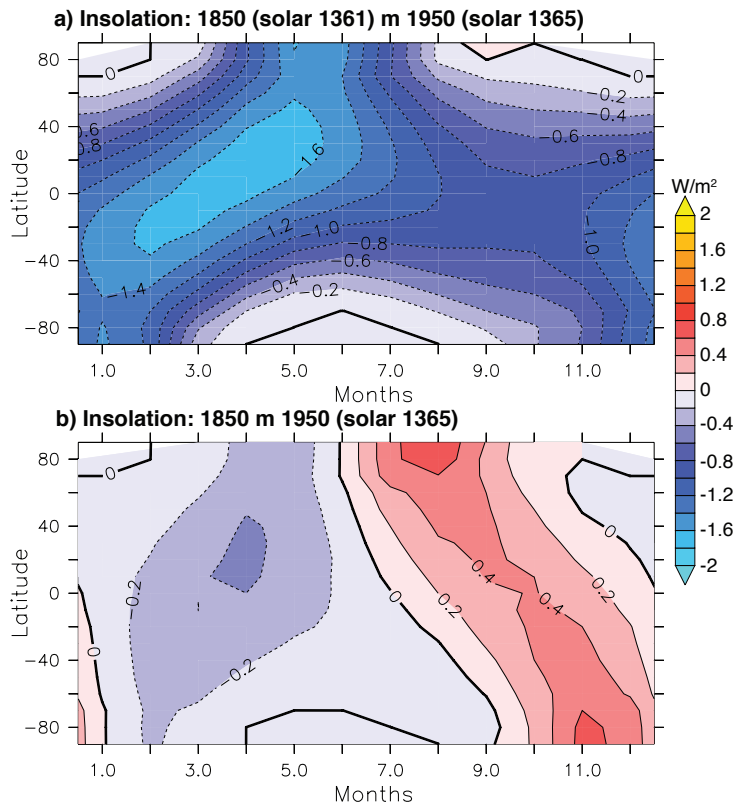
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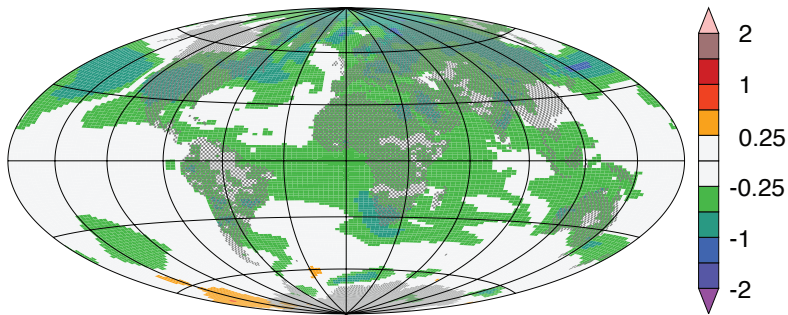
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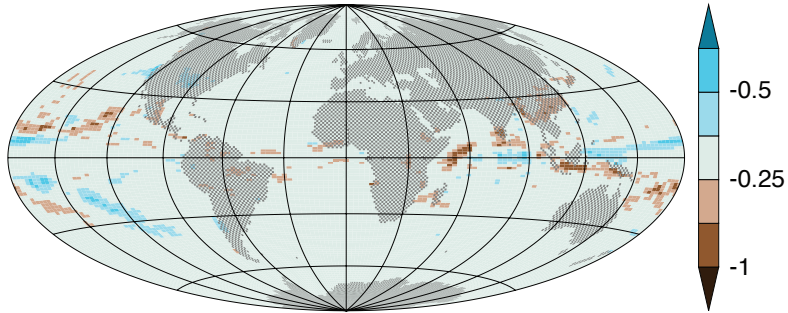
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**Figure 4. Difference in incoming solar radiation at the top of the atmosphere ( $\text{W m}^{-2}$ ) between PMIP4 and PMIP3 protocols, a) considering the changes in Earth's orbital parameters between 1850 and 1950 and the reduction of the solar constant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

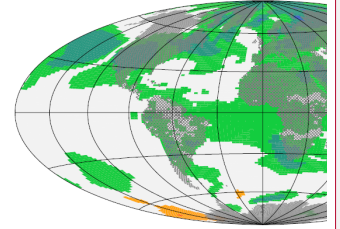
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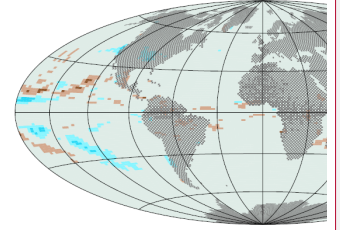
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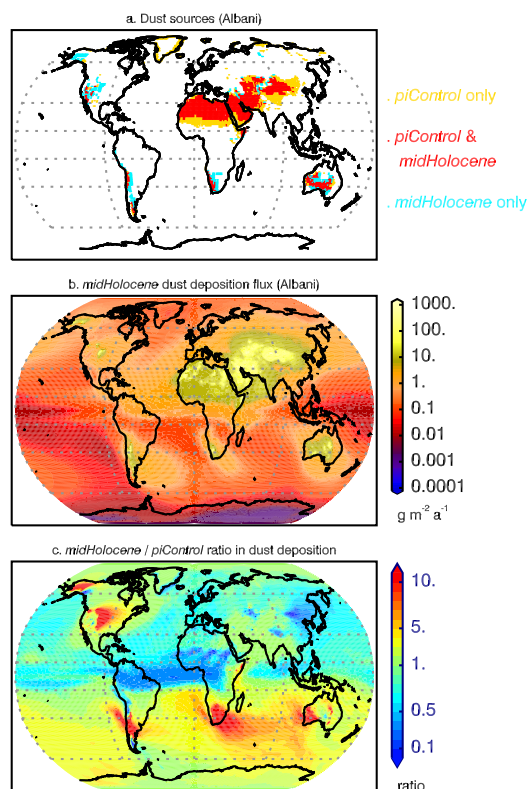
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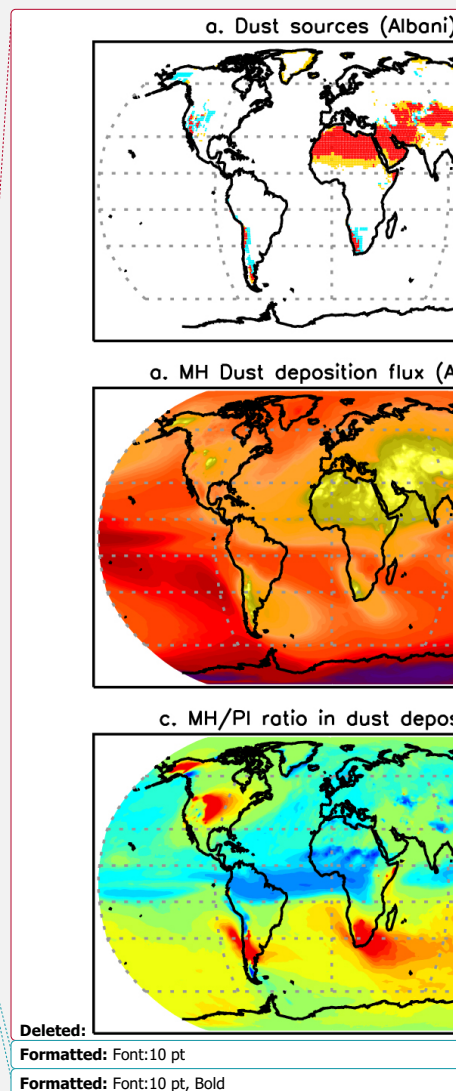
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Figure 5. Impact of the changes in trace gases specified for 6 ka between PMIP3 and PMIP4 on surface air temperature ( $^{\circ}\text{C}$ ) and precipitation ( $\text{mm d}^{-1}$ ) as estimated with the IPSLCM5A model. Only significant values are plotted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



**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 ( $\text{g m}^{-2} \text{a}^{-1}$ ) 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](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](https://pmip4.lsce.ipsl.fr/doku.php/database:pmip4request#the_pmip4_request)).

The simulations should follow the CMIP6 data request and format. For groups only contributing to PMIP, the data format and organization on the ESGF archive is the same as for CMIP6, except that the provision of daily values can be limited to 2D surface variables, including temperature, precipitation and winds. Groups are also asked to keep a 20 year period with all the output needed to force regional area-limited models, since we would like to strengthen the linkages between global and regional simulations for regional model-data comparisons.

The difference in orbital configuration between 127 ka, 6 ka and preindustrial means that there are differences in season length that should be accounted for in calculating seasonal changes (Kutzbach and Gallimore, 1988). The bias introduced from using the modern calendar rather than the celestial calendar to calculate seasonal averages is shown in Fig. 2, when the date of the vernal equinox is assigned to March 21 at noon. To be able to account for this effect when comparing the simulations to the paleoclimate reconstructions, daily outputs of at least surface temperature, precipitation and winds must be archived. Programs that provide an approximate estimate of monthly means on the fixed-angular celestial calendar from fixed-day calendar will be available on the PMIP4 web page.

CMIP DECK *piControl*

SSI, ap if needed

| PMIP4-CMIP6 Tier 1 simulations |                |
|--------------------------------|----------------|
| Entry card: <i>midHolocene</i> | <i>lig127k</i> |

vegetation reconstructions<sup>2</sup>  
*midHolocene* equilibrium veg with dgvm in *piControl*

Orbital: 8.2 ka  
Ice sheet: ICE-6G or GLAC-1D reconstruction<sup>1</sup>  
GHG: same as for the deglaciation experiment<sup>1</sup>  
Initial state: 8.5 ka simulation

<sup>2</sup>Hoelzmann et al., 1998; Bigelow et al., 2003; available on the PMIP4 web page

