Paleoclimate Modeling Intercomparison Project (PMIP)
Application for CMIP6-Endorsed MIPs

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Please return to CMIP Panel Chair Veronika Eyring (email: Veronika.Eyring@dlr.de)

Proposals from MIPs should include the following information:

**	Preliminary information used to determine whether a MIP should be endorsed for CMIP6 or not.*

***	Information that must be provided later (and before the panel can determine which experiments, if any, will be incorporated in the official CMIP6 suite).*

- Name of MIP*

  Paleoclimate Modeling Intercomparison Project

  (This will be the fourth phase of PMIP: PMIP4)

- Co-chairs of MIP (including email-addresses)*

  - Pascale Braconnot (Pascale.Braconnot@lsce.ipsl.fr)
  - Sandy Harrison (s.p.harrison@reading.ac.uk)

- Members of the Scientific Steering Committee*

  - Pascale Braconnot / LSCE, France (model and model-data)
  - Sandy P. Harrison / University of Reading, UK and Macquarie University, Australia (data and model-data)
  - Ayako Abe-Ouchi / AORI, University of Tokyo (ice-sheet and PCMIP)
  - Pat Bartlein / University of Oregon, USA (Continental data)
  - Alan Haywood / University of Leeds, UK (Mid-pliocene)
  - Sylvie Joussaume / LSCE, France
  - Johann Jungclaus / MPI-M, Germany (Last millennium)
  - Michal Kucera / MARUM, Germany (Ocean data)
  - Bette Otto-Bliesner / NCAR, USA (warm climates)
  - Gilles Ramstein / LSCE, France (glacial and ice sheet)
  - Karl Taylor / PCMDI, USA (Link with CMIP5)
  - Paul Valdes / BRIDGE, UK (abrupt changes)

- Link to website (if available)*

http://pmip3.lsce.ipsl.fr + http://pmip.lsce.ipsl.fr (PMIP1) and http://pmip2.lsce.ipsl.fr (PMIP2)

Goal of the MIP and a brief overview*

Since the 1990s, PMIP has developed with the following objectives:

- to evaluate the ability of climate models used for climate prediction in simulating well-documented past climates outside the range of present and recent climate variability
- to understand the mechanisms of these climate changes, in particular the role of the different climate feedbacks

To achieve these goals, PMIP has actively fostered paleo-data syntheses, multi-model analyses, including analyses of relationships between model results from past and future simulations, and model-data comparisons. These have first been focusing on the results from Atmospheric General Circulation Models (PMIP1) and then been extended to coupled Ocean-Atmosphere General Circulation Models and AOGCM including carbon cycle feedbacks, thereby closely following model developments for CMIP (PMIP2 and PMIP3). Three PMIP3 simulations were part of the CMIP5 ensemble of simulations: the last millennium, the mid-Holocene (~6,000 years ago) and the Last Glacial Maximum (~21,000 years ago), hence allowing, for the first time, the rigorous comparison of model results for past and future climates. The rationale for considering these periods was:

- for the Last Glacial Maximum, to evaluate the models on a well-documented climatic extreme, especially in terms of temperatures, and study the role of forcings and feedbacks in establishing this climate;
- for the mid-Holocene, to evaluate and analyse the models on a climate "optimum" for the northern hemisphere, characterized by enhanced monsoons, extra-tropical continental aridity and much warmer summers;
- for the last millennium, to study the mechanisms (natural variability vs impact of solar, volcanic and anthropogenic forcings) of decadal to centennial climate variability and evaluate the models' performance w.r.t numerous detailed records.

For CMIP6, we propose to include two new warm periods in the PMIP/CMIP set of experiments: the Last Interglacial and the Mid-Pliocene, for which simulations have been performed and significantly contributed to AR5.

PMIP3/CMIP5 and PlioMIP have been very successful in terms of participation and publications. 19 groups have contributed to PMIP3/CMIP5 simulations, 12 groups have taken part in PlioMIP. PMIP3/CMIP5 simulations have been used in more than 40 publications (as of Sept 11th, 2014) and PlioMIP simulations have been the topic of more than 20 publications. PMIP simulations have brought strong contribution to 2 IPCC AR5 chapters: chapter 5 "information from paleoclimate archives" and chapter 9 "evaluation of climate models".

PMIP simulations specifically address CMIP6 key question on "How does the Earth System respond to forcing" for a variety of forcings and with possible comparisons to data for climates states very different from the current or historical climate. PMIP also addresses question 2 ("What are the origins and consequences of systematic model biases?") about systematic model biases, with the perspective given by documented climates different from today: PMIP simulations, with comparisons to data, can help assessing whether the biases for present-day are also found for other climate states and whether present-day biases have an impact on the magnitude of simulated climate changes. Finally, PMIP is relevant for question 3 ("How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios?"), by examining these very questions for documented past climate cases and via the use of the last millennium simulations as reference state for natural variability.

PMIP simulations are being analyzed within the Grand Challenge "Clouds, Circulation and Climate Sensitivity". They can also provide valuable input for other grand challenges, such as those on the Cryosphere and on Regional Climate Information, with the challenge of paleoclimate modelling at fine scale. Indeed, PMIP model output is increasingly used in "paleo-impact studies", on biodiversity or on understanding the potential impact of climate and environmental changes on early Humans. Several initiatives have already been proposed along these themes and will be reinforced in the future (e.g. Future Earth "Fast Track Initiatives and Cluster Activities" project "Making better use of the Paleoclimate Modeling Intercomparison Project simulations (MAPS)" led by P. Braconnot, a project concerning WGCM, PAGES, CLIVAR, CLiC and bioDISCOVERY).

The five proposed experiments constitute a reference ensemble for further studies within PMIP: single forcing experiments, transient experiments (testing the models on abrupt climate change and on glacial-interglacial transitions).

- References*

PMIP1:

Joussaume, S. and Taylor, K. E., 1995. Status of the Paleoclimate Modeling Intercomparison Project (PMIP), Proceedings of the first international AMIP scientific conference (Monterrey, California, USA, 15-19 May 1995), WCRP report 92, 425-430. Text available at: https://pmip.lsce.ipsl.fr/publications/overview.html

PMIP2:

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

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

PMIP2/PMIP3:

Braconnot, P., S. P. Harrison, M. Kageyama, P. J. Bartlein, V. Masson-Delmotte, A. Abe-Ouchi, B. Otto-Bliesner and Y. Zhao, 2012. Evaluation of climate models using palaeoclimatic data, Nature Climate Change, DOI: 10.1038/NCLIMATE1456

Schmidt, G.A., J. D. Annan, P. J. Bartlein, B. I. Cook, E. Guilyardi, J. C. Hargreaves, S. P. Harrison, M. Kageyama, A. N. LeGrande, B. Konecky, S. Lovejoy, M. E. Mann, V. Masson-Delmotte, C. Risi, D. Thompson, A. Timmermann, L.-B. Tremblay, and P. Yiou, 2014. Using paleo-climate comparisons to constrain future projections in CMIP5, Climate of the Past, 10, 221-250

An overview of the proposed experiments*

The following table summarizes the experiments proposed by PMIP for CMIP6. These experiments all build from the DECK experiments and are part of the core of PMIP simulations (~10), which will themselves constitute a basis for other PMIP experiments (sensitivity analyses, transient simulations starting from the core ones). Within PMIP, each PMIP working group will organize their set of simulations, as PMIP also federates focused MIPs such as PlioMIP on the Pliocene climate, LIGMIP on the Last Interglacial, PAST2K on the last two millennia.

Table 1: summary of proposed experiments. In yellow: PMIP3/CMIP5 experiments. In green: new experiments for CMIP6. The PMIP3/CMIP5 experiment names in the ESFG nomenclature are indicated in italic below each period name.

Period	Purpose	Imposed boundary conditions	# of years
Last millennium (*past1000*) 850-1850 CE	a) Evaluate the ability of models to capture observed variability on multi-decadal and longer time-scales. b) Determine what fraction of the variability is attributable to "external" forcing and what fraction reflects purely internal variability. c) Provides a longer-term perspective for detection and attribution studies	• Solar variations • Volcanic aerosols • Atmospheric concentration of well mixed greenhouse gases • Land use • Orbital parameters	1000 (after spin-up period)
Mid-Holocene (*midHolocene*) 6 kyr ago	a) Compare with paleodata the model response to known orbital forcing changes and changes in greenhouse gas concentrations. b) Relationships between changes in mean state and variability	• Orbital parameters • Atmospheric concentration of well-mixed greenhouse gases	≥100 (after spin-up period)
Last Glacial Maximum (*lgm*) 21 kyr ago	a) Compare with paleodata the model response to ice-age boundary conditions. b) Attempt to provide empirical constraints on global climate sensitivity.	• Ice-sheet and land-sea mask • Atmospheric concentration of well-mixed greenhouse gases • Orbital parameters	≥100 (after spin-up period)
Last Interglacial 128 kyr ago	a) Evaluate climate model for warm period, high sea-level stand b) Impacts of smaller ice-sheets/higher sea-level on climate	• Orbital parameters • Atmospheric concentration of well-mixed greenhouse gases	≥100 (after spin-up period)
Mid-Pliocene Warm Period 3.2 Ma ago	a) How does the Earth System respond in the long term to CO_2 forcing analogous to that of the modern? b) What is the significance of CO_2 induced polar amplification for the stability of the ice sheets, sea-ice and sea-level?	• Ice-sheet and land-sea mask, topography (smaller ice-sheets) • Atmospheric concentration of well-mixed greenhouse gases • Orbital parameters	≥100 (after spin-up period)

For all these periods the model to be used is the same as the one used for future climate projections. Therefore depending on the groups the model will be only atmosphere-ocean coupled models or Earth System models. The reference for the analyses will be the CMIP6 pre-industrial simulation. Hereafter, we shortly describe the Mid-Holocene and Last Glacial Maximum, periods which have already been a focus of PMIP since its start and which have been part of the PMIP3-CMIP5 simulations. More details are given below on the Last Millennium (part of PMIP3-CMIP5 as well) and on the two new periods proposed for CMIP6: the Last Interglacial and the Mid-Pliocene Warm Period.

- Mid-Holocene (*midHolocene*) and Last Glacial Maximum (*lgm*):

The mid-Holocene (~6000 years ago) and the Last Glacial Maximum (LGM, ~21000 years ago) constitute the most recent quasi-stable climatic extremes: the mid-Holocene is often described as a warm state, or "climate optimum", in which dominant features of the global hydrological cycle, such as the North African and Asian monsoon, were amplified; the LGM is a cold extreme in which greenhouse gas concentrations were at their minimum and continental ice-sheet at their maximum size, covering large areas of northern North America and northwestern Eurasia.

These periods have been the focus for paleo-data syntheses since the beginning of the PMIP project and therefore are well documented in terms of temperature, hydrological cycle and land surface type. Some long standing model-data disagreement are echoing preoccupations for future climate change, such as the systematic underestimation of the northward penetration of the African monsoon rainfall onto the continent compared to available records for the Mid-Holocene. The LGM is relevant for studying feedback mechanisms at work in establishing a temperature response as large as (although with an opposite sign) as that predicted for the end of the 21st century. Both periods constitute test cases for our understanding of mechanisms of climate change, such as the interplay between circulation changes and radiation/cloud changes, the respective strengths of feedbacks from different components of the climate system, and for our understanding of the connections between global and regional climate changes.

Compared to the previous phases of PMIP a particular amphasis will be put on the impact of dust on the mean climate and climate feedbacks, as well as on uncertainties in boundary conditions or surface feedbacks related to the vegetation or interactive carbon cycle.

The reference experiments for both the *midHolocene* and *lgm* simulations are the pre-industrial control and it is very interesting to compare those experiments with an idealized experiment designed to study mechanisms of future climate change, such as abrupt4xCO2. PMIP4 will benefit from idealized experiments proposed by CFMIP, such as AMIPminus4K or abrupt0.5CO2 which will help comparing feedbacks at work in setting up a cold climate vs. those at work for a warm climate. Similarly, an AMIP experiment with insolation prescribed at a 6ky BP value will be very useful to analyze the strengths of forcings and feedbacks within the climate system and the mechanisms for common/different responses for past and future climates. These sensitivity experiments will be discussed as part of PMIP in the Past to Future working group. They would echo PMIP1 simulations (http://pmip.lsce.ipsl.fr), while ESM simulations would echo PMIP2 and PMIP3 (http://pmip2.lsce.ipsl.fr and http://pmip3.lsce.ipsl.fr) simulations, hence allowing a characterization of the models' evolution in their ability to represent documented large climate changes.

➢ Last Millennium (*past1000*):

The last millennium is the best-documented period of climate change in a multi-century time frame. Climate has varied considerably during the late Holocene and these changes left their traces in history (Medieval Climate Optimum, Little Ice Age). However, the relative magnitude of natural fluctuations due to internal variability of the Earth's climate system and to variations in the external forcings (Sun, orbital, volcanic) and the present global warming, attributed to anthropogenic greenhouse gases, is still under debate. Simulations of the last millennium (LM) therefore directly address the first CMIP6 key scientific question "How does the Earth System respond to forcing". Investigating the response to (mainly) natural forcing under climatic background conditions not too different from today is crucial for an improved understanding of climate variability, circulation, and regional connectivity. LM simulations also allow assessing climate variability on decadal and longer scales and provide information on predictability under forced and unforced conditions. These are crucial for near-term predictions and thus address the third CMIP5 scientific question "How can we assess future climate changes given climate variability, predictability and uncertainties in scenarios". In providing in-depth model evaluation with respect to observations and paleoclimatic reconstructions in particular addressing details of response to forcing, LM simulations serve to "understand origins and consequences of systematic model biases", thus addressing also the second CMIP6 scientific question.

LM will build on DECK experiments, in particular the pre-industrial control simulation as unforced reference and the historical simulations. Moreover, LM provide initial conditions for historical simulations starting in the 19th century that are considered superior to the *piControl* state as it includes integrated information from the forcing history (e.g. large volcanic eruptions in the early 19th century).

Within PMIP, a considerable number of individual researchers and modelling groups is committed to perform LM simulations. The simulations will base on experience gained in PMIP3/CMIP5 where more than a dozen modelling groups participated and a total of 15 LM experiments where stored in the ESGF database. Several studies, partly reflected by entries in the AR5 chapter 5, have highlighted the value of the LM multi-model ensemble. The PMIP3 LM working group (WG Past2K) is closely cooperating with the PAGES initiative PAGES2k promoting regional reconstructions of climate variables and variability modes. Collaborative work has focused on reconstruction-model intercomparison (e.g. Bothe et al., 2013) and assessment of variability modes (e.g. Raible et al., 2014). Integrated assessment of reconstruction and simulations has led to progress in model evaluation and process understanding (e.g. Lehner et al., 2013; Sicre et al., 2013; Jungclaus et al., 2014). WG Past2K will promote future common analyses and workshops bringing together observational and modelling expertise.

For CMIP6 progress is expected owing to new, more comprehensive reconstructions of volcanic forcing (Sigl et al., in preparation), improved models, and an experimental protocol that ensures seamless simulations from the pre-industrial past to the future. Higher-resolution simulations will allow assessing more regional details and processes, e.g. storm-tracks, precipitation.

➢ Last Interglacial:

The Summary for Policymakers for both the IPCC WG1 AR4 and AR5 included statements on the Last Interglacial (LIG):

“There is very high confidence that maximum global mean sea level during the last interglacial period (129,000 to 116,000 years ago) was, for several thousand years, at least 5 m higher than present, and high confidence that it did not exceed 10 m above present. During the last interglacial period, the Greenland ice sheet very likely contributed between 1.4 and 4.3 m to the higher global mean sea level, implying with medium confidence an additional contribution from the Antarctic ice sheet. This change in sea level occurred in the context of different orbital forcing and with high-latitude surface temperature, averaged over several thousand years, at least 2°C warmer than present (high confidence).”

Yet the AR4 and AR5 had no coordinated simulations for the LIG to assess the interplay of polar amplification of temperature, seasonal memory of sea ice, and precipitation/storm track changes on the stability of the Greenland ice sheet and its contribution to the sea level high stand nor the interplay of oceanic and atmospheric temperatures and circulation on the stability of the Antarctic ice sheet. Climate model simulations for the LIG assessed in the AR5, although completed by many modeling groups, varied in their forcings and often were not made with the same model/same resolution as the CMIP5 future projections, thus providing a useful but incomplete means for assessment (Chapter 5; Lunt et al., 2013). Similarly, Greenland ice sheet simulations assessed in the AR5 used offline models with a variety of climate forcing setups, not then allowing feedbacks among the Earth system components (Chapter 5). No simulations were available to assess the Antarctic ice sheet (particularly, the West Antarctic Ice Sheet) contribution to the LIG sea level high stand.

We propose a CMIP6 time-slice experiment for the LIG to determine the interplay of warmer atmospheric and oceanic temperatures, changed precipitation, and changed surface energy balance on ice sheet thermodynamics and dynamics during this period. Still uncertain are how well ice sheet-climate models can predict the stability of the ice sheets and if thresholds may be passed this century. A LIG simulation will be of high societal relevance because of implications for sea level changes as well as sea ice and monsoons. The LIG simulation will also provide an ‘out-of-sample’ evaluation of new features of CMIP6 models: coupled climate-ice sheet models. The LIG is the most suitable of the warm interglacials for a CMIP6 assessment because of the wealth of data including: ice cores providing measurements of well-mixed greenhouse gases, aerosols including dust and sea salt, and stable water isotopes as a proxy for temperature, as well as for Greenland, ice sheet elevation and extent; marine records for ocean temperatures and geotracers that can be interpreted in terms of water masses and overturning strength; speleothems that provide indication of monsoon strength; and terrestrial records that indicate temperature and vegetation. As well, new records are refining our knowledge of sea ice extent, fire, and biodiversity.

The proposed CMIP6 simulation for the LIG is particularly relevant to the WCRP Grand Challenges: Changes in Cryosphere and Regional Sea-level Rise, but also to Regional Climate Information and Clouds, Circulation and Climate Sensitivity because of the large forcings and thus large regional responses as recorded in the data. It addresses well the broad scientific questions: 1. How does the Earth System respond to forcing? and 2. What are the origins and consequences of systematic model biases (especially at high latitudes and relevant to the stability of the ice sheets)? As part of PMIP, some groups will additionally perform transient coupled ice sheet-climate simulations that will provide rates of change for sea level, including regional sea level if offline GIA models applied, as well as a measure of the capability of these models to initiate the next glacial inception.

- Pliocene warm period

The Pliocene epoch was the last time in Earth history when atmospheric CO_2 concentrations approached modern values (~400 ppmv) whilst at the same time retaining a near modern continental configuration. The IPCC 5th Assessment report chapter 5 (Masson-Delmotte et al., 2013) states that that model–data comparisons for the Pliocene provide high confidence that mean surface temperature was warmer than pre-industrial (Dowsett et al., 2012; Haywood et al., 2013). Global mean sea surface temperatures have been estimated to be +1.7°C above the 1901–1920 mean based on large data syntheses (Lunt et al., 2010; Dowsett et al., 2012). Exiting climate model simulations have produced a range of global mean surface air temperature of +1.9°C and +3.6°C relative to the 1901–1920 mean (Haywood et al., 2013). Model simulations have indicated that meridional temperature gradients were reduced (due to high latitude warming), which has significant implications for the stability of polar ice sheets and sea level in the future (e.g. Miller et al. 2012). Compilations of vegetation (Salzmann et al., 2008) have indicated that the global extent of arid deserts decreased and boreal forests replaced tundra, and climate models predict an enhanced hydrological cycle, but with a large inter-model spread (Haywood et al., 2013). The East Asian Summer Monsoon, as well as other monsoon systems, may also have been enhanced (Zhang et al. 2013). Although climate model simulations for the Pliocene were assessed in the AR5, these simulations were not derived from the same model/same resolution as the CMIP5 future projections, thus reducing the communities' ability to assess and compare changes in global and regional Pliocene climates, vis-à-vis similar predictions of future climate change (Haywood et al., 2013).

We propose a CMIP6 time-slice experiment for the Pliocene to understand the long term response of the Earth's climate system to a near modern concentration of atmospheric CO_2 (longer term climate sensitivity or Earth System Sensitivity), and to understand the response of ocean circulation, Arctic sea-ice, modes of climate variability (e.g. ENSO), as well as the global response in the hydrological cycle and regional changes in monsoon systems. A Pliocene simulation will be of high societal relevance because of its potential to inform policy makers on required emission reduction scenarios designed to prevent global annual mean temperatures increase by more than 2 to 3 °C in the long term (beyond 2100 AD).

The proposed CMIP6 simulation for the Pliocene is relevant to two of the WCRP Grand Challenges. This includes Clouds, Circulation and Climate Sensitivity because of the enhanced CO_2 forcing (contemporaneous with modern CO_2 forcing), providing a unique opportunity to examine an equilibrium climate state to a near modern concentration of atmospheric CO_2. The pattern of polar amplification preserved Pliocene climate archives can be compared directly with the latest generation of CMIP models making a valuable contribution towards addressing the potential polar amplification problem. Through the analysis of Pliocene polar amplification in CMIP models, and examining the geological interpretation of a seasonally sea-ice free Arctic Ocean during the Pliocene, our CMIP6 simulation will also address the WCRP Grand Challenge of Changes in the Cryosphere. Whilst uncertainty exists in Pliocene sea level reconstruction, IPCC AR5 states with high confidence that Pliocene sea-levels were higher than the pre-industrial era, with a number of independent methods indicating a sea-level rise of between 10 and 20 m. This indicates potential long term instability of both the Greenland and Antarctic Ice Sheets (Miller et al. 2012) with CO_2 concentrations at approximately 400 ppmv.

CMIP6 Pliocene experiments will be used within the Pliocene Ice Sheet Model Intercomparison Project in order to better constrain the climatological forcing in ice sheet model simulations for the Pliocene in the future. There is a well-organized and highly active of community of Pliocene climate modellers within PMIP, with the Pliocene working group being one of the most successful working groups within PMIP3. The working group is closely associated with the United States Geological Survey (USGS) who has had a highly productive core program focused on Pliocene environmental reconstruction for the last 25 years, and their data has been used to underpin almost all model-data comparisons performed for the Pliocene. Thus, CMIP6 can expect a high degree of continued support and new Pliocene data sets from the USGS for comparison with model outputs.

The experiment will address the broad scientific questions: 1 How does the Earth System respond in the long term to CO_2 forcing analogous to that of the modern? and 2 What is the significance of CO_2 induced polar amplification for the stability of the ice sheets, sea-ice and sea-level?

An overview of the proposed evaluation/analysis of the CMIP DECK and CMIP6 experiments*

midHolocene* and *lgm: evaluation w.r.t available data (systematic benchmarking, cf. Harrison et al, Climate Dynamics, 2013), both in terms of temperature and hydrological cycle. These evalutions make use of independent climate reconstructions over land and ocean. A specific focus will be put on the link with model biases and model results for future climate. Specific working groups in PMIP have been set up to improve the comparisons with marine data (COMPARE group) and isotopic data (cf. http://pmip3.lsce.ipsl.fr/, "working groups" tab). This provides new methodologies and new possibilities for quantitative model assessments.

***past1000*:** In-depth analyses using novel statistical approaches (Sundberg et al., 2012; Moberg et al., 2014; Bothe et al., 2013) and detection/attribution techniques (Schurer et al., 2014).

Process-oriented analyses on variability and changes in circulation modes. Partly supported by dedicated sensitivity studies, e.g. in VolMIP.

LIG: The CMIP6 experiment will analyse the strength of feedbacks at work in the Arctic, and their potential implications for the stability of the Greenland ice sheet. A particular emphasis will be put on the annual redistribution heat by the ocean circulation and the potential role of the transmission of the subsurface warming from North Atlantic to Southern ocean, with implication for basal melting of West Antarctic ice Sheet. High latitude feedbacks from sea-ice, water vapor and cloud will be a focus, as well as the relative changes between the tropical and high latitude water cycle.

Pliocene Warm Period: The CMIP6 experiment will evaluate the ability of models to simulate a recent interval of CO_2-induced global warmth, and assess the response of critical components of the climate system to near modern CO_2 forcing in the long term (sea-ice, modes of variability, monsoons, storm tracks, vegetation). Unlike other warm periods or interglacials the Pliocene retains critical modern boundary conditions such as the continental configuration and astronomical forcing. The signal of change in Pliocene is large and therefore the signal to uncertainty ratio enables model-predicted changes to be attributed with confidence.

Some of these diagnoses and model evaluations will be performed as part of PMIP transverse analyses groups. In particular, the PMIP "Past2Future" working group aims at identifying and understanding relationships between model simulations for past and future climates and at using available paleodata to evaluate the consistency of these relationships. Its work is therefore potentially based on all PMIP simulations together with selected simulations relevant for future climate change.

Proposed timing*

Ideally past1000 should be run before the historical simulations. All other experiments can be run as soon as the reference simulation in DECK is run.

Experimental design of proposed CMIP6 experiments

- midHolocene and lgm

(taken from Braconnot et al, Nature Climate Change, 2012) + http://pmip3.lsce.ipsl.fr

Mid-Holocene (MH) and Last Glacial Maximum (LGM) simulations are equilibrium experiments, presenting a “snapshot” of climate at a specific time. Table 2 summarises the boundary conditions used for MH and LGM experiments during the various phases of the Palaeoclimate Modelling Intercomparison Project (PMIP). The ultimate external forcing (or driver) of climate is change in incoming solar radiation (insolation) as determined by changes in the Earth’s orbit. These changes can be specified precisely. Due to the slow variations of Earth’s orbital parameters, the seasonal and latitudinal distribution of MH insolation was different from present (1950 C.E), enhancing the magnitude of the seasonal contrast in the Northern Hemisphere by about 60 Wm^{-2}. Insolation forcing at the LGM was very similar to present. When models do not explicitly simulate slow processes such as the build up of ice sheets, concomitant changes in land-sea distribution, or the evolution of atmospheric composition, all of which lead to changes that have to be considered as climate forcings on shorter timescales, then these boundary conditions (hereafter forcings) have to be prescribed in the MH and LGM experiments. As models have evolved in complexity, so the set of forcings that has to be prescribed has also evolved. In the first phase of the Palaeoclimate Modelling Intercomparison Project (PMIP1), the experiments were performed with atmospheric general circulation models and the state of the ocean was prescribed as a forcing. In the second phase of PMIP (PMIP2), some models incorporated vegetation dynamics but vegetation cover and albedo still had to be specified for the coupled ocean-atmosphere general circulation models (OAGCMs). Some processes, such as those associated with the terrestrial and marine carbon cycle, have been ignored in the earlier PMIP experiments, but will be included as interactive components of some of the models used in PMIP3. In all experiments the atmospheric composition is prescribed using results from ice-cores.

The next phase of PMIP will make use of the PMIP3 boundary conditions whenever possible. A major foreseen evolution is related to the interactive computation of the dust cycle in atmospheric models, for which changes in vegetation also have to be taken into account. PMIP2 and PMIP3 recommended the use of either interactive vegetation or prescribed pre-industrial vegetation. For PMIP4, those models which include an interactive representation of the dust cycle will have to account for changes in vegetation. This particular topic will be discussed with the modelling groups.

The *lgm* experiment will be the reference from which sensitivity experiments to uncertainties in boundary conditions will be developed. In particular, the sensitivity to ice sheet reconstructions will be tested within the PMIP working group on LGM ice sheet uncertainties. These CMIP6 and PMIP4 LGM experiments will also be starting points for transient deglaciation experiments (coordinated by the working group on the deglaciation).

Table 2 : Evolution of the boundary conditions prescribed in the different phases of the PMIP project. Boundary conditions that remain the same between different sets of simulations are highlighted in yellow; blue highlighting shows boundary conditions that are not included in a given set of experiments. More details on the protocols used in PMIP3 can be found on the PMIP3 web site (see http://pmip3.lsce.ipsl.fr/), which also provides links to the webpages detailing the protocols used in PMIP1 and PMIP2. Note that in the MH experiment the CO2 concentration is the pre-industrial one. CO2ctrl refers to the CO2 concentration of the present-day control simulation.

	PMIP1	PMIP2	PMIP3
Mid Holocene (6000 years BP)* *In this experiment ice-sheet, coastline, solar constant and aerosols are prescribed as in the PI simulation.			
Insolation	eccentricity = 0.018682 **obliquity** = 24.105° perihelion-180° = 0.87°	eccentricity = 0.018682 **obliquity** = 24.105° perihelion-180° = 0.87°	eccentricity = 0.018682 **obliquity** = 24.105° perihelion-180° = 0.87°
Trace gases	**CO_2** = 280 ppm or 280/345* CO_2ctrl **CH_4** = 650 ppb **N_2O** = 270 ppb CFC = 0 **O_3** = not considered	**CO_2** = 280 ppm **CH_4** = 650 ppb **N_2O** = 270 ppb CFC = 0 **O_3** = not considered	**CO_2** = 280 ppm **CH_4** = 650 ppb **N_2O** = 270 ppb CFC = 0 **O_3** = same as in CMIP5 PI
Vegetation and land surface	Prescribed to be the same as modern vegetation	Either prescribed to be the same as modern vegetation or computed using a dynamical vegetation module	Computed using a dynamical vegetation module, Or prescribed as in PI, with phenology computed for models with active carbon cycle or prescribed from data
Carbon cycle	Not considered	Not considered	Interactive, with atmospheric concentration prescribed and ocean and land carbon fluxes diagnosed as recommended in CMIP5
Last Glacial Maximum (21000 years BP) * * In this experiment solar constant and aerosols are prescribed as in the PI simulations.			
Insolation	eccentricity = 0.018994 **obliquity** = 22.949° perihelion-180° = 114.42°	eccentricity = 0.018994 **obliquity** = 22.949° perihelion-180° = 114.42°	eccentricity = 0.018994 **obliquity** = 22.949° perihelion-180° = 114.42°
Trace gases	**CO_2** = 200 ppm or (200/280) * CO_2ctrl **CH_4** = 350 ppb **N2O** = 190 ppb CFC =0 **O_3** = same as in PI	**CO_2** = 185 ppm **CH_4** = 350 ppb **N_2O** = 200 ppb CFC =0 **O_3** = same as in PI	**CO_2** = 185 ppm **CH_4** = 350 ppb **N_2O** = 200 ppb CFC =0 **O_3** = same as in PI
Ocean	SST prescribed from CLIMAP (1981) Or SST computed using a slab ocean model	3D Ocean model and sea-ice	3D ocean model and sea-ice

Ice sheet	ICE-4G (Peltier et al, 1994)	ICE-5G (Peltier et al, 2004)	PMIP3 Blended ice sheet
Land-sea mask	–105 m sea level	Prescribed following Peltier (2004) land-sea mask –120 m	Prescribed from the blended ice-sheet land-sea mask. Sea-level change consistent with the change in land-sea mask.
Freshwater		Excess LGM freshwater added to the ocean in 3 different regions	Excess LGM freshwater added to the ocean in 3 different regions
Ice sheet ice streams	Not considered	Not considered	Not considered
River runoff	Not considered	As in CTRL or river pathway modified	As in PI or river pathway modifier according to PMIP protocol
Mean ocean salinity	Not considered	Not considered	+1 PSU everywhere
Carbon cycle	Not considered	Not considered	Interactive, with atmospheric concentration prescribed and ocean and land carbon fluxes diagnosed as recommended in CMIP5 For PCMIP: fully interactive with atmospheric concentration computed by the model

- Last Millennium

Updated PMIP3 protocol (http://pmip3.lsce.ipsl.fr) based on Schmidt et al (2011, 2012):

Schmidt, G. A. et al. (2011). Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0), Geosci. Model Dev., 4, 33–45.

Schmidt, G. A. et al. (2012). Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), Geosci. Model Dev., 5, 185–191

Transient simulations 850-1849 followed by historical experiments, set of boundary conditions for solar, volcanic, land-cover-change, greenhouse gases to be blended with those for historical (1850-2010) simulations. The continuity between the past1000 and historical scenarios has to be improved and fully discussed within CMIP6.

- Last Interglacial

Based on the protocol discussed within PMIP3.

For CMIP6, we propose to perform a simulation for the 128ky BP time slice - large orbital forcing (Figure 1), large responses.

- Orbital parameters set to 128ka.
- Greenhouse gas concentrations well-known from ice cores [CO_2 275ppm; CH_4 709ppb; N_2O 266 ppb].
- modern geography, ice sheets, and vegetation;
- Initialize from CMIP6 pre-industrial DECK simulation;
- length: ≥ 100 years after spinup.

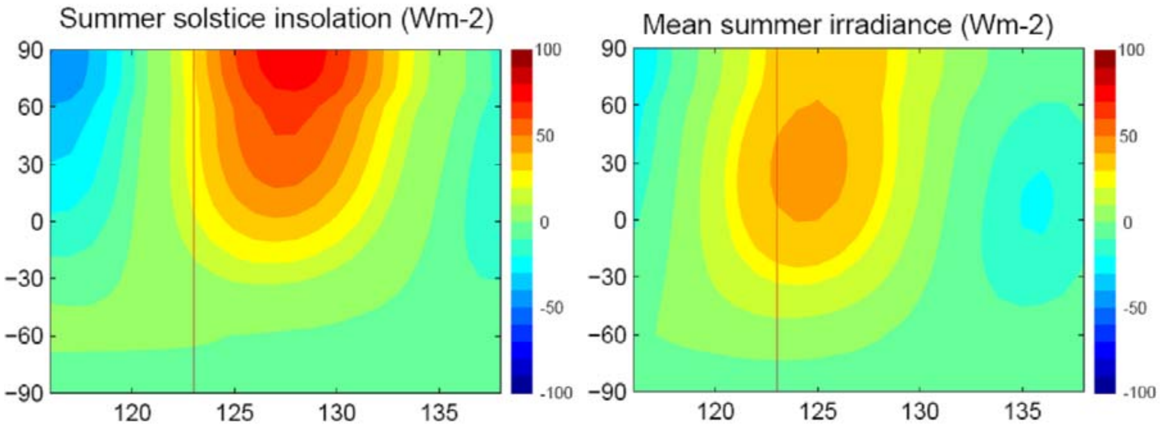


Figure 1. Anomalies of summer solstice insolation (left) and mean summer irradiance (right) as compared to present. Left axes are latitude and bottom axes are in thousands of years before present.

This simulation will constitute a reference for PMIP LIG simulations: other snapshots within the last interglacial (125, 122 ky BP), transient simulations for the whole interglacial. This will also be a target period for testing AOGCMs coupled with polar ice-sheet models, as proposed in ISMIP. Discussions are on-going with ISMIP are on-going in order to coordinate a LIG experiment with them.

➢ Pliocene warmth

Time slice equilibrium climate experiment modifying CO2 (to 400 ppmv), topography, ice sheet extent and running with dynamic vegetation.

Updated from PlioMIP experiment 2 (Haywood et al, GMD, 4, 571-577, 2011), under discussion for minimum changes in boundary conditions w.r.t. pre-industrial.

As for the other proposed CMIP6 experiments, this Pliocene experiment is the basis for a full range of experiments coordinated within PMIP by the PlioMIP working group. In particular, the sensitivity of the results to insolation, ice sheet configuration and other boundary conditions will be investigated.

Science question and/or gap addressed with the PMIP experiments

Cf. introduction and summary excel table.

New foci for analyses will be:

- Forced vs. internal variability, putting in context climate changes in the industrial historical period
- Clouds/Circulation: WCRP Grand challenge Initiative on Leveraging the past record (http://www.wcrp-climate.org/index.php/gc-clouds-circulation-activities/gc4-clouds-initiatives/116-gc-clouds-inititative4)
- Analyses of cryospheric feedbacks under natural forcings (transient simulations over the last millennium put in perspective the recent changes e.g. in Arctic Sea ice, coupling between ice-sheets and climate (*lgm*, LIG, Pliocene)
- Regional climate and decadal predictions:
  - Improved assessment of decadal to centennial variability as carrier of near-term prediction potential (*past1000*, *midHolocene*, *lgm*).
  - Regional assessment of response to natural forcing and interaction with variability modes and teleconnections (all experiments)
- Assessment of extremes under natural forcing, e.g. volcanoes. Natural variations in droughts in connection with paleo-reconstructions (*past1000*). Analyses of mechanisms of mega-droughts (*midHolocene*). → link with Grand challenges on extremes and on water availability.

Possible synergies with other MIPs

PMIP simulations can serve to interact with other MIPs on the following themes:

- CF-MIP (cloud feedbacks): dedicated common idealized sensitivity experiments to be run in aquaplanet set up: AMIP simulations with SSTs minus 4K, abrupt0.5xCO2, abrupt solar perturbation experiments, to be co-analysed in CF-MIP and PMIP.
- OCEAN/SEA_ICE: Mutual assessment of the role of the ocean in low-frequency variability, e.g. multi-decadal changes in ocean heat content or heat transport. Provide initial conditions for the ocean including long-term forcing history.
- CARBON CYCLE (C4MIP): Assessment of carbon-cycle evolution and feedbacks between sub-components of the Earth System. Evaluation of paleo reconstructions of carbon storage.
- LAND USE: Links should be reinforced for better connecting past1000 to historical simulations. Useful for analysis of past1000 simulations, for biophysical as well as carbon cycle aspects.
- VolMIP (volcanic forcing): analysis of specific volcanic events very useful for critical analysis of past1000 simulations. VolMIP would systematically assess uncertainties in the climate response to volcanic forcing, whereas LM simulations describe the climate response to volcanic forcing in long transient simulations where related uncertainties are due to chosen input data for volcanic forcing: mutual assessment of forced response.
- DETECTION/ATTRIBUTION: long millennium simulations can be very useful for this topic.

Potential benefits of the experiments

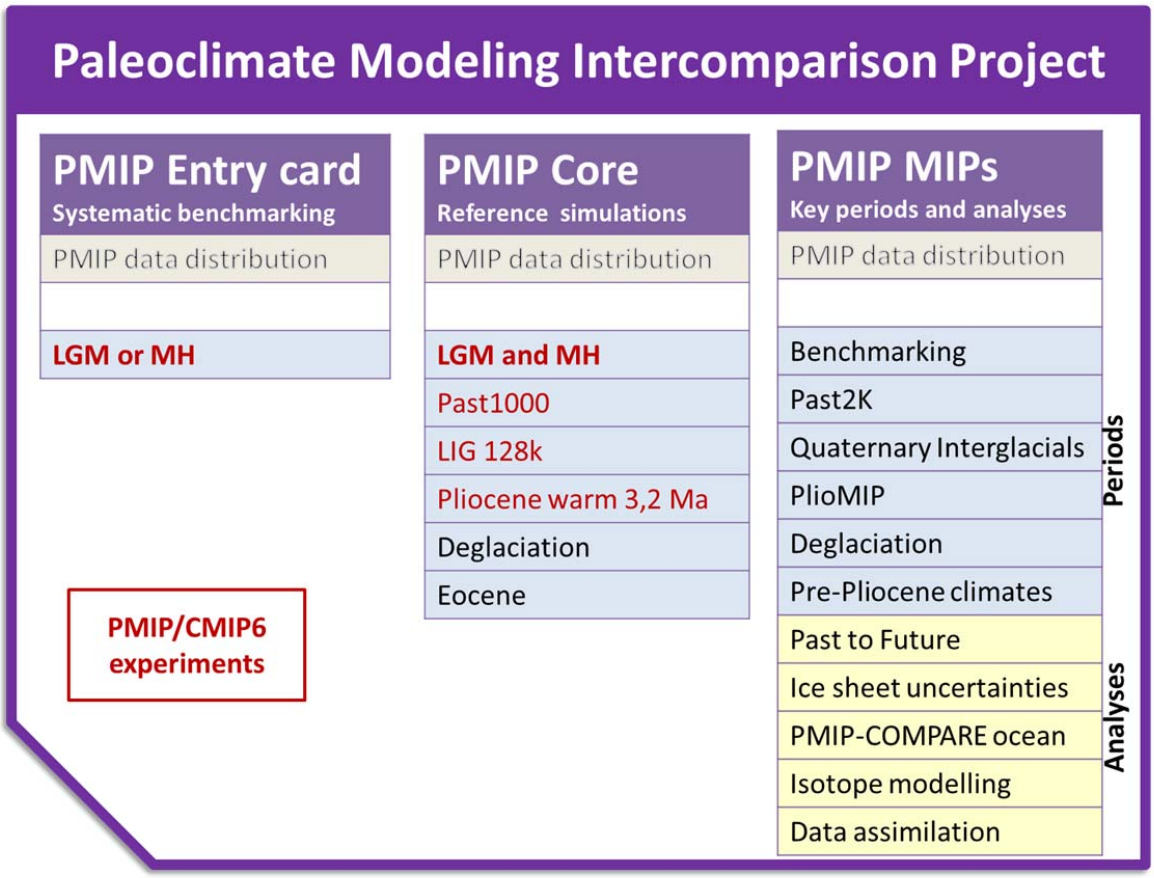
Potential benefits of the experiments to

- (A) climate modeling community
    - Improved assessment of forced response and forced vs. internal variability
    - Improved knowledge on which processes are important in the forced response to natural forcing (e.g. ozone changes owing to solar radiation changes for the past1000 experiment)
- (B) Integrated Assessment Modelling (IAM) community,
- (C) Impacts Adaptation and Vulnerability (IAV) community
    - All experiments:
    - Identification of thresholds for ecosystems and water availability under different climate conditions
    - Improved assessment of natural variability including extreme events under pre-industrial boundary conditions. Identification of regions where, under natural forcing, changes, changes lead to specific vulnerability (e.g. regional sea-level)
- , and (D) policy makers.
    - Quantification of magnitude and speed of a range of past climatic changes compared to the natural variability and recent and future climatic trends.Impact of these changes on water availability and ecosystems.

Prioritization of the proposed experiments

➢ If possible, a prioritization of the suggested experiments, including any rationale**

Each proposed PMIP experiment for CMIP6 can be run independently, because they focus on different time periods. The *midHolocene* and *lgm* experiments have been the focus of PMIP since its start and allow for an evaluation of new model versions since the first atmosphere-only GCMs in PMIP1. We therefore require one of these two simulations to be performed as an entry card to CMIP6-PMIP4 experiments. All five PMIP experiments proposed for CMIP6 have equal priority, each experiment being the core of a set of sensitivity experiments to be run within PMIP. The organization of the PMIP experiments w.r.t CMIP6 is given in the figure below.



Model output

- All model output archived by CMIP6-Endorsed MIPs is expected to be made available under the same terms as CMIP output. Most modeling groups currently release their CMIP data for unrestricted use. If you object to open access to the output from your experiments, please explain the rationale.**

PMIP (all experiments): no objections

- List of output and process diagnostics for the CMIP DECK/CMIP6 data request**
    - whether the variable should be collected for all CMIP6 experiments, or only some specified subset and whether the output is needed from the entire length of each experiment or some shorter period or periods;

PMIP (all experiments): same set of CMOR variables as historical/scenario (possibly reduced set of high-frequency output owing to length of experiment), some simulations with COSP simulator (subset of years)

- whether the output might only be relevant if certain components or diagnostic tools are used interactively (e.g. interactive carbon cycle or atmospheric chemistry, or only if the COSP simulator has been installed);

PMIP all-experiments: diagnostics needed for ESM (i.e all components of the ESM + forcings + feedback analyses) + tracers and isotopes when available (list to be established)

- whether this variable is of interest to downstream users (such as impacts researchers, WG2 users) or whether its principal purpose is for understanding and analysis of the climate system itself. Be as specific as possible in identifying why the variable is needed.

PMIP all periods: subset of variables for driving regional climate models, ice-sheet models (ISMIP) or ecological models (land surface variables) or dust models.

PMIP *past1000* and *midHolocene*: subset of variables for investigating extreme events or variability

- whether the variables can be regridded to a common grid, or whether there is essential information that would be compromised by doing this;

PMIP: same as for CMOR variables from historical/scenario;

- the relative importance of the various variables requested (indicated by a tiered listing) is required if the data request is large.

See previous PMIP requests (CMIP5 or PMIP3 ESGF): same set of CMOR variables as historical/scenario (possibly reduced set of high-frequency output owing to length of experiment)

- Any proposed changes from CMIP5 in NetCDF metadata (controlled vocabularies), file names, and data archive (ESGF) search terms.**

Needs to discussed with all MIPs

- Explanation of any proposed changes (relative to CMIP5) that will be required in CF, CMOR, and/or ESGF.**

PMIP benefits from two entries on ESGF: via the CMIP5 Project for PMIP3-CMIP5 experiments or the PMIP3 project for other PMIP3 experiments or for groups which do not take part in CMIP5. It would be very convenient to still be able to search through both (or indeed multi-MIP) data bases on the same system, as can be done now.

Proposed contributions for model diagnostics and evaluation

- Any proposed contributions and recommendations for**
  - model diagnostics and performance metrics for model evaluation;

past1000: use diagnostics that have been defined for DECK historical/scenario simulations. In addition to integrated quantities such as hemispheric temperature averages, *past1000* experiments will increasingly be analysed w.r.t. circulation regimes, extreme events etc.

midHolocene, lgm: PMIP specific diagnostics have been developed for benchmarking. A working group is dedicated to this topic. cf. Harrison et al (2014), Climate Dynamics, 43, 671–688

  - observations/reanalysis data products that could be used to evaluate the proposed experiments. Indicate whether these are available in the obs4MIPs/ana4MIPs database or if there are plans to include them;

past1000 simulations will benefit from observations to be extended to the early 19th century. *past1000* simulations will be compared, mutually analysed with paleo reconstructions, most importantly the growing set of PAGES2K reconstructions that are available through Paleodata data bases.

PMIP data syntheses for *midHolocene* and *lgm* (http://pmip3.lsce.ipsl.fr/synth/)

new syntheses will be available for characterizing high resolution variability during the Holocene (paleoVar PMIP working group)

  - tools, code or scripts for model benchmarking and evaluation in open source languages (e.g., python, NCL, R).

Common analyses scripts are being discussed within PMIP.

For *past1000*: in the framework of the PMIP working group Past2K advanced statistical analyses and evaluation tools have been developed (e.g. Bothe et al., 2013; Moberg et al., 2014).

Expression of interest from modelling groups

On Nov 28th 2014, PMIP has received the expression of interest from 9 modelling groups for the LIG experiment, 10 modelling groups for the *midHolocene*, *lgm* and *past1000* experiments and 11 modelling groups for the Pliocene Warm Period experiment.