Palaeoclimate Modelling Intercomparison Project : Scientific issues and implementation plan

The Palaeoclimate Modelling intercomparison Project (PMIP) is a long standing initiative endorsed by both WCRP/CLIVAR/WGCM and IGBP/PAGES. It has provided an efficient mechanism for coordinating palaeoclimate modelling activities that provide valuable information on the mechanisms of climate change, the identification of key feedbacks operating in the climate system and, through model evaluation, the capability of climate models to reproduce climates different from today. Thanks to the production of data syntheses and to rigorous model-data comparisons, the mid-Holocene climate (MH: ca 6000 yr BP) and the Last Glacial Maximum (LGM, ca 21,000 yr BP) are now recognised as benchmark periods for climate models.

In the last 10 years climate models have moved from atmosphere-only to coupled ocean-atmosphere models and ocean-atmosphere-vegetation models. Models which include the coupling between the physical climate and biogeochemical cycles, such as the carbon cycle, have also been developed. These couplings, and the corresponding feedbacks, shape the response of the climate system to external variations and are required to understand how climate has evolved through time and will evolve in the future in response to human activities. As models become more complex, through incorporation of these important feedbacks, they pose both challenges and opportunities: challenges because these "Earth-system models" require benchmarking against observations to be sure that they can simulate radically different climates, and opportunities because these models allow us to address new aspects of climate change with direct societal relevance. State-of-the-art models can now be used to examine not only the evolution of the mean climate but also changes in short-term climate variability and in climate extremes such as droughts or storms.

Drawing on our experience during the past 10 years, PMIP will continue to use simulations made with state-of-the-art models and palaeoenvironmental data syntheses together to:

- understand the mechanisms of climate change
- identify the different climatic factors that shape our environment
- evaluate the capability of state-of-the-art models to reproduce different climates.

This will be achieved through simulations of ***key periods in the past*** for which there are enough observations to produce well-documented, global-scale data syntheses and when the differences from the modern climate can be detected unambiguously (i.e. when the signal to noise ratio is large). We will make these simulations with ***state-of-the-art models***, and as far as possible with the same models that are used for simulating future climates. ***Systematic model-model and model-data comparisons*** will remain a key element of our programme, and we will continue to develop new methodologies to ensure that these comparisons focus on appropriate variables and scales. Specifically, we will seek to address the fact that many palaeoenvironmental sensors of climate change record changes in non-standard aspects of the climate (e.g. the depth of the mixed-layer in the ocean or the length of the growing season) and over an area that may be smaller than that of a model grid cell. Given recent model developments and our ability to simulate interannual variability and climate extremes, it will also be necessary to ***develop new data sets*** that address these aspects of climate. In addition to inverse reconstructions of climate parameters, it will be important to exploit forward models (e.g. of water isotopes, mineral aerosol transport) in data-model comparison exercises.

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PMIP Achievements

PMIP was designed as a model intercomparison project and initially focused on two periods, the Last Glacial Maximum (LGM, ca 21,000 years ago) and the mid-Holocene (MH, ca 6000 years ago) that represent different forcing conditions. The LGM simulation was conceived as an experiment to examine the climate response to the presence of large ice sheets, cold oceans and low greenhouse gas concentrations. The MH simulation was designed to examine the climate response to a change in the seasonal and latitudinal distribution of incoming solar radiation (insolation) caused by known changes in orbital forcing. Seventeen modelling groups participated in simulations of these time periods with atmosphere-only models (PMIP1), and twelve groups in the second phase of the project using ocean-atmosphere or ocean-atmosphere-vegetation models (PMIP2). Several hundred scientists were involved in running and analysing the simulations, in producing palaeodata sets for model evaluation, and in model-model and model-data comparisons. PMIP has produced over 100 publications and PMIP results have been used extensively in the last two IPCC assessments.

However, the contribution of PMIP cannot be measured by these numbers alone. PMIP has also:

- Demonstrated that models that are capable of adequately reproducing modern and historical climates, nevertheless fail to reproduce observed changes in the past. Thus, the ability to simulate the present-day is not a sufficient test of model capability and the ability to simulate future climate changes.
- Shown that model biases influence the simulated response to a change in forcing, and documented improvements in the ability to simulate such a response with improvements to model resolution or physical parameterisation
- Demonstrated, initially through sensitivity experiments, the importance of vegetation feedbacks to the climate system and this, in large part, was responsible for the push to include vegetation as a dynamic and interactive component of climate models
- Demonstrated the model complexity needed to simulate past (and hence also future) climate changes, and thus promoted the development of earth system models.

In practical terms, PMIP has promoted synergies with the palaeoenvironmental community and thus:

- Motivated the development of regional and continental syntheses of palaeoclimate and palaeoenvironmental data (e.g. BIOME 6000, DIRTMAP, MARGO)
- Promoted the development of improved methods of reconstructing climate parameters from palaeo-observations
- Motivated the development of forward models, including for example models of vegetation, for use in model evaluation and increasingly for coupling directly within a climate-model framework
- Promoted the development of rigorous statistical approaches to comparing simulated and observed climates, in order to be able to quantify the degree to which an individual model reproduces (or fails to reproduce) known responses to external forcing.

PMIP, in addition to its focus as an intercomparison project, has acted as an important discussion forum which has promoted ***the understanding of past climate changes as a necessary basis for having confidence in future predictions***. In particular, PMIP has demonstrated the validity of the approach employed by the IPCC, and others, that uses coupled global climate models to simulate climates with large-scale controls that differ substantially from those of the present day.

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How will PMIP address questions relevant for the future

The 4th IPCC assessment clearly shows that the current generation of climate models produce more reliable simulations of modern and historical climates, more consistent predictions of some aspects of projected future climate than previous assessments, and that we have a better understanding of the mechanisms of climate change. Nevertheless, there are still large uncertainties in the magnitude of predicted future warming, the direction of change in the hydrological cycle in tropical regions, in the possible changes of the major modes of interannual to decadal variability such as ENSO and the NAO, and in the role of feedbacks given their highly non-linear nature. Although the potential importance of physical and biogeochemical feedbacks has been recognised, only a limited number of the models used to predict future climates include the carbon cycle and virtually no model incorporates interactions with dynamic vegetation or with ice-sheets in simulating future climate changes. Furthermore, there are considerable uncertainties associated with the influence of changes in freshwater fluxes on the thermohaline circulation and feedbacks with sea ice, ice-sheet melting, climate sensitivity and sea level rise. Reducing these various uncertainties will be a major focus of work in the coming years. In planning the future of PMIP, we have focused on ways in which PMIP is best-placed to contribute to this effort.

PMIP will encompass three activity streams: benchmarking, climate analysis, and exploration.

Benchmarking: Models that perform equally well for present-day and historical climate may produce very different responses to likely changes in forcing in the future. This makes it vital to evaluate and benchmark models, by comparing simulations of past climates against palaeo-observations. As new components addressing important feedbacks are incorporated within the current model framework, palaeo-benchmarking should be a critical part of the evaluation procedure. PMIP will take the lead here, by defining experimental protocols, assembling evaluation data sets, and undertaking quantitative assessments of simulations. Given the wealth of well-documented data sets already assembled, the LGM and MH will provide the focus for benchmarking activities within PMIP.
Analysis: The strength of PMIP lies in the ability to examine multi-model ensembles and to analyse the causes of differences in model ability to reproduce observed climate changes in the past. Thus, we will continue to focus on the analysis of the mechanisms of past climate change, specifically during past interglacials and warm periods, during intervals when there have been abrupt changes in the climate system, and during intervals when feedbacks related to changes in the land-surface or ocean circulation have played an important role.
Exploration: PMIP has always provided a discussion forum which includes both modellers and observationalists, and is therefore extremely well placed to identify how emerging issues and uncertainties in global change science can be addressed through confronting models and data. There are clearly palaeo-dimensions to several emerging issues and uncertainties, for example, feedbacks through ice-sheet melting and sea-level rise, how vegetation changes influence trace gas and aerosol emissions to the atmosphere, the frequency of extreme events like tropical storms, and the relationships between changes in the mean state of the hydrological cycle and the occurrence of extreme floods and droughts. PMIP will therefore encourage the investigation of these issues and provide an active forum in which to discuss the results.

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Scientific Issues and Future Planning

Our future plans take into account the evolution of Earth system modelling, increased interest in climate variability and abrupt change, and the need to develop appropriate methodologies to understand and reduce uncertainties in climate projection. The work is divided into four major themes:

1. Evaluation of Earth system models (ESMs) at 6ka and 21 ka
2. Interglacials and warm periods
3. Abrupt climate change
4. Uncertainties : characterisation and understanding

Theme 1: Evaluation of ESMs at 6ka and 21 ka

In addition to improving existing parameterisations, work is already underway to incorporate new sub-system components, including e.g. dynamic vegetation, biogenic emissions, fully-interactive chemistry, and interactive ice sheets, within the framework of models to be used for projection of future climate. PMIP will promote the use of palaeo-benchmarks for model testing, both of offline versions of new components and subsequently of new fully-coupled models through coordination with ongoing or planned model-component intercomparisons (e.g. LUCID, PC4MIP, FIREMIP). PMIP will take the lead here by defining experimental protocols, assembling evaluation data sets, and undertaking quantitative assessments of simulations. Benchmarking of model components will focus on the LGM and the MH, times when the signal-to-noise ratio is large and when we already have a number of well-documented palaeodata syntheses for evaluation. Benchmarking activities will allow us to determine whether the incorporation of new components and feedbacks produces an improvement in the simulation of regional climates. It will also help to determine whether some treatments of specific processes are more realistic than others and, in so far as this is done with offline model versions first, may help to inform decisions about which treatments to include in coupled mode.

Initial benchmarking activities will focus on the use of existing palaeo-data sets and diagnostic techniques. However, there will be a need to develop new data sets, both to address specific aspects of the simulations that have not previously been evaluated (e.g. the ability to capture short-term variability) and to test new components (e.g. the incorporation of fire-controlled emissions requires evaluation of simulated fire regimes). These evaluations will require the development of new diagnostic techniques, addressing the fact that many palaeoenvironmental sensors of climate change record changes in non-standard aspects of the climate (e.g. the depth of the mixed-layer in the ocean or the length of the growing season) and over an area that may be smaller than that of a model grid cell. There is also a need to develop techniques that will overcome the mismatch in temporal scales between simulations and palaeoenvironmental records. We will continue to promote model-data comparisons in both forward and inverse mode. There is still considerable work to be done in the area of forward modelling, both in comparing the uncertainties associated with using different models of a specific component and in developing new forward models.

Our ultimate goal is to facilitate regular use of PMIP diagnostics and data sets for model benchmarking by the community, by making these resources easy to use and freely available to the through the PMIP website (http://pmip2.lsce.ipsl.fr/).

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Theme 2: Interglacials and warm periods

In addition to the Holocene (last 11,000 years), earlier warm climate epochs provide further opportunities to examine feedback mechanisms and evaluate ESMs. PMIP will focus on two new “warm periods”: the last interglacial (LIG, ca 129-116 kyr BP) and the mid-Pliocene (ca. 3.3-3.0 Myr BP). The LIG is characterised by significantly less glacial ice than present with strong evidence for a reduced Greenland ice sheet (equivalent to a few metres of sea level change). The climate was warmer than present, particularly at high latitudes with the CAPE Last Interglacial Project showing Arctic summer temperatures up to 5^0C warmer than present. Understanding the similarities and differences between the LIG and the MH will also improve our understanding of the present interglacial. The mid-Pliocene is the most recent time in Earth history when global temperatures were substantially warmer than present (ca 2–3^oC) yet continents were in a similar position and ocean gateways were identical (the Panama isthmus is closed at the mid-Pliocene). It is estimated that the Rockies were 50% of their present height and the Greenland Ice Sheet was considerably smaller. CO_2 concentrations are uncertain but probably no greater than 400 ppmv. Orbitally forced climate variability is relatively small during this period.

The key scientific issues to be addressed with these periods include:

- Ice Sheets: During the Pliocene, ice sheets were probably in near equilibrium with the forcing and substantially reduced from present. In the last interglacial, Greenland was reduced but responding to the changes in orbital forcing. How well can coupled climate-ice sheet models simulate this period? How robust are the predictions from such models?
- Polar Amplification: Both time periods show substantial polar amplification of the temperature response. In the case of the LIG, this is most clearly seen in the seasonal response, whereas for the mid-Pliocene the changes are year round. Do models correctly simulate the changes in latitudinal temperature gradient? And are the mechanisms of change (ocean v. atmosphere, mean v. eddy transport, overturning v. gyre) similar between models?
- Tropical Response: During the LIG and similar to the mid-Holocene, there are major changes in monsoon circulations. Can models simulate these changes and what is the role of oceanic and vegetation feedbacks? In the mid-Pliocene, there is considerable evidence of major changes in the tropical Pacific Ocean. The changes resemble the changes associated with El-Nino and hence is often referred to as a “permanent ENSO”. Can coupled atmosphere-ocean models simulate such changes? What are the dynamics of such changes, and what are the impacts on the whole Earth system?
- Climate Sensitivity: Are the large scale changes in temperature and hydrological regime well simulated by climate models? What does this imply for climate sensitivity? What are the key feedback processes, and are they similar between the LIG, mid-Pliocene, and mid-Holocene?

To implement this new theme, we will need to define a common protocol for the simulations. Several PMIP groups have already made simulations for these periods and can provide input to the protocol. We expect that model simulations will be with OA, OAV and IOAV GCMs, depending on the research groups involved. In addition to evaluation of model performance and analysis of the mechanisms of climate change, the simulations will be compared to equivalent MH simulations. Comparison of planned simulations with palaeoenvironmental data will be crucial to determining whether we can explain the mechanisms giving rise to these earlier warm periods. We will build on ongoing data synthesis initiatives, specifically CAPE for the LIG and PRISM (Pliocene Research Interpretations Synoptic Mapping) and PRISM-3D for the Mid-Pliocene and engage with new activities such as NEEM for the ice cores.

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Theme 3: Abrupt Climate Changes

The IPCC AR4 was unable to estimate the likelihood of abrupt climate changes in the future. To inform the next assessment, PMIP will move towards transient experiments with coupled climate models. These simulations will aim to understand the mechanisms, feedbacks, and responses that determined past abrupt changes in regional climates. The time period of focus will be the last deglaciation from the LGM to present. Proposed experiments include a transient simulation for the entire period as well as experiments exploring individual events, including Heinrich Event 1, the Bolling-Allerod warming, Meltwater Pulse 1a, the Younger Dryas, the 8.2 ka event, and the abrupt collapse of the monsoons in the later part of the Holocene.

The key science questions to be answered with these PMIP simulations and data include:

- Deglaciation: What are the mechanisms and feedbacks that govern the rates of ice sheet decay during the deglaciation? How is the decay determined by ice sheet dynamics versus feedbacks with the climate system? What are the mechanisms for ice sheet instabilities? What are the mechanisms and feedbacks that govern the changes in atmospheric carbon dioxide and methane? What are the leads and lags between insolation forcing, climate response, ice sheets, and greenhouse gases?

- Abrupt meltwater events: What is the thermohaline (THC) response to freshwater changes to the ocean? How is the response similar/different for warm versus cold climates? What is response of the climate system to a THC slowdown, especially tropics, monsoons, bipolar connections? What determines the abruptness of the response and recovery?

- Other abrupt thresholds: What controls the “abrupt” termination of the African monsoon? Are there other abrupt terrestrial thresholds during the deglaciation and Holocene?

Model experiments will be diagnosed to determine the feedbacks between the components of the climate system – atmosphere, ocean, sea ice, and vegetation – and with new model developments of carbon and land ice. The role of preconditioning as well as seasonality and interannual variability in setting the rates of change and sensitivity to the forcings will be assessed. To implement this new theme of PMIP will require new data reconstructions of both the forcings/boundary conditions and responses of the climate system. The first experiments will be done with currently available climate models, and will require reconstructions of the ice sheet size and shape during the deglaciation and a detailed sequence of meltwater flowing into the oceans, including timing, amount, location, and means (i.e. freshwater or calving icebergs). Key to understanding and evaluating these experiments will be the development of data synthesis detailing the transient behaviour in oceanic and terrestrial records. Emphasis must be given to identifying data records that document key changes in the global monsoons, tropical Atlantic, South American, and Africa, and Southern Hemisphere high latitudes. ESMs need to be developed which include modelling of data indicators, such as isotopes, kinematic tracers, as well as coupling of AOV models to ice sheet and biogeochemistry modules. The first ESM transient simulations of the last deglaciation will likely rely on intermediate complexity models because of the large computational burden of these experiments. A suite of data-analysis tools (e.g. change-point detection, intervention analysis) will be required to characterize the nature of abrupt changes in both the data syntheses and model simulations.

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Theme 4: Uncertainties: characterisation and understanding

A key challenge is to quantify the reliability of future climate projections. In the IPCC Fourth Assessment Report (AR4), multi-model ensembles were used to obtain both a "best estimate" of future climate change and also some measure of the uncertainty (i.e., range) in those estimates. For the most part, individual models were considered equally reliable by the authors of the AR4. One of the values of multi-model palaeo-experiments is that the relative skill of models can be assessed by comparison with observations. An outstanding question, however, is whether some measure of this relative skill can be used to provide a more constrained and correct projection of future climate change. In our fourth theme, PMIP will explore the extent to which *unequal* weighting of models, based on some set of measures of model skill in simulating palaeoclimate conditions, can reduce the uncertainty in future projections. This will require

- an assessment of uncertainties in the palaeoclimate "boundary conditions" imposed in forcing models,
- an estimate of uncertainty in palaeoclimate reconstructions,
- development of metrics that quantify model performance in simulating palaeoclimates, and
- a determination of the relationship between skill in simulating observed climate (past and present) and skill in projecting climate change.

The multi-model perspective provides essential information needed to assess whether the simulated and observed climates are consistent within the range of model results. PMIP will build on its previous work in this area to provide probabilistic information useful in the interpretation of palaeoclimate data. However, PMIP scientists are involved in projects to explore how palaeoclimate data might constrain future climate projections by utilizing a large ensemble of "perturbed physics" versions of a single model. Perturbed-physics ensembles are unable to explore "structural" uncertainty, i.e. the uncertainty associated with the particular structure of a model. The PMIP multi-model ensemble can explore this type of uncertainty but the small number of models in the ensemble means that this analysis produces less robust statistics. By combining results from the PMIP multi-model ensemble with "perturbed physics" ensembles, the limitations of each ensemble can to some extent be overcome.

In the short-term, PMIP will develop an array of metrics that gauge the model performance in PMIP benchmark experiments against available palaeoclimate data. Although no claims will be made that these metrics are optimal for any particular purpose, they will provide a summary of some of the characteristics of individual models. In conjunction with information coming from "perturbed physics" ensemble analyses, the relationships between the performance metrics and model skill in simulating future climate change can be explored. In the longer-term, this should lead to the development of a palaeoclimate skill index that can be used to weight models and potentially reduce the uncertainty in model projections of future climate change. Given the need to assess the uncertainties in the palaeoenvironmental observations, close synergies with the observational community will be required to ensure success of work within this theme.

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Implementation plan

Implementation of the work outline above will require coordination, both within the PMIP community and between PMIP and other bodies. PMIP will organise regular open meetings open to both palaeoclimate modellers, scientists engaged in palaeoenvironmental data synthesis, and those using palaeoclimate simulations to study the impacts of climate changes on the Earth system. We will also use opportunities provided by externally-organised conferences and workshops, both to communicate PMIP science and to foster further collaboration. Finally, several other organisations are involved in activities that can enhance the work of PMIP. We will promote dialogues between PMIP and e.g. IGBP PAGES, IGBP AIMES, and the INQUA Palaeoclimate Commission (PALCOMM) in order to foster these synergies. Specifically, we envisage a number of jointly-sponsored workshops to promote relevant palaeo-science activities. Examples of possible specific actions in each of these areas are outline below.

Future PMIP Meetings

- *Autumn 2008, USA.* This workshop will focus on assessing the current state of PMIP analyses and on planning future work
- *Spring 2010, Japan.* This workshop will focus on the potential contribution of PMIP to AR5
- *Summer 2011, Bern, Switzerland.* This workshop will be linked to the INQUA Congress, and will thus provide an opportunity to focus on data syntheses and model evaluation.

PMIP involvement in externally-organised meetings.
We already anticipate that there will be a significant PMIP presence at workshops and conferences organized by our sponsoring bodies and by other synergistic organizations, including:

- April 2008: EGU
- May 2008: IGBP Congress. PMIP will participate in a session on model-intercomparison projects, to ensure that model benchmarking against past climate changes is included in the forward planning of all model-intercomparison projects.
- December 2008: AGU
- 2009 : PAGES open science conference
- 2010 : AIMES open science conference
- December 2010: AGU. We envisage organising a session to present the results of ongoing PMIP analyses.

Possible joint workshops

- Reconstruction of interannual to interdecadal variability and climate extremes from the palaeo-record (jointly with PALCOMM and PAGES/CLIVAR)
- Reconstruction of the physical, biological and biogeochemical state of the 3-D ocean through the palaeo-record (jointly with PALCOMM)
- Past climate forcing (jointly with PAGES/CLIVAR)
- Pliocene climates (jointly with NASA GISS and USGS PRISM)
- PC4MIP (jointly with PAGES and AIMES)

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