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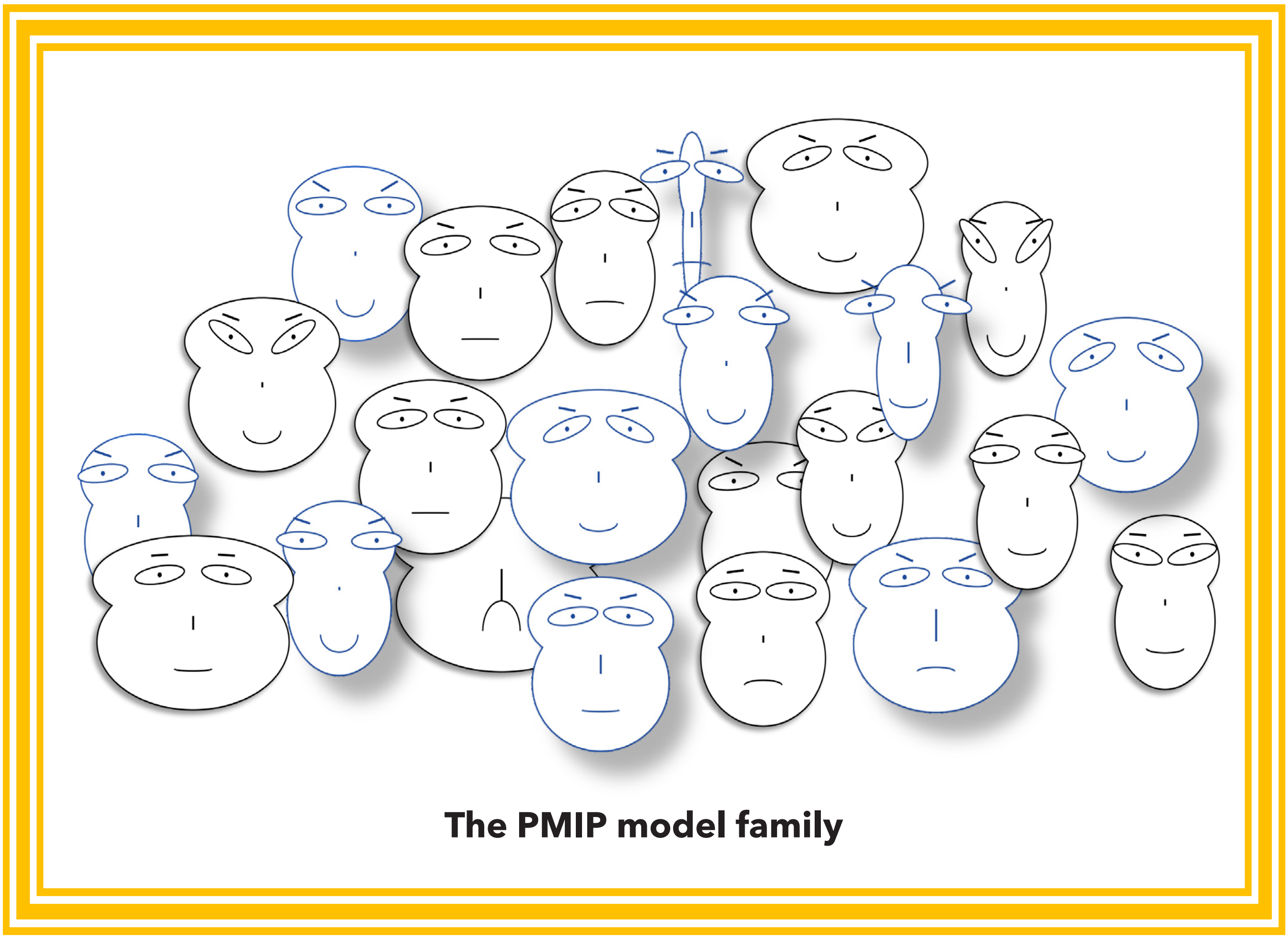
MAGAZINE



The PMIP model family

PALEOCLIMATE MODELLING INTERCOMPARISON PROJECT (PMIP): 30TH ANNIVERSARY

EDITORS

Paul J. Valdes, Pascale Braconnot, Katrin J. Meissner and Sarah Eggleston

PAGES

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Research. Innovation. Sustainability.

News

6th Open Science Meeting and 4th Young Scientists Meeting

Due to the continuing uncertainties related to the COVID-19 pandemic, the decision was made by the Local Organizing Committee, the PAGES SSC, and the PAGES EXCOM to hold the Open Science Meeting (OSM) and Young Scientists Meeting (YSM) online in 2022. The dates for the OSM are 16-20 May 2022 and the YSM will be taking place from 9-13 May 2022. The deadline for OSM abstract submissions and YSM applications is 31 January 2022. More information: pages-osm.org

PAGES IAI and African Mobility Fellowships

2021 saw the launch of two mobility fellowships for early-career scientists studying past global changes: The PAGES-IAI International Mobility Research Fellowship Program for Latin American and Caribbean early-career scientists and The PAGES Inter-Africa Mobility Research Fellowship Program for African early-career scientists. More details: pastglobalchanges.org/support#mobility

New PAGES website

In the summer of 2021 PAGES launched its new website. While we are thrilled with the fresh and updated look, we are experiencing issues which we are working tirelessly to iron out. We appreciate your patience and understanding in this teething phase. You are welcome to email us about any issues you spot: pages@pages.unibe.ch

Goodbye and welcome to SSC and EXCOM members

PAGES says thank you and bids farewell to five members who will be rotating off the SSC at the end of 2021: Asfawossen Asrat, Cristiano Chiessi, Michael Evans, Lindsey Gillson, and Katrin Meissner. In January 2022, we welcome Ilham Bouimetarhan, Martin Grosjean, and Fabrice Lambert to the SSC, and Paul Valdes and Boris Vannière will replace Michael Evans and Katrin Meissner on the EXCOM.

Apply to be on our SSC

PAGES is pleased to announce that the call for applications from scientists to serve on its Scientific Steering Committee for the term starting January 2023 is now open. The next deadline for applications is 4 April 2022. Details: pastglobalchanges.org/be-involved/ssc/apply

PAGES Early-Career Network

PAGES' ECN is pleased to welcome two new members to the steering committee: Georgy Falster (Postdoctoral Fellow, Australian National University, Australia) and Ignacio Jara (Postdoctoral Researcher, CEAZA Scientific Centre, Chile). They will join the steering committee in its primary tasks of visioning, coordination, communication, and organization for the ECN.

New working group

PAGES is pleased to announce the launch of the new PaleoEcoGen working group, which aims to improve our understanding of past critical ecological transitions based on a key and emerging proxy: ancient environmental DNA. The group is motivated to address the key question: what can we learn about the mechanisms leading to critical transitions and their subsequent evolutionary and ecological trajectories based on the comparison of biomes in paleorecords from terrestrial and aquatic biomes? Find out more and join its activities: pastglobalchanges.org/paleoecogen

New endorsed group

The Climate Change & History Research Initiative (CCHRI) was recently endorsed by PAGES. CCHRI is an international interdisciplinary project to bring together archaeologists, historians, and climate historians as well as paleoenvironmentalists to address past responses to environmental challenges. All details: pastglobalchanges.org/science/endorsed-wg/cchri

Deadline for new working groups and financial support

The next deadline to propose a new PAGES working group or apply for financial support for a workshop, meeting, or conference, as well as for Data Steward Scholarship applications will be on 31 March 2022. All details: pastglobalchanges.org/support

PAGES IPO staff update

PAGES' International Project Office recently bade farewell to Angela Wade, who navigated PAGES' communications and office management for six years. We thank Angela for her dedication over the years and welcome Chené van Rensburg and Leigh Martens Winiger, who have replaced Angela. In addition, we welcome Ursula Widmer as the new Finance and Office Manager, who has taken over from Monika Hofer, and Francesco Verde, who has replaced Shashika Sedara Hettige as IT Coordinator. All new contact details can be found on the PAGES website: pastglobalchanges.org/about/structure/international-project-office

Upcoming issue of *Past Global Changes Magazine*

The next magazine, guest edited by Lindsey Gillson, Peter Gell, Cathy Whitlock, Willy Tinner, and Sabine Prader, focuses on paleoecology and restoration ecology. Members of the DiverseK working group are additionally organizing a mini-section within the issue. Although preparations are well underway, if you would like to contribute, please contact our Science Officer: sarah.eggleston@pages.unibe.ch

Calendar

LandCover6k: New land-cover and land-use datasets for evaluation and improvement of anthropogenic land-cover change scenarios
2-4 December 2021 – Online

SISAL: Towards a global compilation of speleothem trace element records
28 Feb-4 Mar 2022 – Jerusalem, Israel

C-SIDE: Integrating sea-ice proxies, model simulations, and complementary records of glacial-interglacial climate change
May 2022 (exact dates TBC) – Bordeaux, France

VICS: Moving forward by looking back
2022 (exact dates TBC) – Aarhus, Denmark

Due to COVID-19 disruptions, dates and venues are subject to change. Please check the website regularly for updates from the organizers.

pastglobalchanges.org/calendar

Featured publications

Thresholds, tipping points, and multiple equilibria in the Earth system

Victor Brovkin, together with members of the PAGES integrative activity on Thresholds and the Future Earth global research project AIMES, showed that past abrupt climate changes provide evidence of cascading tipping points and early warning signals in the Earth system: pastglobalchanges.org/publications/128389

PALSEA

Blake Dyer et al. compared paleo sea-level observations from the Bahamian archipelago to results from several Earth deformation models to explore the sensitivity of polar ice sheets to high-latitude warming. Results indicate that previous estimates should be corrected downward: pastglobalchanges.org/publications/128491

C-PEAT

In collaboration with PAGES and Future Earth, C-PEAT leaders took part in the UN Framework Convention on Climate Change (COP26). They were present at the Peatland Pavilion, showing an interactive peatland map with >75 sites from 20 countries that have been studied by the C-PEAT community: pastglobalchanges.org/c-peat

CRIAS

The group's special issue in *Climate of the Past* "International methods and comparisons in climate reconstruction and impacts from archives of societies" currently includes seven papers focusing on different world regions, and two papers under review: pastglobalchanges.org/publications/special-issues/13159

Cover

Group "photo" representing the different models used to simulate the mid-Holocene climate following PMIP3 or PMIP4 protocols.
The different parts of the heads represent different climate indicators. These statistics are presented as Chernoff faces, which allows us to compare how the different models represent the change in temperature seasonality over the Eurasian continent and monsoon precipitation over India and Africa. Illustration by Jean-Yves Petershmitt and Pascale Braconnot.

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Paleoclimate Modelling Intercomparison Project

Paul J. Valdes[1], P. Braconnot[2] and K.J. Meissner[3]

Thirty years is a long time in science. New data leads to revisions of old theories, and new theories challenge interpretations. Thirty years is a particularly long time in climate research, with huge advances in our understanding and ability to predict climate change and its impacts. Throughout this time, the Paleoclimate Modelling Intercomparison Project (PMIP) has been at the forefront of testing the latest generation of climate and Earth system models against paleoclimate data, acting as an important conduit between the paleodata community and the climate modelers involved in future projections. It has also acted as an important motivator of paleodatabase development, which is so essential for rigorous model–data comparisons.

Thirty years ago, the paleo community was quite divided between the scientists developing and collecting data and the paleoclimate modelers. Researchers collected paleoenvironmental data and developed interpretations of this data in terms of past climate, but many were somewhat suspicious of climate modelers, who seemed to sit in front of their computers and never go out into the field. The modelers confidently discussed the changes in climate around the globe for particular time periods of the past, yet they could not calculate the uncertainty in their model results.

PMIP has changed all of this. By ensuring that modelers perform identical simulations, we can now quantify (some aspects) of the uncertainty intrinsic to climate models; by performing simulations with different boundary conditions, such as using alternative ice-sheet reconstructions, we can quantify uncertainties arising from a single source of interest. In the early days of PMIP, the climate models were often slightly older than the state of the art, but in recent years, PMIP modelers have been using the same models as those being used to support the IPCC assessments, ensuring that the lessons learned can directly inform future projections.

Similarly, PMIP has also helped bridge the divide between modelers and paleodata scientists. It is now common for both modelers and data collectors to work together to analyze model output and compare data, and it is increasingly common for members of the paleodata community to spend time in modeling labs and perform model simulations. Some modelers even spend time in the field! Such collaborations drive innovation, and some of the most exciting recent developments are in cross-over areas such as data assimilation.

This issue of *Past Global Changes Magazine* contains a range of contributions highlighting the amazing achievements of PMIP and the exciting new developments for the future. We hope you enjoy the read and the time spent with the growing PMIP model family.

Some of us have been lucky to have seen the full evolution of PMIP, attending the very first meeting in Paris involving about 40 researchers, to the latest workshop with more than 120 researchers of all nationalities and ages. The workshops have always been stunning in terms of the excitement in the science, and the enjoyable and lively discussions (and also the fun dancing and singing and dining which have become a tradition at these workshops). Future challenges and opportunities continue, with exciting developments including the use of Earth system models and the integration of transient simulations all ensuring that PMIP will continue to have a long and exciting future.

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Figure 1: Participants at the PMIP workshop in Collonges-la-Rouge, France. Many are still involved in the PMIP community, though some are looking a lot older! Front row: Pat Bartlein, Robin Webb (?), John Kutzbach, Dave Pollard, Bob Oglesby. Second row: Pascale Braconnot, Karl Taylor, Sandy Harrison, Gerhard Krinner, Klaus Herterich, Sylvie Joussaume, Norman MacFarlane, Jozef Sytkus. Third row: (?), Ayako Abe-Ouchi, Bette Otto-Bliesner, Lisa Sloan, Natalie de Noblet, Michael Lautenschlager (?), Marie-France Loutre, Masa Kageyama, Valerie Masson, Gilles Ramstein, Akio Kitoh, Tony Broccoli. Back row: Buwen Dong, Jai-Oh Oh (?), John Mitchell, Paul Valdes, Michael Schlesinger, Chris Hewitt, David Rind, Christophe Genthon (?), Alex Kislov, Dominique Jolly (?), Joel Guiot, Mikhail Verbitsky.
Corrections and additions sent to pages@pages.unibe.ch are very welcome!

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PMIP: Looking back to its first phase

Sylvie Joussaume[1] and Karl E. Taylor[2]

The Paleoclimate Modelling Intercomparison Project celebrates its 30th anniversary in 2021. The first phase initiated systematic model-model and model–data comparisons for the Last Glacial Maximum and Mid-Holocene. Here, we describe the historical context of PMIP, the experiment design, and the project's early impacts.

PMIP Launch

The Paleoclimate Modelling Intercomparison Project (PMIP) was launched 30 years ago at an international North Atlantic Treaty Organization (NATO; nato.int) workshop in Saclay, France, in 1991. Its main objectives were to investigate the mechanisms of climate change and to evaluate model capabilities in simulating past climates. At this workshop, the first PMIP experiments were conceived, which focused on two very different climatic periods: the Last Glacial Maximum (LGM; 21,000 years before present (BP)) with extremely cold conditions and the mid-Holocene (6,000 years BP) with an orbitally-forced change in seasonal cycle.

PMIP built on ground-breaking paleoclimate experiments performed with earlier models and capitalized on well-documented data syntheses for these periods, notably the extensive work of the Cooperative Holocene Mapping Project (COHMAP) group led by John Kutzbach. In the initial phase of the project, the main features of the selected paleoclimates were investigated by offering an experimental protocol where all models would be run with the same prescribed boundary conditions. From the start, PMIP was endorsed by both the International Geosphere Biosphere Program through PAGES and the World Climate Research Programme (WCRP; wcrp-climate.org), first through the Working Group on Numerical Experimentation and later by the Working Group on Coupled Modelling as part of Climate and Ocean – Variability, Predictability, and Change (CLIVAR; clivar.org).

During its first phase (1991–2001), PMIP focused only on atmospheric general circulation models (AGCMs), which at that time were the standard climate models. The final design of the PMIP experiments was only arrived at following intense discussions that began with the initial 1991 NATO workshop with a focus on the experimental design for the LGM. A major point of contention was whether to constrain the PMIP simulations of the LGM by prescribing sea surface temperatures (SSTs) as reconstructed by the Climate: Long range Investigation, Mapping, and Prediction (CLIMAP) project in 1981, with the prospect that the resulting climate would be more realistic, or to use AGCMs coupled to slab oceans, allowing for some surface ocean interactions, but with ocean horizontal heat transport fixed as present-day and, therefore, inconsistent with paleoclimate data. Each of these approaches had its proponents and its merits, and in the end, both were endorsed as options for the LGM.

For the mid-Holocene experiment, the choice of surface boundary conditions was easier since SSTs are nearer to present-day conditions. In this case, to help isolate the impact of orbital changes, the SSTs were simply prescribed to be the same as in the Atmospheric Modelling Intercomparison Project (AMIP) experiments. In the few years following the first workshop, consensus was reached concerning the LGM ice-sheet boundary conditions; the Peltier ice-sheet reconstruction was adopted in 1992 following discussions at a workshop at Lamont–Doherty Earth Observatory, USA, organized by Bill Ruddiman. Considerable work was required to iron out details concerning definition of the insolation forcing for the mid-Holocene and the proper way to compare seasonal cycles from past and present climates when statistics are based on civil calendar months, but climate responds to astronomically-determined seasons.

From the beginning, PMIP modelers and the paleoclimate data community forged a strong working relationship, as this had been key to the success of COHMAP. Thus, one of PMIP's many objectives was to encourage data syntheses for the two paleoclimate periods that would enable model–data comparisons. A model–data sub-committee organized this work, led by Sandy Harrison, Joël Guiot and Pat Bartlein. At a workshop in Aussois, France, in 1993, participants discussed both inverse and forward approaches for evaluating models using paleoclimate observations. These discussions highlighted the importance of fostering close interactions between the two communities.

By 1994, all experimental conditions were fixed and described in a foundational paper by Joussaume and Taylor (1995). This first phase of PMIP attracted the participation of 18 modeling groups, from Europe, the USA, Canada, Australia, Russia, Korea, and Japan. Following the lead of its slightly older sibling AMIP, PMIP relied on infrastructure support from the Program for Climate Model Diagnosis & Intercomparison (PCMDI; pcmdi.llnl.gov) and its director, Larry Gates. In PMIP's first phase, data were collected and stored at PCMDI in a restricted-access database, as was the practice for AMIP as well. Several papers were published (see

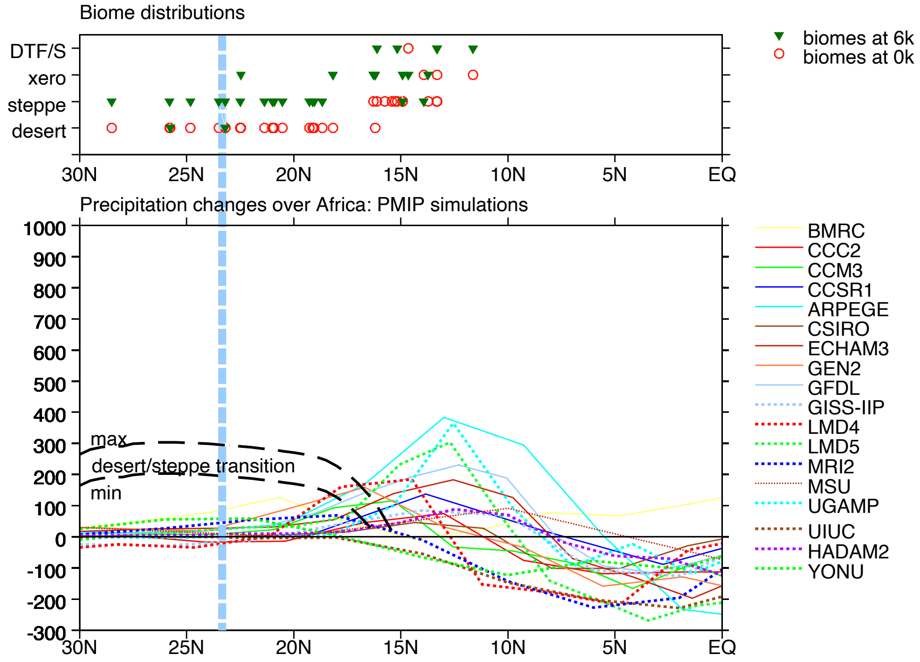

Figure 1: PMIP1 simulations of annual mean precipitation changes (6 kyr BP minus present; mm/year) in the African monsoon region (20°W–30°E). **(A)** Biome distribution (desert, steppe, xerophytic and dry tropical forest/savannah; DTF/S) as a function of latitude for 6 kyr BP (green triangles) and present-day (red circles). The limit of desert-steppe at 6 kyr BP around 23°N (blue vertical dashed line) provides a range of precipitation excess above model results shown in (B). **(B)** Model results with hatched lines showing estimated upper and lower bounds excess precipitation needed to support grasslands based on present climatic limits. Figure reproduced from McAvaney et al. (2001); redrawn from Joussaume et al. (1999).

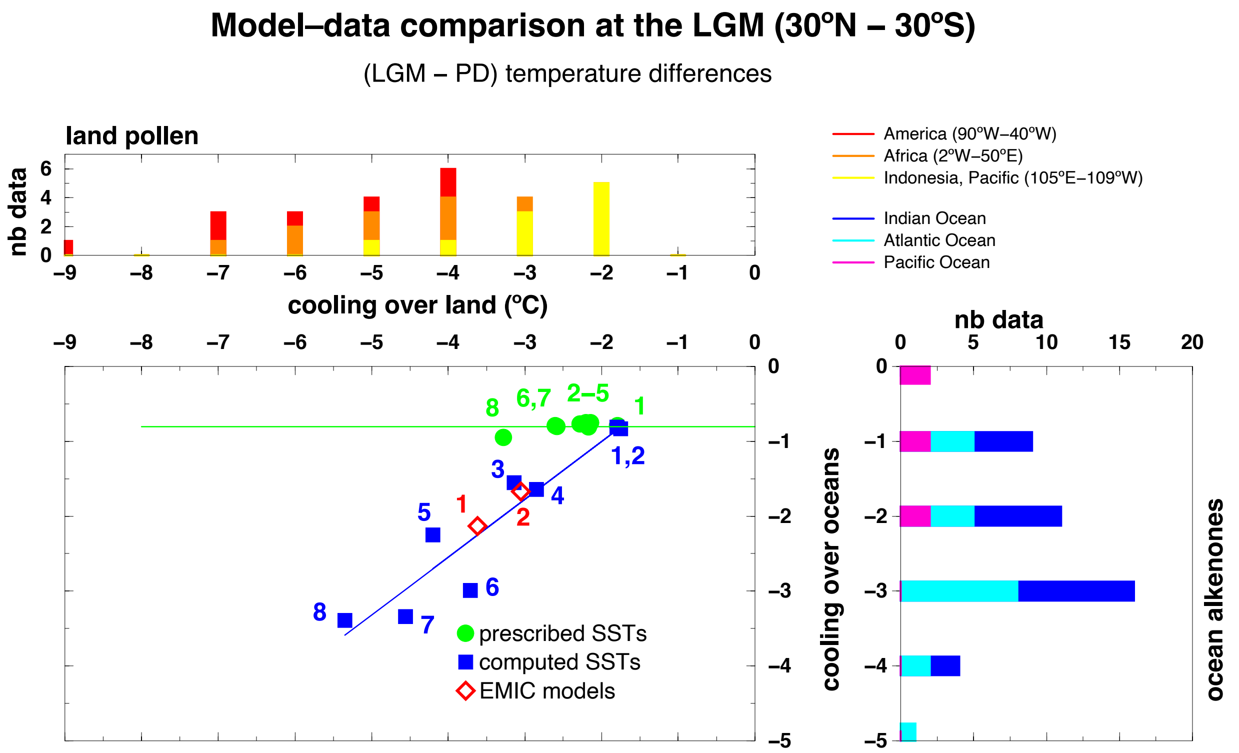

Figure 2: Annual mean simulated tropical cooling over ocean and land from PMIP1 LGM simulations, compared to estimates of terrestrial cooling from pollen (Farrera et al. 1999) and from ocean SSTs estimated from alkenones (Rosell-Melé et al. 1998). Figure reproduced from McAvaney et al. (2001; adapted from Pinot et al. 1999).

pmip1.lsce.ipsl.fr), and the major findings were emphasized in the third IPCC Assessment Report (McAvaney et al. 2001). Two key PMIP figures are reproduced here in Figures 1 and 2.

PMIP results became the focus of several community workshops that included both paleoclimate modelers and specialists in paleoclimate data. At the first workshop in 1995 in Collonges-la-Rouge, France, initial analyses were shared. Then in 1997 at San Damiano, USA, subprojects were organized and papers planned. Subsequently, in 1999 at La Huardière, Canada, a synthesis of the results was prepared and then published in a WCRP special report (Braconnot 2000). These workshops have been essential to PMIP's success. They were instrumental in developing the close working relationship between modelers and data specialists that led to a better appreciation of the limitations of both models and observations and to development of improved understanding of the climate system. The PMIP workshops have all been intensive, interactive, and lively; and we will not forget the "PMIP song" introduced in the Collonges-la-Rouge workshop (pmip1.lsce.ipsl.fr/goodies/song.html), and revised in San Damiano; and the dancing and revelry in La Huardière!

Main highlights from the first PMIP phase

In what became known as the "Big Picture Paper", Joussaume et al. (1999) showed that as a result of increased summer insolation, all the models simulated an increase in the summer monsoon precipitation over Africa and Asia during the mid-Holocene (Fig. 1). A quantitative comparison over Africa using results from BIOME 6000 (Jolly et al. 1998) showed that all the models underestimated the northward displacement of the desert-steppe transition, which was also confirmed by vegetation simulations using PMIP outputs (Harrison et al. 1998). This is a modeling problem that continues to challenge state-of-the-art models.

The model–data comparisons over Europe led to the establishment of new bioclimatic variables such as temperature of the coldest month and growing degree-days, rather than the commonly-used January and July temperature estimates (Cheddadi et al. 1996). These more robust variables enhance confidence in model–data comparisons (Masson et al. 1999).

For the LGM, models simulated a global cooling of about 4°C when forced with CLIMAP SST reconstructions, whereas AGCMs coupled to slab oceans produced a global cooling between 2° and 6°C. Following the issue raised by Rind and Peteet (1985) about the underestimation of the simulated terrestrial tropical cooling at LGM, a detailed model–data comparison study was conducted for the tropics that relied on a new data synthesis effort fostered by PMIP (Farrera et al. 1999). In the tropics, models forced by the relatively warm CLIMAP SSTs confirmed an underestimated terrestrial cooling, whereas models that computed SSTs obtained estimates in better agreement with the observed tropical cooling (Fig. 2), compensating for their relatively weak cooling over land with excessive ocean cooling (Pinot et al. 1999). In addition, an extensive comparison over Europe (Kageyama et al. 2001) concluded that according to pollen data (Peyron et al. 1998), models tended to underestimate winter cooling, at least over western Europe.

Looking forward

When launching PMIP in 1991, we did not expect the project would still be relevant, let alone vibrant, 30 years later. During this time, younger scientists have brought new energy and ideas to the project, and have re-invigorated the quest to understand paleoclimates. We believe that PMIP will continue to attract a community of researchers who enjoy working together and who will seize opportunities to expand our knowledge of our climate system by looking at the past.

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PMIP key dates and achievements over the last 30 years

Pascale Braconnot[1], M. Kageyama[1], S.P. Harrison[2], B.L. Otto-Bliesner[3], A. Abe-Ouchi[4], M. Willé[1], J.-Y. Peterschmitt[1] and N. Caud[1]

Over the last 30 years, PMIP has made significant progress in the development of Earth system models, climate reconstructions, and model–data comparisons. It has contributed greatly to our understanding of climate sensitivity, ocean circulation and abrupt events, the hydrological cycle, the linkages between climate and ecosystems, and climate variability.

From infancy to a mature project

During the last 30 years, the Paleoclimate Modelling Intercomparison Project (PMIP) has fostered synchronized model simulations, climate reconstructions, and model-model and model–data comparisons for key climate periods in the past (Fig. 1). The major objectives of the project developed for the first phase of PMIP are still valid today (see Joussaume and Taylor, this issue): to understand the mechanisms of climate change, test models in a climate context different from modern, and define evaluation criteria that are relevant to assess the credibility of future climate projections. However, the project has refined these objectives in four successive phases (Fig. 1 and 2).

The PMIP niche is to produce paleoclimate simulations with the same general circulation models (GCMs) used for future climate projections. During PMIP's lifetime, these models have evolved from atmosphere-only to Earth system models (Fig. 1), initially through the inclusion of either ocean or vegetation couplings with the atmosphere. The choice of the complexity of the model used, such as the inclusion of the carbon cycle or interactive aerosols, still varies across modeling groups. However, currently, the main focus is on full integration of the different components of the system. PMIP has provided a way both to test different climate feedbacks related to land surface, ocean, or ice sheets, and to improve understanding of the relationship between climate and variations in terrestrial and marine biogeochemistry. Because of its unique focus, PMIP has been endorsed from the beginning by PAGES and the World Climate Research Programme (WCRP) through its core project Climate Variability (CLIVAR) and subsequently the Working Group on Coupled Models (WGCM). These endorsements have allowed PMIP to maintain strong connections to the modeling and climate reconstruction communities throughout the last 30 years.

PMIP encourages growth in its activities while maintaining a focus on a limited number of key questions. It plays a key role by providing results in the open database for global climate simulations supported by WCRP (Peterschmitt et al. 2018). These results have been used for studies well beyond those originally envisaged by people outside the main PMIP community, including for impact studies, or to assess changes in biodiversity or ecological niches.

Evolution of the context and scientific questions

PMIP1 highlighted robust model responses to external forcings for the mid-Holocene and the Last Glacial Maximum (LGM) and discussed model uncertainties. The number of independent climate indicators from different natural archives has increased with time, allowing for tests of the modeled response to the forcings of the land, ocean, and ice sheets (see Bartlein et al. and Jonkers et al. this issue). The role of carbon cycle and other feedbacks has been considered since PMIP2. PMIP3 introduced a focus on analyses of interannual-to-centennial climate variability (Braconnot et al. 2012). New methodologies for model–data comparison have been continuously developed, from simple visual comparisons, to application of specific metrics, and finally to the use of forward modeling of the various climate indicators such as water or carbon isotopes. The importance of model–data comparison meant that there had to be a balance between the use of a strict experiment protocol to be able to understand model differences and more flexible protocols allowing different groups to sample uncertainties in boundary conditions.

New periods and questions have been included progressively in PMIP to address a broader range of external forcings and climate issues. These choices were discussed and made at the regular PMIP meetings every 2–3 years (Fig. 1). A challenge has been to foster collaboration around key periods, with standardized simulations and associated databases, while also acting as a network to share new results and sensitivity experiments that improve our understanding of major climate feedbacks. The early Holocene and last glacial inception were included in PMIP2 to address questions about water cycle feedback from the ocean and vegetation, and the role of snow and ice sheets (PMIP 2000). Multi-model results were developed for the last interglacial in PMIP3. However, a common protocol for the last interglacial was only proposed in PMIP4 (Otto-Bliesner et al. 2017). Pre-Quaternary climates have also been included since PMIP3 because of their ability to provide constraints on climate sensitivity (Haywood

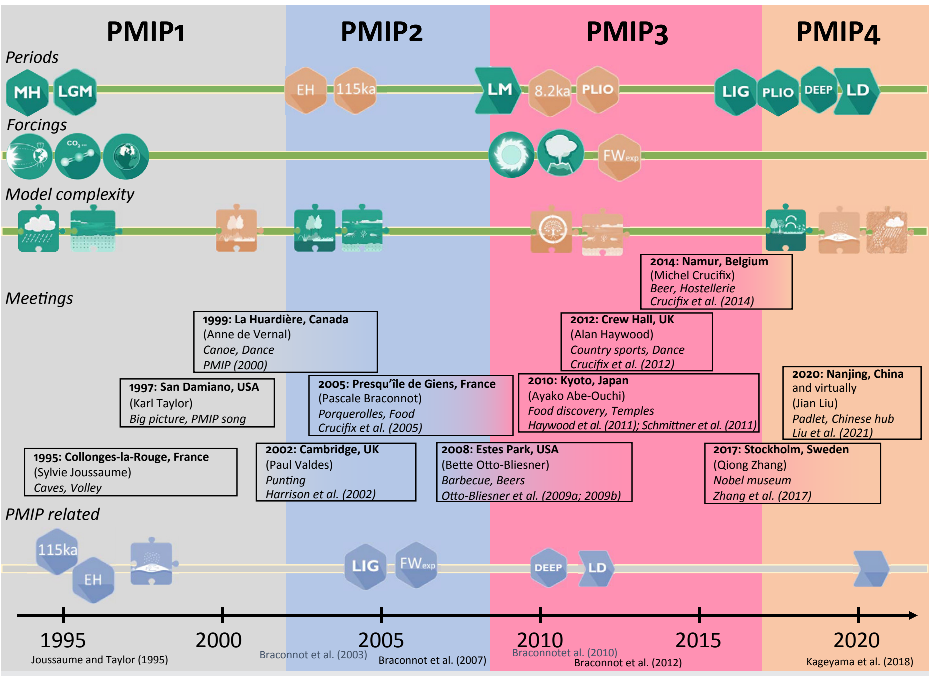

Figure 1: PMIP phases highlighting major meetings (date, location, host, activities, and meeting report), together with the key periods, external forcings, and model complexity represented with small infographics either as core PMIP activities (green), small groups (orange), or as part of the wider network (blue). MH = Mid-Holocene, LGM = Last Glacial Maximum, EH = Early Holocene, LM = Last Millennium, PLIO = Pliocene, DEEP = deep time, LIG = Last Interglacial, and LD = Last Deglaciation. When a number is included (e.g. "115ka"), it refers to the exact period as discussed during PMIP meetings.

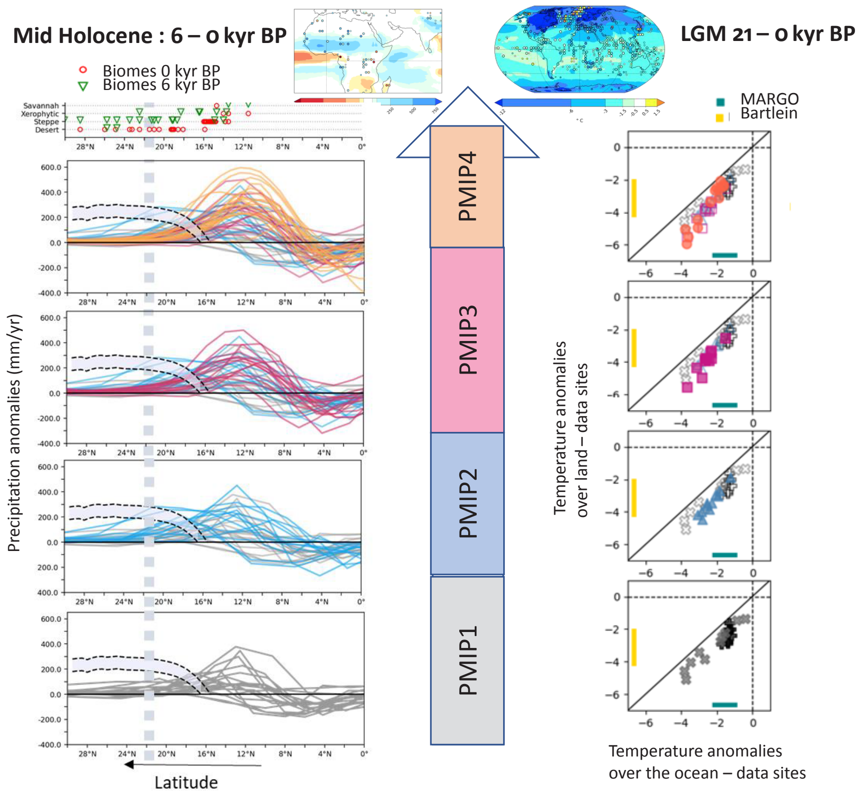

Figure 2: Iconic PMIP graphics to show how well models represent the increase and northward extent of the mid-Holocene West African monsoon and the Last Glacial Maximum land–sea contrast through the different phases of PMIP. **(Top)** Summary of the data constraints. Temperature anomalies compiled from MARGO Project Members (2009) and Bartlein et al. (2011); biome reconstruction from Joussaume et al. (1999).

et al. 2010). The Last Millennium in PMIP is associated with the PAGES 2k Network and the need to improve pre-industrial reference climates (Schmidt et al. 2011). Several fresh water flux experiments have also been regularly discussed, either for the Holocene 8.2 kyr event (see Gregoire and Morrill, this issue) or complementary experiments around the LGM. Recently the deglaciation has become one of the major flagships for PMIP simulations (Ivanovic et al. 2016).

The current organization into eight working groups (pmip.lsce.ipsl.fr/working_groups) favors exchanges on the different climatic periods, transverse analyses for model–data comparisons, and cross-period analyses. Five PMIP experiments have been included in CMIP6 (Fig. 1). More details of the PMIP journey are available online: www.tiki-toki.com/timeline/entry/1566548/HISTORY-OF-PMIP

What do PMIP iconic figures tell us about advances in modeling?

The two PMIP iconic figures presented in Joussaume and Taylor (this issue) are reproduced here to provide an overview of how simulated changes in mid-Holocene precipitation or in LGM land–sea contrast has been represented with increasing model complexity and resolution throughout the four phases of PMIP (Fig. 2). Figure 2 illustrates the 30-year quest to simulate sufficient precipitation in the Sahel-Sahara to support the reconstructed mid-Holocene vegetation cover, which has led to improved understanding of the role of global and regional feedbacks (soil, vegetation, albedo, etc.; Brierley et al. 2020). There has been a shift between PMIP phases such that models now produce more consistent representations of increased precipitation between 6°N and 16°N, but continue to struggle to reproduce the large observed changes from 16°N to 30°N.

For the LGM, PMIP results have consolidated the understanding of the ratio between temperature over land and over the ocean, which is relevant for discussions about future climate (Stocker et al. 2013). Independent reconstructions over land and ocean support this ratio, and can be used to define which of the results better fits with past conditions. The current generation of climate models and new proxy reconstructions produce a large range of results, however, suggesting that the debate on the LGM land–sea ratio has not yet been resolved (Kageyama et al. 2021).

Paleoclimate modeling and systematic benchmarking within PMIP have demonstrated that feedbacks from ocean and vegetation are needed to reproduce climate changes at global or regional scales. PMIP has also demonstrated that models that produce good simulations of present-day climate do not necessarily have good skill in simulating past changes. This raises questions about how to pre-select models only looking at modern conditions when considering future climate projections, for example for impact studies. The current phase of PMIP should provide a wider range of past constraints from the combination of the different climate periods to isolate missing mechanisms or the impact of model biases on the seasonal, annual, or interannual-to-centennial scale characteristics of climate changes.

In conclusion

During the last 30 years PMIP has provided a scientific basis to define the level of model complexity needed to understand climate change processes and interactions between the different timescales fully. This is one of the reasons why PMIP results serve as reference in IPCC assessment reports (Kageyama et al. this issue, p. 68). Little by little, paleoclimate simulations are no longer being considered just to check confidence in the models, but also as a necessary step for identifying model deficiencies and contributing to the improvement of the physical and biogeochemical content of the models. Paleoclimate simulations represent an essential element in understanding climatic events with a high impact on ecosystems or societies.

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The contributions of PMIP to the IPCC assessment reports

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PMIP contributed to the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports (ARs) by placing current climate change into a wider context, evaluating climate model performance in very different climatic states, and constraining climate sensitivity based on paleoclimates.

Before PMIP

Back in 1990 when the First Assessment Report (FAR) of the Intergovernmental Panel for Climate Change (IPCC; Houghton et al. 1990) was published, PMIP did not exist. However, in its fourth chapter, entitled "Validation of climate models", the report drew on the pioneering results from CLIMAP Project Members (1981), who produced the first set of boundary conditions for LGM experiments, and COHMAP Members (1988), who produced paleodata syntheses and model simulations for key periods between the LGM and present. It stated that "studies of paleoclimate changes are an important element in climate model validation for two reasons: (1) they improve our physical understanding of the causes and mechanisms of large climatic changes so that we can improve the representation of the appropriate processes in the models, and (2) they provide unique data sets for model validation."

This view has guided the contribution of PMIP results to subsequent assessment reports. The creation of PMIP was announced in the Second Assessment Report (Houghton et al. 1996) in Chapter 5 ("Climate models – evaluation"): "The earlier ice age SST (sea surface temperature) data sets […] are now being revised for use in the newly organized Paleoclimate Modelling Intercomparison Project (PMIP) which is focusing on simulations for the Last Glacial Maximum and for 6000 years BP using atmospheric models with both fixed SST and mixed-layer oceans".

PMIP in the Third Assessment Report: mid-Holocene and Last Glacial Maximum

PMIP studies on both topics outlined in the FAR, model evaluation and process understanding, have been included in every subsequent assessment report of the IPCC. In the Third Assessment Report (TAR; Houghton et al. 2001), PMIP results can be found in Chapter 8 ("Model evaluation"). The iconic figure for the mid-Holocene African monsoon (Joussaume and Taylor, this issue; Fig. 1, adapted from Joussaume et al. 1999) shows that models agree with precipitation reconstructions in simulating an increased monsoon, but that they underestimate the reconstructed northward displacement of the monsoon area. The text states that this is also the case for the northward displacement of the Arctic tree line, and highlights the inconsistency between the simulated drier Eurasia and reconstructed wetter climate there.

Also in the TAR, PMIP results for the Last Glacial Maximum (LGM) are in terms of the potential link between the global mean cooling and climate sensitivity, and an estimate of the LGM radiative forcing is given. The text then evaluates model results in comparison to new reconstructions for the tropics (Joussaume and Taylor, this issue, Fig. 2) and the extratropics. The cooling over the tropics was a highly debated topic, in particular because the cooling over land was found to be much larger than over the oceans. This characteristic could only partly be explained by the "land–sea contrast" later found in observations of current climate change and projections for the future.

At the time of the third assessment, the main conclusion was that the CLIMAP reconstructions were probably too warm over the tropics. Results from slab-ocean models were in better agreement with reconstructions, despite the fact they used present-day meridional heat transport. The TAR also points to a good agreement between models and data over Europe, except for winter for which the models underestimate the reconstructed cooling. All these themes would be addressed in subsequent reports.

PMIP in the Fourth Assessment Report: addition of the Last Interglacial

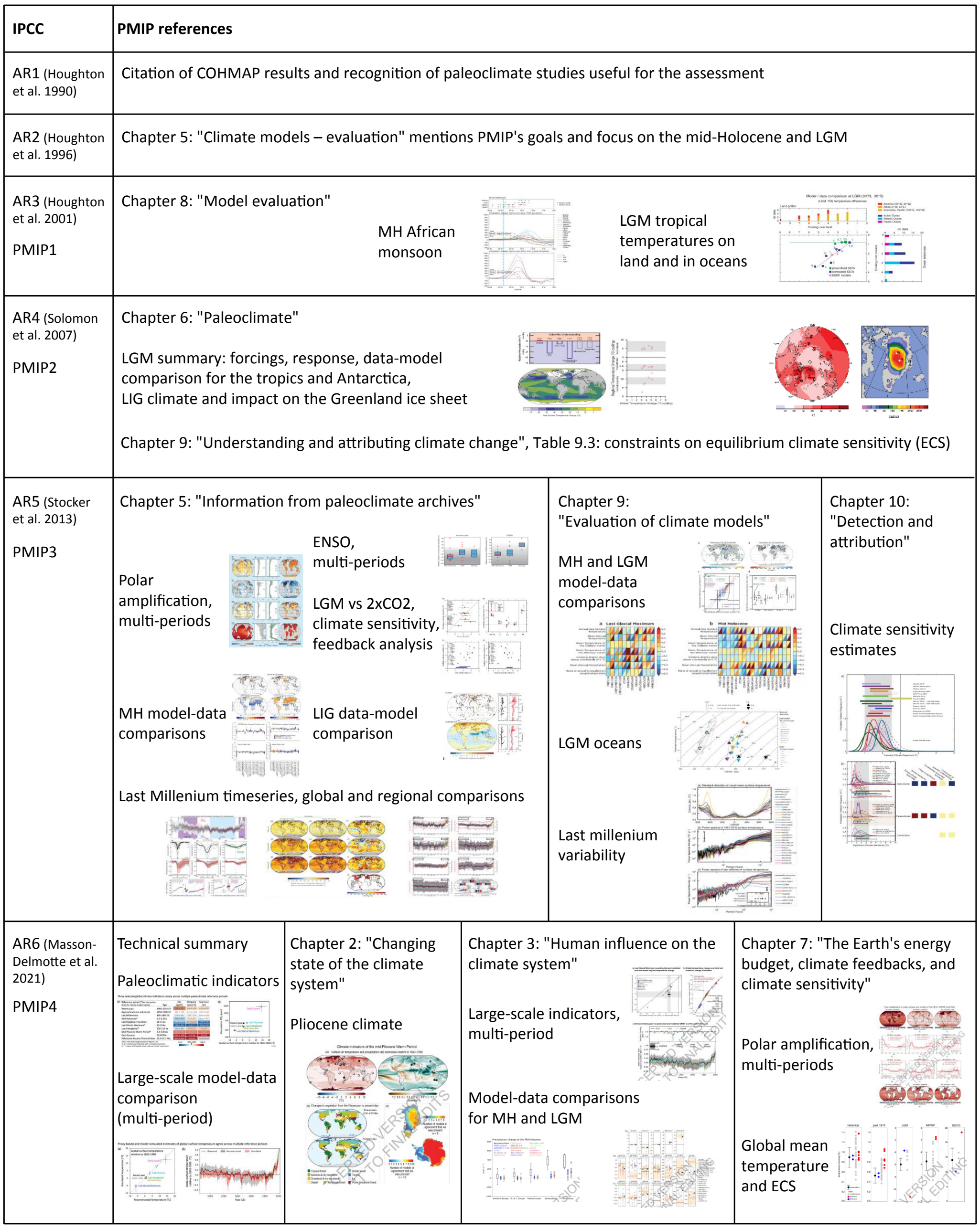
In the Fourth Assessment report (AR4; Solomon et al. 2007), PMIP disappears from the evaluation chapter (apart from a citation on modeling abrupt climate change) and appears in Chapter 6, a new chapter entirely dedicated to paleoclimate, and in Chapter 9, on "Understanding and Attributing Climate Change". Figure 6.5 shows components of the radiative forcing for the LGM, together with the simulated cooling in terms of sea surface temperatures and the relationships between global and regional temperature changes from the LGM to pre-industrial. This figure thereby highlights processes leading to the temperature change, and simultaneously provides an evaluation of the results. The conclusion is that AOGCMs "are able to simulate the broad-scale spatial patterns of regional climate change recorded by paleodata in response to the radiative forcing and continental ice sheets of the LGM, and thus indicate that they adequately represent the primary feedbacks that determine the climate sensitivity of this past climate state to these changes."

The AR4 also introduces AOGCM simulations of the Last Interglacial and, for the first time, some simulations of the last millennium from AOGCMs and Earth system models of intermediate complexity, which announces subsequent coordinated work within PMIP. The AR4 quantifies the estimated global LGM cooling of 4–7°C, which makes this period very relevant to the warming projected for 2100. PMIP results are also highlighted in Chapter 9 in relation to future climate, and contribute to the estimated ranges of equilibrium climate sensitivity in Table 9.3.

PMIP in the Fifth Assessment Report: multi-period analyses

The Fifth Assessment Report (AR5; Stocker et al. 2013) contains the largest number of figures showing PMIP results; these appear in chapters 5 ("Information from paleoclimate archives"), 9 ("Evaluation of climate models"), and 10 ("Detection and attribution of climate change"). The results are based on the PMIP3 mid-Holocene, LGM, and last millennium simulations, and the chosen figures show updated process understanding for the LGM and data–model comparisons for the mid-Holocene and the Last Interglacial. For the last millennium, AR5 highlights the large increase in the number of available AOGCM simulations relative to AR4. Furthermore, the consistency of these simulations with reconstructions and external forcing changes is evaluated, showing our understanding of the processes involved in the unprecedented present warming at hemispheric and continental scales.

A novelty in AR5 is that results (specifically regarding polar amplification) are shown from multiple past periods (including for the mid-Pliocene Warm Period and the Eocene Climate Optimum), together with an idealized future scenario (2xCO2) in the same figure. Another new topic is the analysis of changes of ENSO variability for different periods. Several lines of evidence, including paleoclimate reconstructions and simulations are also combined to assess Equilibrium Climate Sensitivity in a comprehensive section on this topic in Chapter 10. Model evaluation (Chapter 9) focuses on the last millennium variability, large-scale and regional features of the LGM and mid-Holocene surface climate, as well as LGM large-scale deep ocean gradients in temperature and salinity. Model performance is also quantified in terms of metrics, similar to the approach used for evaluating present climate in comparison to observations. However, in the case of PMIP, the metrics are based on bioclimatic variables.



IPCC	PMIP references
AR1 (Houghton et al. 1990)	Citation of COHMAP results and recognition of paleoclimate studies useful for the assessment
AR2 (Houghton et al. 1996)	Chapter 5: "Climate models – evaluation" mentions PMIP's goals and focus on the mid-Holocene and LGM
AR3 (Houghton et al. 2001) PMIP1	Chapter 8: "Model evaluation" MH African monsoon LGM tropical temperatures on land and in oceans
AR4 (Solomon et al. 2007) PMIP2	Chapter 6: "Paleoclimate" LGM summary: forcings, response, data-model comparison for the tropics and Antarctica, LIG climate and impact on the Greenland ice sheet Chapter 9: "Understanding and attributing climate change", Table 9.3: constraints on equilibrium climate sensitivity (ECS)
AR5 (Stocker et al. 2013) PMIP3	Chapter 5: "Information from paleoclimate archives" ENSO, multi-periods Polar amplification, multi-periods LGM vs 2xCO2, climate sensitivity, feedback analysis MH model-data comparisons LIG data-model comparison Last Millenium timeseries, global and regional comparisons Chapter 9: "Evaluation of climate models" MH and LGM model-data comparisons LGM oceans Last millenium variability Chapter 10: "Detection and attribution" Climate sensitivity estimates
AR6 (Masson-Delmotte et al. 2021) PMIP4	Technical summary Paleoclimatic indicators Large-scale model-data comparison (multi-period) Chapter 2: "Changing state of the climate system" Pliocene climate Chapter 3: "Human influence on the climate system" Large-scale indicators, multi-period Model-data comparisons for MH and LGM Chapter 7: "The Earth's energy budget, climate feedbacks, and climate sensitivity" Polar amplification, multi-periods Global mean temperature and ECS

Figure 1: Summary of paleoclimate modeling mentions in the IPCC first and second assessment reports, and of the figures showing PMIP results in subsequent assessment reports.

The Sixth Assessment report: PMIP distributed throughout the report

Simpler diagnostics have been chosen for the Sixth Assessment Report, in which most chapters are devoted to process understanding and provide a holistic assessment of broad topics, including paleoclimatic information. PMIP results, and results from paleoclimate studies more generally, are distributed throughout the report–with figures found in chapters 2 ("Changing state of the climate system"), 3 ("Human influence on the climate system"), 7 ("The Earth's energy budget, climate feedbacks, and climate sensitivity"), and 8 ("Water cycle changes"). One remarkable result is that within the combination of constraints on equilibrium climate sensitivity, paleoclimatic reconstructions, supported by modeling work associated with PMIP, were key to reducing the likely range of equilibrium climate sensitivity from the AR5 range of 1.5–4.5°C to 2.5–4.0°C. We are optimistic that this presentation may improve the public's awareness of PMIP results, and their potential for use by policymakers and other stakeholders.

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Paleoclimatic data syntheses from the terrestrial realm: History and prospects

Patrick J. Bartlein[1] and Thompson Webb III[2]

Syntheses of terrestrial paleoclimatic data have a long history, but in the 1980s they rapidly developed into the database-in-a-repository form we know today. Over time they have anchored the productive interaction with climate-model simulations aimed at both testing the models and explaining patterns in the data.

One of the basic tasks of PMIP (and its predecessor studies) is the comparison of climate-model simulations with paleoenvironmental observations. This is motivated by the dual objectives of using the observations to "benchmark" or test the models, and using the physically based models to provide mechanistic explanations for the observed patterns in the data (Braconnot et al. 2012; Harrison et al. 2015). These objectives have in turn motivated the synthesis of paleoenvironmental data from both terrestrial and marine sources and their interpretation. Here we review some of the past terrestrial syntheses, and their evolution over time.

Early syntheses

Before the mid-1970s, syntheses of terrestrial paleoenvironmental data were available in book form, as textbooks (e.g. Brooks 1949; Zeuner 1959; Frenzel 1967; and R.F. Flint's evolving sequence: 1947, 1957, and 1971), edited volumes (e.g. Nairn 1961; Wright and Frey 1965), and H.H. Lamb's (1971, 1977) two-volume treatise. Although not databases in any sense, such publications were the places to go for broad descriptions of past climates and the observations they were based on.

Also of note from this era was a U.S. National Academy of Sciences report, *Understanding Climatic Change*, prepared by the U.S. Committee for the Global Atmospheric Research Program (USCGARP 1975). This study included *Appendix A*, a survey of past climates by Imbrie, Broecker, Mitchell, and Kutzbach, that included some temporal and spatial syntheses of climatic variations. Many of the themes and proposals for climate-research action discussed there (such as the joint elaboration of paleoclimatic databases and development of simulation models of both present and past climates) would seem familiar today.

CLIMAP era

CLIMAP (Climate: Long range Investigation, Mapping, and Prediction) was a collaborative project aimed at reconstructing conditions at the Last Glacial Maximum, in particular the distribution of ice sheets, seasonal sea-surface temperatures, and land-surface albedo. The main results of the reconstructions appeared in *Science* (CLIMAP Project Members 1976), and more fully in an edited volume (Cline and Hays 1976), and a set of maps (CLIMAP Project Members 1981). In a companion paper, Gates (1976) described the results of a GCM simulation with surface boundary conditions provided by the CLIMAP reconstructions. Although not the first attempt at paleo simulation, the paper did feature what might be regarded as a canonical mode of data-model comparison—dots on a map.

Running through the CLIMAP-era discussions was the notion that if the goal was comparison of paleo-observations and climate-model simulations, then more paleo-data were surely needed. This began to be realized late in the 1970s. For example, Bernabo and Webb (1977) described mapped summaries of Holocene pollen data from northeastern North America, and similar work was underway for Europe (Huntley and Birks 1983). A special issue of *Quaternary Research* (Hecht et al. 1979) contained the first really comprehensive syntheses of terrestrial paleoclimatic data on a global scale (Peterson et al. 1979; Street and Grove 1979).

Peterson et al. (1979) brought together data for the LGM, and introduced the notion of "levels of analysis of the data: I: "raw" pollen, lake-level, etc. data; II: Level I data converted to estimates of specific climatic variables; and III: Level II data combined from various sources, and interpolated and contoured. (From a data-preservation perspective, we might now consider a Level 0—the materials themselves, e.g. Palmer et al. 2021, and Level IV—coordinated data sets of multiple kinds of data linked to one another, Grobe et al. 2021). Peterson et al. also addressed chronological uncertainties, introducing a three-level classification (later refined to seven levels by Webb 1985a), and the question of how much data is enough for valid comparisons. Street and Grove (1979) described lake-status data both temporally and spatially over the past 30 kyr. The syntheses were not electronic, and the results exist today only as .pdfs of the articles. However, they contained data-availability statements, perhaps some of the earliest. The 150-page Appendix to Peterson et al. could be obtained for the price of photocopying (probably ~USD 7.50), while the Street and Grove data would be furnished on microfiche for USD 2.50.

COHMAP era

COHMAP (Cooperative Holocene Mapping Project; Wright et al. 1993; Wright and Bartlein 1993) was an international, interdisciplinary research group that became organized in the late 1970s, benefiting from the experiences of several of the participants in CLIMAP. The project evolved to focus on a suite of paleoclimatic simulations at 3-kyr intervals from the Last Glacial Maximum to present, and parallel syntheses of terrestrial and marine data and climate reconstructions based on them (e.g. COHMAP Members 1988).

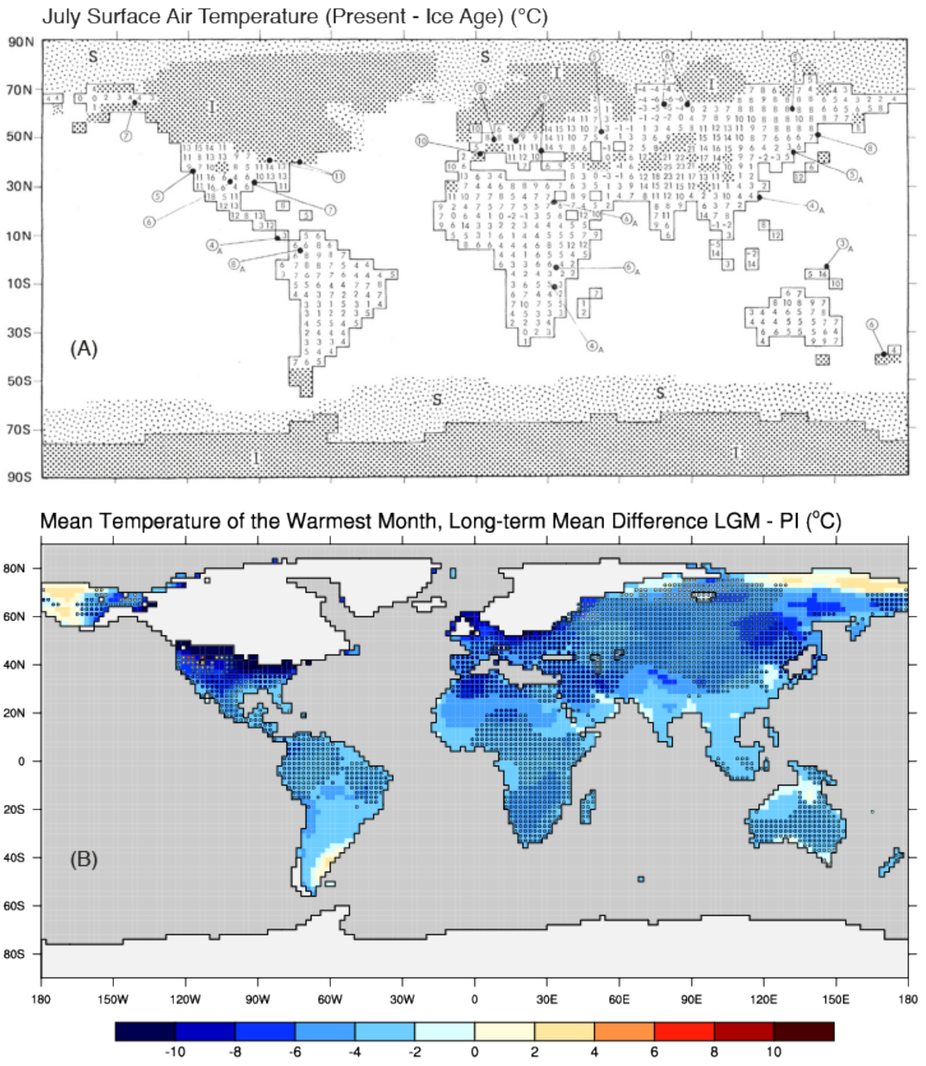
By 1980, it became obvious that photocopy and microfiche distribution was not ideal. Personal computers were becoming widely available as were connections to the forerunners of the internet, and this pushed along the electronic distribution of data.

What might be regarded as the first "modern" syntheses were a global compilation of the climate of 6000 yr BP and the supporting data (Webb 1985a) and a synthesis of lake-level status for the COHMAP target times (Street-Perrott et al. 1989). These studies had both printed and electronic components (on magnetic tape), and remarkably, the .pdfs of the printed reports and the data files are still available online. The collections of individual files are easily recognizable as the elements of a relational database, and feature such components of 21st-century databases as "rich" site metadata, separation of the chronologies or age models from the data, adoption of common vocabularies, harmonization of taxa, sediments, depositional environments, and links to publications and to the data originators.

The databases of that era represented snapshots of data available at the time of publication, and, unlike today, there was no provision for updating. This led to another strategy for database development that is still in use today: a distinction between a database (in a repository) and a "research data set", which may include newer published and unpublished data. The published databases, along with continuously updated research data sets, supported analysis of the data (e.g. Webb 1985b; Street-Perrott and Harrison 1985; COHMAP Members 1988; Harrison 1989).

PMIP era

By the mid 1990s, databases of the 1980s were being regularly elaborated and enlarged, while contributing to the evaluation of newer sequences of climate-model experiments (e.g. Webb and Kutzbach 1998) and to the first generation of PMIP experiments (Joussaume et al. 1999).


July Surface Air Temperature (Present - Ice Age) (°C)

Mean Temperature of the Warmest Month, Long-term Mean Difference LGM - PI (°C)

Figure 1: Forty-five years of progress in terrestrial data-model comparisons. **(A)** CLIMAP-era comparisons of simulated (values on the model grid) and reconstructed (circles and dots) July temperature difference (present-day minus ice age); figure modified from Gates (1976). **(B)** Gridded reconstructions of the Last Glacial Maximum minus present mean temperature of the warmest month (colored dots, data from Cleator et al. 2020), plotted over CMIP5/PMIP3 lgm – piControl multi-model means on a 2-degree grid (see Harrison et al. 2014).

Examplesinclude lake-status records for Europe and elsewhere produced by Sandy Harrison and associates, often published as a journal article and companion data release (e.g. Yu and Harrison 1995a; 1995b) – anticipating the current FAIR Principles for data management and stewardship. Pollen databases were organized for each continent (e.g. NAPD and EPD, the North American and European Pollen Database(s), Grimm et al. 2018 provides a history). The pollen databases contributed to Level III-type syntheses, such as that represented by the reconstruction of vegetation at 6000 yr BP and the LGM (Prentice and Webb 1998; Boenisch et al. 2001).

Over the past decade, databases or syntheses that contribute to the design or evaluation of the current (PMIP4) generation of simulations came online, including those for standard and "deep-time" experiments (e.g. Cleator et al. 2020; Hollis et al. 2019; Dowsett et al. 2016), as well as those for the last millennium, such as the International Tree-Ring Data Bank (Zhao et al. 2018) and the PAGES2k Consortium (2013; 2017) database of temperature reconstructions. Other databases that have yet to "fully participate" in PMIP-style data–model comparisons include those for biomass burning and paleofire (Marlon et al. 2016) and speleothem isotopes (Comas-Bru et al. 2020). Recently "databases of databases" have appeared including the Neotoma Paleoecology Database (Williams et al. 2018b; Grimm et al. 2018), which folded in many earlier paleoecological-focused efforts and greatly expanded the content and usability of the data.

Today the amount of data has begun to impact their usability (Khider et al. 2019), and external (to PMIP or to paleoclimatology in general) demands on paleoscience require answering more complicated questions than "What happened?" or "Do the models really work?" Those issues are being addressed; see, for example, the November 2018 issue of *Past Global Changes Magazine* (Williams et al. 2018a) and Grobe et al. (2021).

One common theme in the history of syntheses of terrestrial paleoclimatic data is the goal of making the data available, whether via book, edited volume, multiple-authored article, or adopted new technologies. A second common theme is the continuous interaction between scientific questions and data availability. Hypotheses about how the climate system works, expressed either as predictions from conceptual models or output from climate-model simulations, demand data for testing. The patterns in the data, both temporal and spatial, demand explanation and in turn generate new questions and hypotheses. That interaction between the data and models makes the intellectual environment of paleoclimatology rich and motivates continued data generation, curation, and synthesis.

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Simulating the Common Era: The Past2K working group of PMIP

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Simulations of Common Era climate evolution coordinated by PMIP's "Past2K" working group together with multi-proxy reconstructions from the PAGES 2k Network provide pivotal understanding for the evolution of the modern climate system and for expected changes in the near future.

Transient simulations of the recent past

Knowledge of past climate evolution is essential for understanding natural variability and for providing context for current and future climate change. One example is the Common Era (CE, i.e. approximately the last 2000 years) with its vast collection of proxy, observational, and documentary datasets, which often feature annual or sub-annual resolution. Simulations covering the CE or the last millennium (LM, i.e. the 1000 years before the industrial era, 850 to 1850 CE) are essential to identify plausible mechanisms underlying paleoclimatic observations and reconstructions. Applying the same models to study past, present, and future climate and its response to external forcing enables the community to use paleodata for the evaluation of the Earth system models that we use for climate projections.

Looking back at more than 20 years of progress in the simulation of CE climate evolution, success of these experiments rests on three pillars: (1) models suitable for a realistic representation of regional and global variability and with an adequate response behavior to external forcing agents; (2) reliable estimates of external forcing factors, such as solar irradiance or volcanic sulfur injections; and (3) the availability of reliable observational or proxy-based reconstructions for model–data comparison.

Simulating 1000 years or even longer periods is challenging in terms of computational resources. Early approaches to simulate the LM have therefore applied simplified models, such as energy-balance models (Crowley 2000), or models of intermediate complexity (Goosse et al. 2005). However, starting already in the late 1990s, millennium-long simulations using comprehensive ocean-atmosphere general circulation models (like the legendary "Erik" runs; González-Rouco et al. 2003) paved the way for more complex analyses of dynamical changes and regional climate variations. Over the first decade of the 21st century, more modeling groups became interested in LM simulations (see Fernandez-Donado et al. 2013 for a review), and progress in model development allowed for more complexity to be included, for example the interactive simulation of the carbon cycle (Jungclaus et al. 2010) or ozone chemistry (Shindell et al. 2001).

Last millennium simulations in PMIP3/CMIP5

Considering the role of information from paleoarchives and modeling in the Intergovernmental Panel on Climate Change (IPCC) assessment reports (AR), the PMIP workshop in Estes Park, USA, in 2008 (Otto-Bliesner et al. 2009) suggested that coordinated simulations of the LM should receive high priority in PMIP's contribution to the fifth phase of the Coupled Model Intercomparison Project (CMIP5). Consequently, a working group was established to coordinate the experiments and to discuss a common basis for "past1000" simulations covering the period 850 to 1850 CE. Schmidt et al. (2011) provided a comprehensive protocol on which modeling groups were able to build their experimental strategy. Additionally, the adaptation of the CMIP5 data format conventions facilitated the distribution of data through CMIP's Earth System Grid Federation framework. The initiative resulted in contributions from 10 modeling groups, including institutions that were previously not active in PMIP. Several of those provided multiple realizations or sensitivity experiments using, for example, different flavors of solar forcing (Masson-Delmotte et al. 2013, Fig. 5.8).

PMIP and PAGES2k collaboration and scientific achievements

The endorsement of the LM simulation as a key experiment in PMIP coincided with the launch of the Past Global Changes PAGES 2k Network (PAGES2k; pastglobalchanges.org/2k) in 2008. Consequently, both initiatives have collaborated and profited from each other. Common work on reconstruction and model simulations was reflected at prominent places in IPCC's AR5 (Masson-Delmotte et al. 2013). For example, based on the comparison between reconstructions and simulations, the authors of AR5 concluded that there is high confidence that not only external orbital, solar, and volcanic forcing but also internal variability contributed substantially to the spatial pattern and timing of surface temperature changes between the Medieval Climate Anomaly and the Little Ice Age. The AR5 also highlighted significant differences between unforced and forced "past1000" simulations that can be identified on timescales larger than 50 years, indicating the importance of forced variability on these timescales.

The first phase of PAGES2k had a focus on regional temperature reconstructions, and a community-building workshop was held in 2013 in Madrid. The workshop led to the initiation of assessments of regional temperature responses to external forcing, and the PAGES2k-PMIP3 group (2015) concluded that the response to external forcing is detectable in the Northern Hemisphere during all time periods over the last 2000 years (Fig. 1). The role of solar forcing was investigated and found to be comparatively smaller than that of the volcanic forcing. Data–model agreement was considerably lower in regions in the Southern Hemisphere compared to the Northern Hemisphere. To understand these still substantial differences over large parts of the globe, improved proxy data coverage and understanding of dynamical processes, such as variability modes, was identified as a priority for future work.

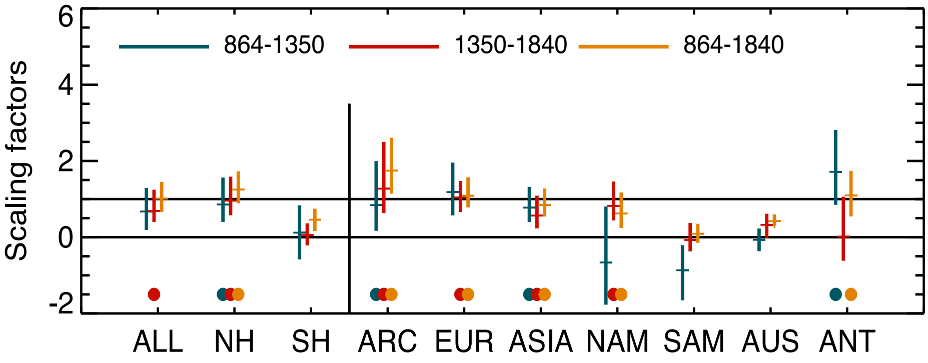

Figure 1: Detection and attribution results for regions defined by PAGES Hydro2k Consortium (2017). Scaling factors (bars, 5-95% range) significantly offset from "0" indicate that the response to forcing is detected, and those that encompass "1" indicate that the magnitude of the forced response agrees with simulations. A circle indicates that the detection analysis was successful, namely the forced response is significantly greater than zero and a residual consistency check was passed (modified from PAGES2k-PMIP3 group 2015).

Moving beyond temperature reconstructions and to the second phase of PAGES2k, another workshop at the Lamont-Doherty Earth Observatory in the Palisades, USA, in 2016 (pastglobalchanges.org/calendar/26535) concentrated on hydroclimatic aspects and refined best practices for model–data comparisons of hydroclimate over the CE (PAGES Hydro2k Consortium 2017). The workshop

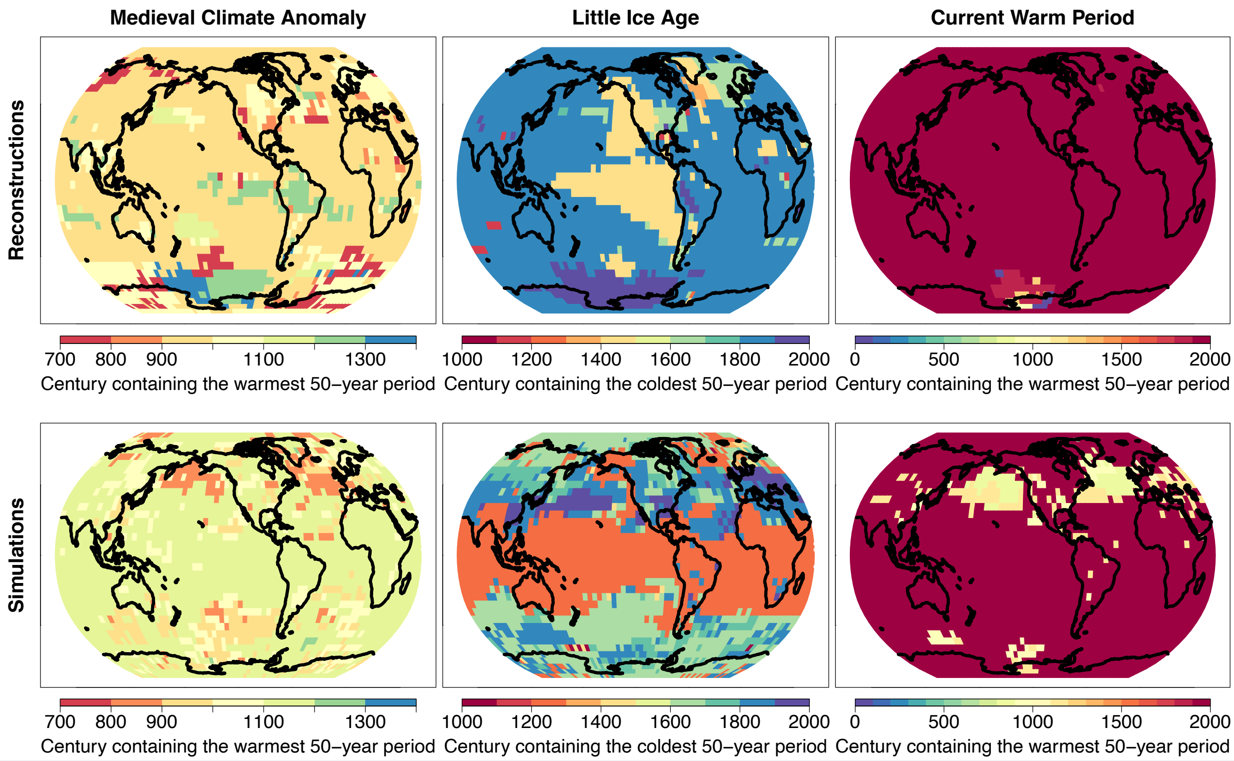

Figure 2: Spatially resolved temperature reconstructions (upper row) and corresponding model simulations (lower row) demonstrate that warm and cold periods prior to the current warm period were not globally synchronous (modified from Neukom et al. 2019).

also covered novel aspects such as proxy system modeling and the interactive simulations of water isotopes as it is promoted in PAGES2k's Iso2k project (pastglobalchanges.org/iso2k).

For other PAGES2k initiatives, for example those working on sub-continental temperature reconstructions, the "past1000" multi-model ensemble was instrumental in understanding the mechanisms driving global and regional climate variability on interannual to centennial timescales. For example, Neukom et al. (2019) confirmed the lack of preindustrial spatial coherence in temperature both in field reconstructions and LM simulations (Fig. 2).

From PMIP3 to PMIP4

Preparing for the sixth phase of CMIP (CMIP6), the PMIP community designed experiments for five different periods. Among others, this included the LM, in order to address the CMIP science objectives defined by the World Climate Research Program. Fostering proper model documentation, CMIP6 introduced a new structure, where a set of common standardized experiments (e.g. idealized CO_2-increase experiments) is accompanied by CMIP-endorsed experiments, like PMIP. The experimental protocol for CE simulations (Jungclaus et al. 2017) reflected refinements in the external forcing agents, in particular solar irradiance, volcanic forcing, and land-cover/land-use changes. The protocol adopted CMIP's "tiered" structure to prioritize certain simulations, e.g. requiring an experiment with an agreed-on standard forcing. The protocol allowed for innovations such as interactive aerosol modules requiring volcanic emissions rather than optical properties to be included. Modeling groups were also encouraged to provide multiple realizations of single-forcing sensitivity experiments, or to expand the temporal range of simulations to include the entire CE. Another novel aspect seen in CMIP6 is that more models include additional features, such as interactive simulation of water isotopes (e.g. Brady et al. 2019).

During the CMIP6 preparation and production phase, PMIP groups concentrated on modeling aspects; now, the new PMIP4/CMIP6 simulations are just about to be harvested by the community. For example, the first "Past2K" simulation was analyzed with a focus on the volcanically active 6th century (Van Dijk et al. 2021).

Moreover, remarkable progress was achieved by individual groups and consortia outside the PMIP working group. We name here in particular the "Last Millennium Ensemble" (LME) project by NCAR (Otto-Bliesner et al. 2016), data assimilation (DA), and DA-based reconstruction (e.g. the "Last Millennium Reanalysis Project"; Hakim et al. 2016), and DA including the reconstruction of hydroclimate (Steiger et al. 2018).

At the same time, PAGES2k is moving into its fourth phase, which will begin at the start of 2022. Community consultation so far has indicated particular interest in hydroclimate, regional and large-scale climate process, data-model integration, and proxy system modeling. Thus, given the progress in modeling during the CMIP6 phase, for example the availability of simulations over the entire CE or more isotope-enabled models, the 30-year anniversary of PAGES and PMIP appears to be an excellent time, in particular for early-career scientists, to continue cooperative research on the climate of the Common Era.

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Simulating the mid-Holocene in PMIP

Chris Brierley[1] and Qiong Zhang[2]

The midHolocene experiment has been a target period for PMIP activity since the beginning. It has gone through four different iterations in the past 30 years. Over 60 models, of various levels of complexity and resolution, have been used for the midHolocene experiment–contributed from around 20 different modeling groups. They all capture a similar large-scale response, but with a level of detail and understanding that increases with every PMIP phase.

Experimental design

Before describing the design, it is probably worth explaining why the mid-Holocene was chosen as a target period. The ideal period to simulate is one that has a large forced climate change (so a high signal-to-noise ratio), as well as plentiful accurate paleoclimate reconstructions with which to compare the model results. Reconstructions suggest that 6,000 years ago, the tail-end of the African Humid Period, was the warmest portion of the Holocene (COHMAP Members 1988). Yet subsequent transient simulations do not show a warming peak: a "Holocene conundrum" that is not fully resolved (Bader et al. 2020). A different time period might have been chosen today, but the wealth of research focused around 6,000 kyr BP since this period was selected by PMIP means there is little point in deviating now.

The midHolocene experiment has kept the same orbital settings since its inception, although other aspects of the design have evolved over the years (Joussaume and Taylor 1995; Otto-Bliesner et al. 2017). The main forcing is an alteration in the precession by roughly a right angle–6,000 years ago the Earth was closest to the sun in Northern Hemisphere (NH) autumn, not during NH winter as is the case today. Determining a consistent way to apply this change was tricky, because of the way orbits, incoming insolation, and internal model calendars are embedded in model radiative codes. The implications of internal calendars being hardwired in models' data output routines are still being felt and need to be considered in analyses (Bartlein and Shafer 2019). The obliquity and eccentricity are also altered. Other settings, such as land cover and atmospheric composition, follow the standard control simulation (i.e. perpetual 1850 CE conditions, except for PMIP1 which used an atmosphere-only set up). For the first time, PMIP4 applied observed greenhouse gas conditions for 6,000 kyr BP, mainly a drop in CO_2 levels of 25ppm from ~284 ppm in the pre-industrial (Otto-Bliesner et al. 2017).

Uptake and reach

More models have performed midHolocene simulations than any other PMIP run–mainly due to the relative ease of prescribing its boundary conditions. The headline papers of the four different PMIP phases include a total of 60 models (Joussaume et al. 1999; Braconnot et al. 2007; Braconnot et al. 2012; Brierley et al. 2020); further, models have performed this standard experiment outside of those publications. There has been a steady increase in both model resolution and complexity throughout the four phases (Braconnot et al. this issue). The simulations have gained models of the ocean, sea ice, and increasingly interactive vegetation. This latter component helps with the expansion of the North African monsoon into the "green Sahara", but models still do not fully capture this transition (Brierley et al. 2020).

There have been a large number of researchers involved with the PMIP midHolocene simulations, with 77 different authors on the four initial description papers alone. Many publications have been written (nearly 2,000 that include PMIP and mid-Holocene in their keywords), and this number will only increase with time. The midHolocene experiment has also been discussed in all IPCC reports since AR3 (Kageyama et al. this issue, p. 68).

Findings

The midHolocene experiment reassuringly demonstrates that climate models show a consistent response to changes in radiative forcings that fits well with our theoretical understanding of the Earth system. The shift in the seasonal distribution of incoming solar energy leads to seasonal temperature changes that are amplified by continentality.

These temperature changes lead to variations in the thermal equator and hence the seasonal march of the intertropical convergence zone (ITCZ) and the associated precipitation patterns. These fundamental features of mid-Holocene climate are found in paleoclimate reconstructions and have been present in results from simulations since PMIP1 (Joussaume et al. 1999).

The creation of ensembles of simulations focused at 6,000 years ago has spurred concerted efforts within the paleoclimate data community. It has motivated researchers to include the period when designing the creation of individual reconstructions. There is a dimensional difference between model simulations, which have global spatial coverage for a limited time, and paleoclimate reconstructions, which track time variations at a fixed location. Data compilations from a time-slice centered on the mid-Holocene have been created to overcome this (Bartlein and Webb, this issue). These compilations also permit the quantitative benchmarking of the midHolocene simulations (Harrison et al. 2014). Although this remains challenging to undertake, results have contributed to IPCC assessments of models (Kageyama et al. this issue, p. 68).

Paleoclimate compilations highlight the dramatic changes in hydroclimate that

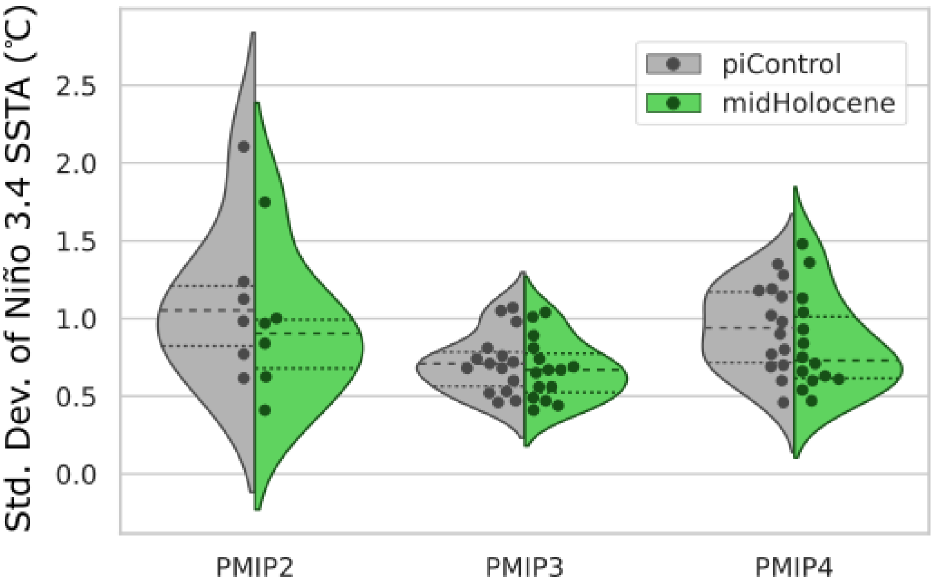

Figure 1: ENSO activity, as measured by the standard deviation of monthly sea surface temperature anomalies averaged over the "Niño 3.4" region of the equatorial Pacific, in PMIP2 (An and Choi 2014), PMIP3, and PMIP4 (Brown et al. 2020).

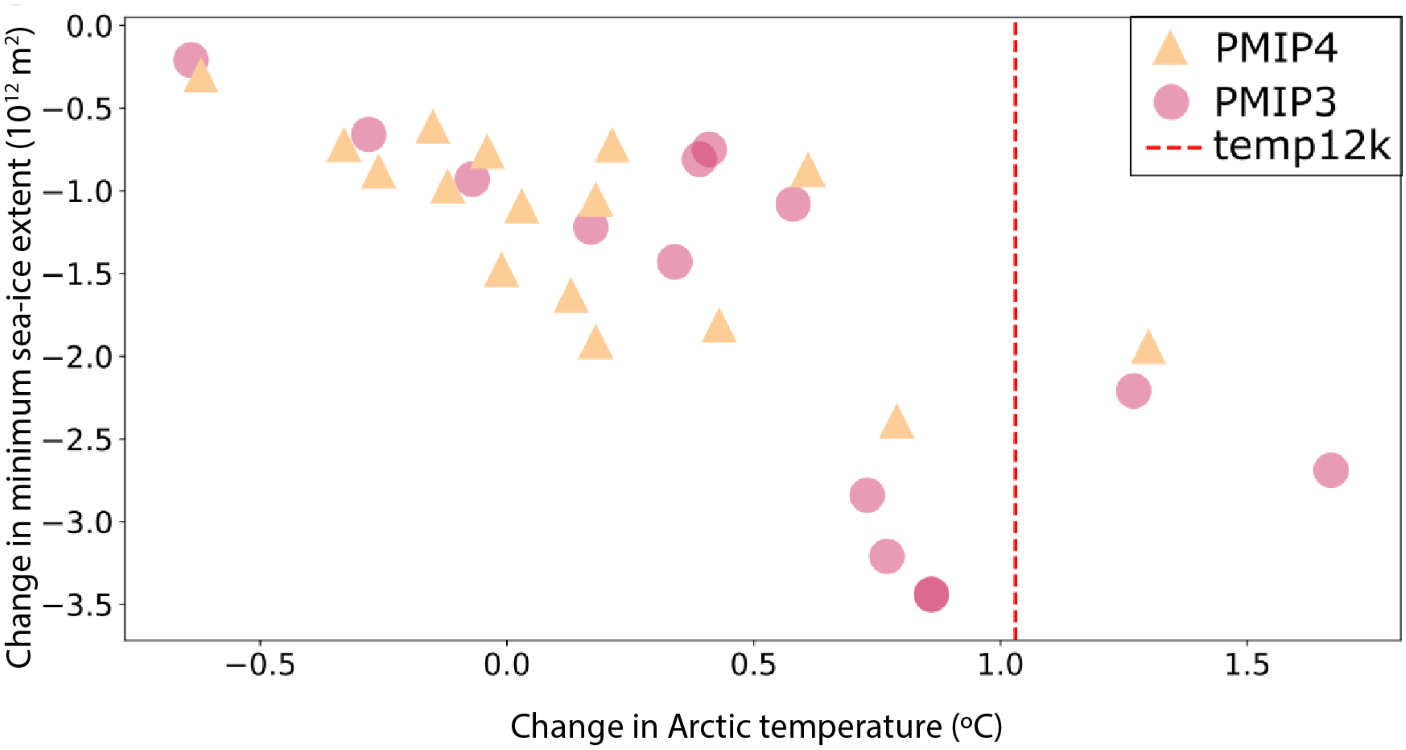

Figure 2: The relationship between the change in annual mean Arctic temperatures and the Northern Hemisphere minimum sea-ice extent (Brierley et al. 2020). The median of the annual mean temperature changes over the Arctic reconstructed by the Temperature 12k compilation of Kaufman et al. (2020) is shown as a vertical line.

happened during the mid-Holocene in the subtropics. The African Humid Period, colloquially called the "green Sahara", is associated with a dramatic poleward extension of the West African monsoon and wetter conditions across northern Africa. It started prior to the Holocene and had already ended in some locations by 6,000 years ago (Shanahan et al. 2015). This has been a focus of analysis since the first phase of PMIP (Joussaume and Taylor, this issue; Braconnot et al. this issue).

Around the time of the completion of PMIP1 came the discovery that ENSO variability in reconstructions was weaker during the mid-Holocene (Rodbell et al. 1999). This opened a new possible research avenue (Rehfeld and Brown, this issue), which has now become a major focus of activity around the mid-Holocene simulations (Zheng et al. 2008; An and Choi 2014; Brown et al. 2020). Models show reduced ENSO activity in response to the mid-Holocene orbital changes. Over the three PMIP phases with coupled models (PMIP2–PMIP4), the ENSO reduction has become more consistent (Fig. 1). Yet the mechanisms for this response are not entirely clear, complicating our ability to pull that success forward into more confident projections of future ENSO changes.

Outside of the tropics, the results of the mid-Holocene experiment show large seasonal temperature variations. One consequence of this is a reduction in summer sea-ice extent in the Arctic (Fig. 2). Non-linear feedbacks of both this and the increase in winter sea ice result in increasing uncertainty regarding the annual mean temperature change in the Arctic. There is however a robust relationship between Arctic temperature change and sea-ice extent in the models, which seems more consistent in PMIP4 compared to earlier phases.

Outlook

The ensemble of PMIP4 midHolocene simulations has only recently been completed, and publications documenting the individual constituent simulations are still emerging. We envisage that the midHolocene simulations will be the focus of many multi-model analyses in the next couple of years. The PMIP structure, part of a global modeling effort that includes future scenarios, permits these analyses to readily include multiple experiments. The combination with the lig127k experiment (Otto-Bliesner et al. this issue) allows the robustness and magnitude of orbital forcing to be assessed. The combination with warming experiments, be they either idealized simulations or future scenarios, allows the lessons from the mid-Holocene to be quantitatively connected to the associated changes anticipated for this century. Personally, we would love to see greater use of the midHolocene simulations amongst the wider climate modeling community, for example by working together with the global monsoon MIP or sea-ice MIP efforts.

Finally, it is worth asking whether the next generation of coupled models should also run midHolocene experiments. We are now in the position where transient Holocene simulations with GCMs are feasible (Otto-Bliesner et al. 2017). These are more intellectually stimulating, remove some problems with data-model comparisons, and perhaps are more helpful for future scenarios (which themselves are mostly transient). However, Holocene transients cannot be made with the shiniest, most computationally expensive models. Over the next few years of analyses on the PMIP4 midHolocene simulations, we must investigate whether the effort and resources needed to use the state-of-the-art models are justifiable, for example, by exploring the experiment's potential to evaluate interactive vegetation, dust, and carbon cycle models.

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The 8.2 kyr event: Benchmarking climate model sensitivity to ice-sheet melt

Lauren J. Gregoire[1] and Carrie Morrill[2]

A century-long cooling of the Northern Hemisphere, caused by accelerated melting of the North American ice sheet 8,200 years ago, offers a critical benchmark of the sensitivity of complex climate models to change.

During the past 10,000 years, the climate has been remarkably stable compared to the natural changes that occurred during glacial periods. However, about 8,200 years ago, the so-called "8.2 kyr event" disrupted this climatic stability. A sharp and widespread cooling of 1–3°C that lasted about 160 years (Fig. 1) can be seen in geological records across the Northern Hemisphere. This was nicknamed the "Goldilocks"[*] event (Schmidt and LeGrande 2005), because it is one of the few past climate changes that could truly test the ability of complex climate models to respond to changes in the ocean circulation induced by meltwater inputs to the North Atlantic. The event's "just right" features include a duration suitable for model simulations, an amplitude large enough to be recorded by proxies, relatively abundant paleoclimatic records for comparison to model output (Morrill et al. 2013a), and meltwater forcing that has been quantified (e.g. Li et al. 2012; Lawrence et al. 2016; Aguiar et al. 2021).

The forcing and mechanism that led to the cooling are now well understood. A release of meltwater into the Labrador Sea freshened sites of deep-water formation, thus slowing the Atlantic Meridional Overturning Circulation (AMOC) and reducing the northward transport of heat in the Atlantic (Barber et al. 1999). Evidence of Labrador Sea freshening and AMOC changes corroborate this story (e.g. Lochte et al. 2019). These changes also coincided with a sudden outburst of the lakes Agassiz and Ojibway (Barber et al. 1999), previously dammed by the remnants of the Laurentide Ice Sheet over North America that was then rapidly retreating (Fig. 2). The lake outburst was thus, for a long time, badged as the culprit for the 8.2 kyr event (Barber et al. 1999).

An ensemble of opportunity

Three climate-modeling groups within PMIP had simulated the event and decided to compare their results for the IPCC Fifth Assessment Report (Morrill et al. 2013b). This exercise was not conducted as a formal model intercomparison project (MIP) as coordinated by PMIP for the mid-Holocene, Last Glacial Maximum, or Pliocene, but was instead an "ensemble of opportunity". The simulations had minor differences in boundary conditions (orbital parameters,

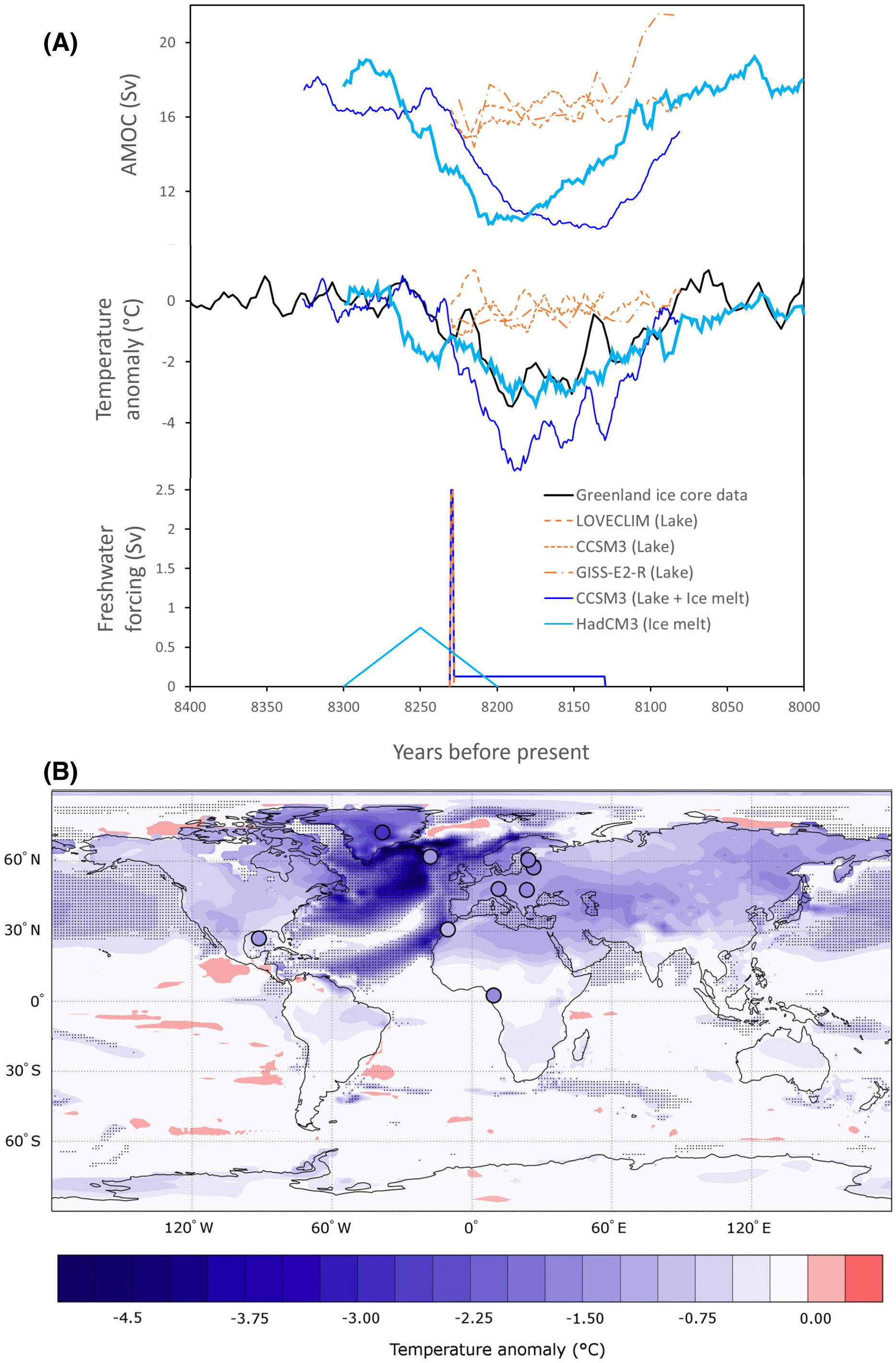

Figure 1: (A) Timeseries of (top) simulated Atlantic Meridional Overturning Circulation, (middle) simulated and observed Greenland temperature, and (bottom) prescribed meltwater forcing from five model experiments of the 8.2 kyr event. Three simulations (orange; Morrill et al. 2013b) that use meltwater fluxes corresponding to the drainage of Lake Agassiz-Ojibway cannot reproduce the duration or magnitude of the event (middle; black), while simulations (blue; Matero et al. 2017; Wagner et al. 2013) that include the much larger and longer ice-melt flux can. **(B)** The change in annual mean surface temperature caused by an ice-melt flux from the Hudson Bay saddle collapse matches the amplitude of changes in geological records shown in filled circles (reproduced from Matero et al. 2017).

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[*] This refers to the fairy tale "Goldilocks and the Three Bears" in which a girl tastes three bowls of porridge (or soup depending on the version): one too hot, one too cold, and prefers the one that is just the right temperature.

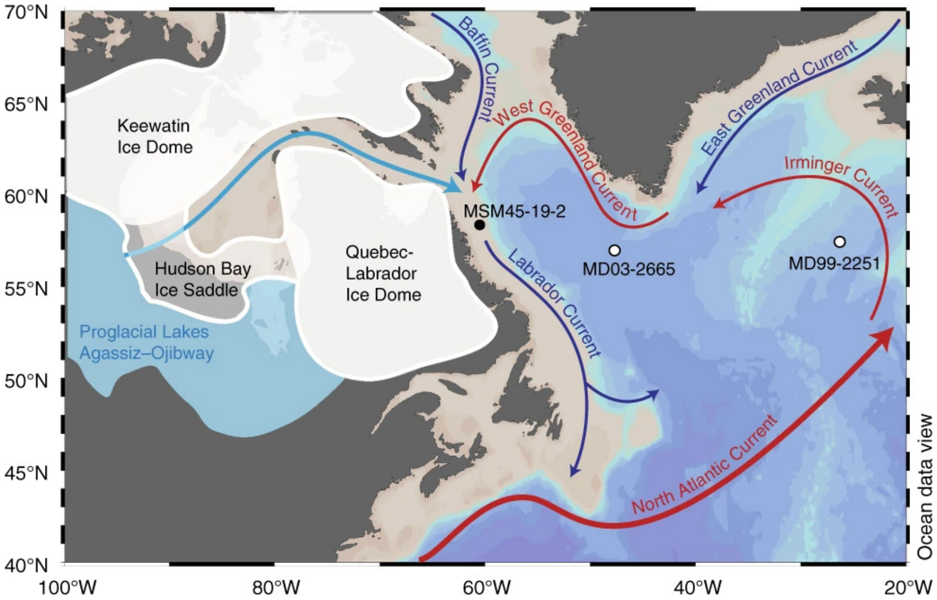

Figure 2: Map of the Laurentide ice sheet showing the Hudson Bay Ice Saddle that collapsed and the Lakes Agassiz-Ojibway that outburst around the time of the 8.2 kyr event. These caused an influx of freshwater into the Labrador Sea and slowed down the Atlantic Meridional Overturning Circulation causing the cooling shown in Figure 1 (reproduced from Lochte et al. 2019).

greenhouse gases, and ice sheets), but all included a lake outburst freshwater pulse of 2.5 Sv for one year added to the ocean near the Hudson Strait with slight differences in how the water was spread. This volume of freshwater was set to match estimates of lake volume. The models reproduced well the largescale pattern of temperature and precipitation changes deduced from a broad compilation of proxy records (Morrill et al. 2013b). However, the changes caused by the lake outburst were too small and much too short (red lines in Fig. 1), as the slowdown in ocean circulation could not be sustained after the meltwater pulse. Were the models not sensitive enough to this forcing, or was the experimental design inadequate in some way?

'Twas the wrong culprit

Fortunately, the story doesn't end there; it turns out a major factor was missing. The collapse of the Laurentide Ice Sheet that triggered the lake outburst was releasing huge amounts of water in the Labrador Sea and North Atlantic at the time of the event (Gregoire et al. 2012). Sea-level records had shown much larger sea-level rise than what could be explained from the lake outburst (Li et al. 2012), compelling modelers to release more freshwater in their models (Wiersma et al. 2006). It eventually became clear that the melt of the Laurentide Ice Sheet was actually more important than the lake outburst in causing the 8.2 kyr event (Wagner et al. 2013). But why was ice-sheet melt suddenly causing a slowdown of ocean circulation when the ice sheet had been steadily melting for thousands of years?

The answer came from the discovery of a mechanism of ice-sheet instability, called the saddle collapse, which occurred on two significant occasions during the last deglaciation: one causing the Meltwater Pulse 1a sea-level rise 14.5 thousand years ago, and the other causing the 8.2 kyr event (Gregoire et al. 2012; Matero et al. 2017). The instability occurs during deglaciations when two domes of an ice sheet, connected via an ice saddle, separate to form distinct ice sheets. The saddle collapse is triggered when warming induces melt in the saddle region. As the saddle melts, it lowers, reaching increasingly warmer altitudes, thus accelerating the melt through the ice-elevation feedback, which produces a pulse of meltwater lasting multiple centuries (Gregoire et al. 2012). This is what happened to the ice sheet that was covering the Hudson Bay at the end of the last deglaciation (Gregoire et al. 2012), a process that was possibly enhanced by heat transported from a warm ocean current (Lochte et al. 2019) and instability of the marine parts of the ice sheet (Matero et al. 2020).

Ice collapse and lake outburst

It is not a coincidence that the Lake Agassiz-Ojibway outburst and the Hudson Bay ice-saddle collapse occurred around the same time. Around the peak of the saddle collapse melt, when the ice saddle became thin enough, the lake was able to initiate its discharge via channels under the ice due to the pressure of the lake that sat hundreds of meters above sea level. The ice-sheet melt would have contributed to filling up the lake, and the ice loss likely reduced the gravitational pull that the ice exerted on the ocean and the lake. Thus, estimating the relative timing, amplitude, and location of meltwater discharge from the ice sheet and lake into the ocean requires the combined modeling of the ice-sheet, hydrology, and sea-level processes.

Towards a benchmark for climate sensitivity to freshwater input

Given reasonable scenarios of meltwater discharge into the Labrador Sea from the Hudson Bay saddle collapse, Matero et al. (2017) were able to simulate the duration, magnitude, and pattern of the 8.2 kyr climate changes (Fig. 1, light blue curve), albeit with a larger volume of melt than sea-level records suggest. Our new understanding of the cause of the 8.2 kyr event thus advances the potential of this event to benchmark the sensitivity of climate models to freshwater forcing. Since the event was short and occurred under climate conditions similar to pre-industrial, it could become a feasible "out of sample" target for calibrating climate models. To reach this goal, we must continue to improve estimates for the magnitude, duration, and location of the meltwater forcing by combining sea-level, ocean-sediment, and geomorphological records with models of the ice sheet and lake.

We have good quantitative proxies for circum-North Atlantic temperature change during the event, but additional proxy records in the Southern Hemisphere are needed to determine the extent of the bipolar see-saw, a pattern of southern warming and northern cooling that often occurs when AMOC slows. We also lack good quantitative proxies for precipitation change during the event, which would provide invaluable information on the sensitivity of the water cycle to ice-sheet melt.

The design of MIPs and model–data intercomparison work within PMIP has become highly sophisticated in the last decade with detailed experimental setup for transient climate changes (e.g. DeGLAC; Ivanovic et al. 2016), which include realistic routing of meltwater flux to the ocean. Forward-modeling proxy data such as oxygen isotopes (Aguiar et al. 2021) or ocean neodymium could also greatly improve uncertainty quantification and benchmarking. With all these developments, the 8.2 kyr event may well fulfil its potential as the "Goldilocks" event that could truly test our ability to model the impacts of ice-sheet melting and the response of surface climate to ocean circulation changes.

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New PMIP challenges: Simulations of deglaciations and abrupt Earth system changes

Ruza F. Ivanovic[1], E. Capron[2] and L.J. Gregoire[1]

Recent cold-to-warm climate transitions present one of the hardest tests of our knowledge of environmental processes. In coordinating transient experiments of these elusive events, the Deglaciations and Abrupt Changes (DeglAC) Working Group is finding new ways to understand climate change.

Our journey to the present

In December 2010, amidst mountains of tofu, late-night karaoke stardom, and restorative trips to the local onsen (hot springs), the PMIP3 meeting in Kyoto, Japan (pastglobalchanges.org/calendar/128657), was in full swing. Results were emerging from transient simulations of the last 21,000 years attempting to capture both the gradual deglaciation towards present day climes and the abrupt aberrations that punctuate the longer-term trend. However, most of these experiments had employed different boundary conditions, and the models were showing different sensitivities to the imposed forcings. It was proposed that to better understand the last deglaciation, we should pool resources and develop a multi-model intercomparison project (MIP) for transient simulations of the period. This was a new kind of challenge for PMIP, which previously had focused mainly on equilibrium-type simulations (the last millennium experiment is a notable exception) of up to a few thousand years in duration. Fast forward to the present: DeglAC has its first results from its last deglaciation simulations. Eleven models of varying complexity and resolution have completed 21–15 kyr BP, with five of those running to 1950 CE or into the future.

Defining a flexible protocol

Real headway was made in 2014, when the PMIP3 meeting in Namur, Belgium (pastglobalchanges.org/calendar/128658), marked the inauguration of the DeglAC Working Group. That summer, the leaders of the Working Group made an open call for state-of-the-art, global ice-sheet reconstructions spanning 26–0 kyr BP, and two were provided: GLAC-1D and ICE-6G_C (VM5a). For orbital forcing, we adopted solutions consistent with previous PMIP endeavors, but the history of atmospheric trace gases posed some interesting questions. For instance, the incorporation of a new high-resolution record in a segment of the longer atmospheric CO_2 composite curve (Bereiter et al. 2015) raised fears of runaway terrestrial feedbacks in the models and artificial spikiness from sampling frequency. A hot debate continued over the appropriate temporal resolution to prescribe, and in the end, we left it up to individual modeling groups whether to prescribe the forcing at the published resolution, produce a spline through the discrete points, or interpolate between data, as needed. See Figure 1 for an overview of the experiment forcings and Ivanovic et al. (2016) for protocol details and references.

The elephant in the room was what to do with ice-sheet melting. It is well known that the location, rate, and timing of freshwater forcing is critical for determining its impact on modeled ocean circulation and climate (and the impact can be large, e.g. Roche et al. 2011; Condron and Winsor 2012; Ivanovic et al. 2017). Yet, these parameters remain mostly uncertain, especially at the level of the spatial and temporal detail required by the models.

We explored a contentious proposal to set target ocean and climate conditions instead of an ice-sheet meltwater protocol. Many models have different sensitivities to freshwater (Kageyama et al. 2013), and it was strongly suspected that imposing freshwater fluxes consistent with ice-sheet reconstructions would confound efforts to produce observed millennial-scale climate events (Bethke et al. 2012). Thus, specifying the ocean and climate conditions to be reproduced by the participant models would encourage groups to employ whatever forcing was necessary to simulate the recorded events. However, the more traditional MIP philosophy is to use tightly prescribed boundary conditions to enable a direct inter-model comparison of sensitivity to those forcings, as well as evaluation of model performance and simulated processes against paleorecords. If the forcings are instead tuned to produce a target climate/ocean, then by definition of the experimental design, the models will have been conditioned to get at least some aspect of the climate "right", reducing the predictive value of the result. Although useful for examining the climate response to the target condition, and for driving offline models of other Earth system components (e.g. ice sheets, biosphere, etc.), we already know that this approach risks requiring unrealistic combinations of boundary conditions, which complicates the analyses and may undermine some of the simulated interactions and teleconnections. Ultimately, the complex multiplicity

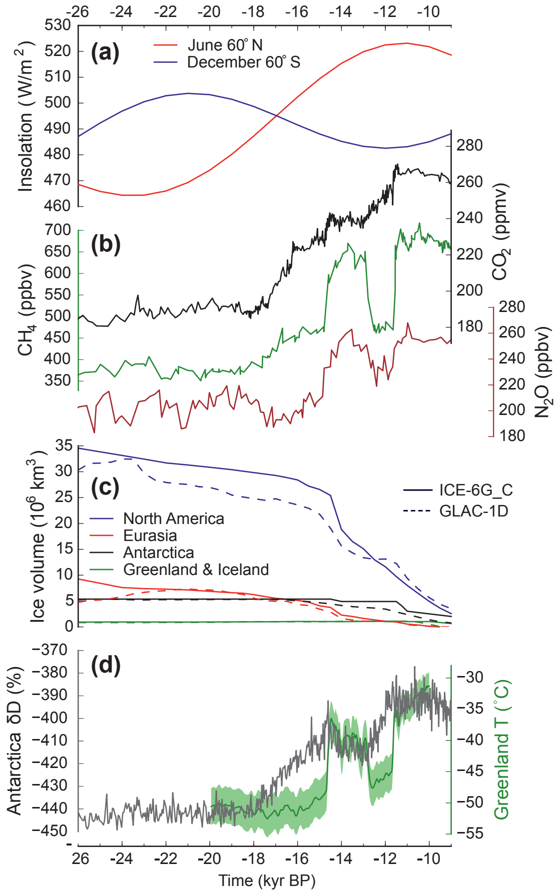

Figure 1: (A-C) Boundary conditions for the DeglAC MIP core experiment (version 1); **(D)** East Antarctic Plateau ice core δD (a proxy for local surface air temperature) and Greenland surface air temperature. After Ivanovic et al. (2016); see references therein.

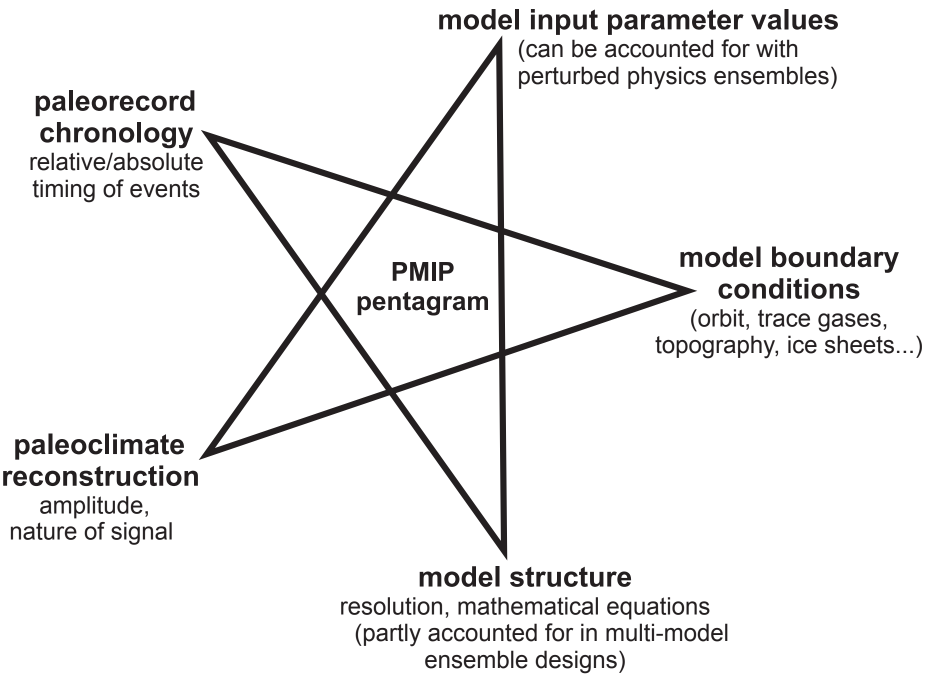

Figure 2: Five sources of high-level quantitative and qualitative uncertainty to address using transient simulations of past climate change.

in the interpretation of paleorecords made it too controversial to set definitive target ocean and climate states in the protocol. Therefore, we recommended the prescription of freshwater forcing consistent with ice-sheet evolution, and allowed complete flexibility for groups to pursue any preferred scenario(s).

Such flexibility in uncertain boundary conditions is not the common way to design a paleo MIP, but this less traditional method is eminently useful. First and foremost, not being too rigid on model boundary conditions allows for the use of the model ensemble for informally examining uncertainties in deglacial forcings, mechanisms, and feedbacks. There are also technical advantages: the last deglaciation is a very difficult simulation to set up, and can take anything from a month to several years of continuous computer runtime. Thus, allowing flexibility in the protocol enables participation from the widest possible range of models. Moreover, even a strict prescription of boundary conditions does not account for differences in the way those datasets can be implemented in different models, which inevitably leads to divergence in the simulation architecture. In designing a relatively open MIP protocol, our intention was to facilitate the undertaking of the most interesting and useful science. The approach will be developed in future iterations based on its success.

Non-linearity and mechanisms of abrupt change

One further paradigm to confront comes from the indication that rapid reorganizations in Atlantic Overturning Circulation may be triggered by passing through a window of instability in the model—e.g. by hitting a sweet-spot in the combination of model inputs (model boundary conditions and parameter values) and the model's background climate condition—and by spontaneous or externally-triggered oscillations arising due to internal variability in ocean conditions (see reviews by Li and Born 2019; Menviel et al. 2020). The resulting abrupt surface warmings and coolings are analogous to Dansgaard-Oeschger cycles, the period from Heinrich Stadial 1 to the Bølling-Allerød warming, and the Younger Dryas. However, the precise mechanisms underpinning the modeled events remain elusive, and it is clear that they arise under different conditions in different models. These findings open up the compelling likelihood that rapid changes are caused by non-linear feedbacks in a partially chaotic climate system, raising the distinct possibility that no model version could accurately predict the full characteristics of the observed abrupt events at exactly the right time in response to known environmental conditions.

Broader working group activities

Within the DeglAC MIP, we have several sub-working groups using a variety of climate and Earth System models to address key research questions on climate change. Alongside the PMIP last deglaciation experiment, these groups focus on: the Last Glacial Maximum (21 kyr BP; Kageyama et al. 2021), the carbon cycle (Lhardy et al. 2021), ice-sheet uncertainties (Abe-Ouchi et al. 2015), and the penultimate deglaciation (138–128 kyr BP; Menviel et al. 2019). However, none of this would be meaningful, or even possible, without the full integration of new data acquisition on climatic archives and paleodata synthesis efforts. Our communities aim to work alongside each other from the first point of MIP conception, to the final evaluation of model output.

Looking ahead and embracing uncertainty

At the time of writing, 19 transient simulations of the last deglaciation have been completed covering ca. 21–11 kyr BP. In the next phase (multi-model analysis of these results) transient model-observation comparisons may present the most ambitious strand of DeglAC's work. Our attention is increasingly turning towards the necessity of untangling the chain of environmental changes recorded in spatially-disparate paleoclimate archives across the Earth system. We need to move towards an approach that explicitly incorporates uncertainty (Fig. 2) into our model analysis (including comparison to paleoarchives), hypothesis testing, and future iterations of the experiment design. Hence, the long-standing, emblematic "PMIP triangle" (Haywood et al. 2013) has been reformulated into a pentagram of uncertainty, appropriate for a multi-model examination of major long-term and abrupt climate transitions.

The work is exciting, providing copious model output for exploring Earth system evolution on orbital to sub-millennial timescales. As envisaged in Japan 11 years ago, pooling our efforts is unlocking new ways of thinking that test established understanding of transient climate changes and how to approach simulating them. At the crux of this research is a nagging question: while there are such large uncertainties in key boundary conditions, and while models all have wide variability in their sensitivity to forcings and sweet-spot conditioning for producing abrupt changes, is there even a possibility that the *real* history of Earth's paleoclimate events can be simulated? It is time to up our game, to formally embrace uncertainty as being fundamentally scientific (Ivanovic and Freer 2009), and to build a new framework that capitalizes on the plurality of plausible climate histories for understanding environmental change.

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Modeling the climate of the Last Glacial Maximum from PMIP1 to PMIP4

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The Last Glacial Maximum is an example of an extreme climate, and has thus been a target for climate models for many years. This period is important for evaluating the models' ability to simulate changes in polar amplification, land–sea temperature contrast, and climate sensitivity.

The Last Glacial Maximum (LGM, ~21,000 years ago), a period during which the global ice volume was at a maximum and global eustatic sea level at a minimum, inspired some of the first simulations of past atmospheric circulation and climates (Gates 1976; Manabe and Broccoli 1985a; Manabe and Broccoli 1985b; Kutzbach and Wright 1985). Because of the extreme conditions during this period, the LGM was documented quite early, notably through the CLIMAP project (e.g. CLIMAP Project Members 1981). This early work gave rise to many questions: how cold, how dry, how dusty was it, and why? How was the Northern Hemisphere ice sheet sustained? How did the massive ice sheet impact the atmospheric and oceanic circulation? What were the impacts of these ice sheets on climate, compared to the impact of other changes in forcings and boundary conditions, such as the decrease in greenhouse gas concentrations? What climate feedbacks were induced by vegetation, the cryosphere, dust, and permafrost? Are the features from paleodata reconstructions also found in the results of the models that are routinely used to compute present and future climate changes? Climate reconstructions for the LGM were also hotly debated, sometimes in relation to one another, such as for tropical cooling over sea and over land (e.g. Rind and Peteet 1985).

In the beginning

PMIP was launched as a result of a NATO Advanced Research Workshop in Saclay, France, in 1991 (Joussaume and Taylor, this issue). At that time, several LGM simulations had already been carried out, and the different modeling groups involved in running these experiments had therefore already gathered some experience. However, these simulations were not strictly comparable since they did not use the same forcings or boundary conditions. For example, the CO_2 forcing, which became a central point of LGM climate analyses due to its connection with climate sensitivity, was actually not taken into account in climate simulations until the work of Manabe and Broccoli (1985b), who cited the CO_2 retrieved from Greenland and Antarctic ice cores published by Neftel et al. (1982). At the Saclay meeting, it was clear that many groups of modelers and data scientists were motivated to build a common project to better understand the climate during the mid-Holocene and the Last Glacial Maximum, based on numerical simulations and on syntheses of paleoclimatic reconstructions.

Developing the approach

It took time, intensive debates, and several PMIP meetings to agree on a common approach, forcings and boundary conditions; develop a strategy for paleodata compilations; and establish a methodology for model–data comparison. Therefore, the real launch of the PMIP1 LGM simulations was in 1994. Despite having chosen to adopt an approach that would be as simple as possible, it took no fewer than four newsletters to describe the corresponding experimental protocol (pmip1.lsce.ipsl.fr/ > Newletters).

To engage as many groups as possible in this new adventure, the decision was made to allow for two types of simulations to be run for the LGM: one using atmosphere-only general circulation models (AGCMs) and therefore prescribing surface conditions (sea surface temperatures and sea ice from the CLIMAP (1981) reconstructions), the other using AGCMs coupled to slab ocean models, which computed the ocean conditions under the (strong) assumption that the ocean heat transport was similar to the pre-industrial one.

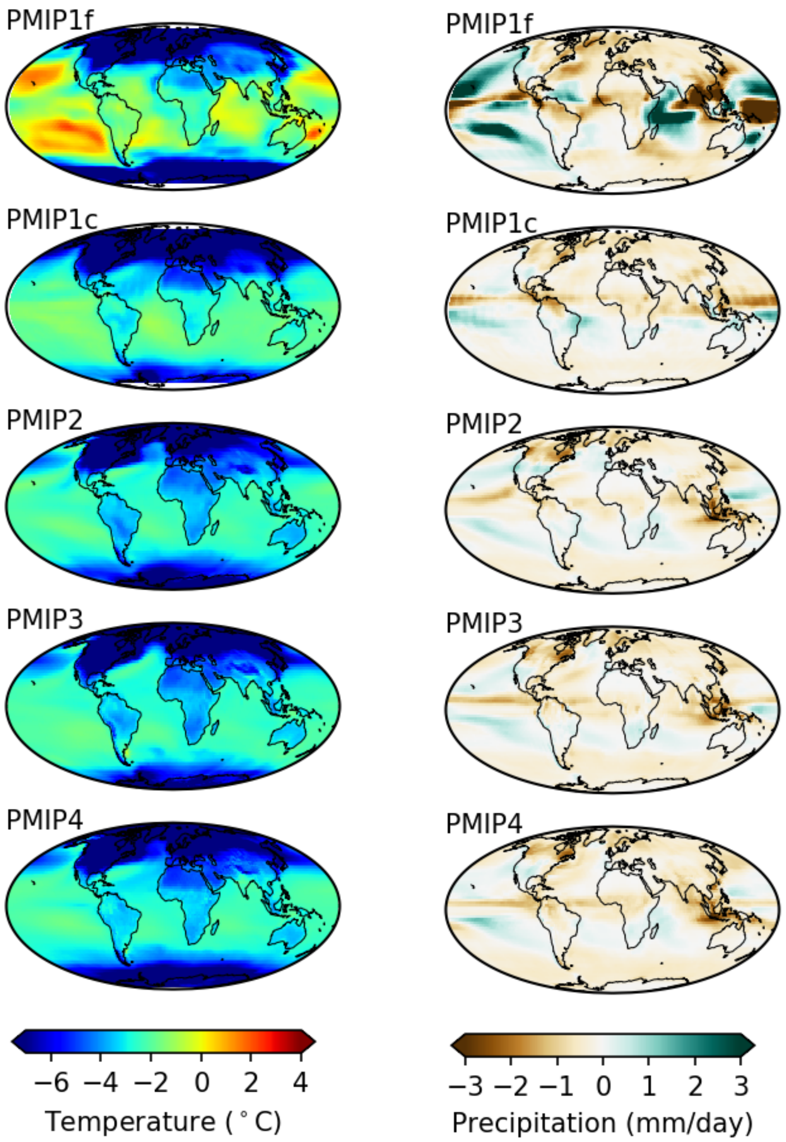

Figure 1: LGM – PI multi-model average anomalies simulated by climate models of the different PMIP phases for Mean Annual Temperature (left) and precipitation (right). PMIP1f: PMIP1-prescribed SST AGCM simulations; PMIP1c: simulations run with AGCMs coupled to slab ocean models. All other PMIP phases used coupled atmosphere-ocean GCMs.

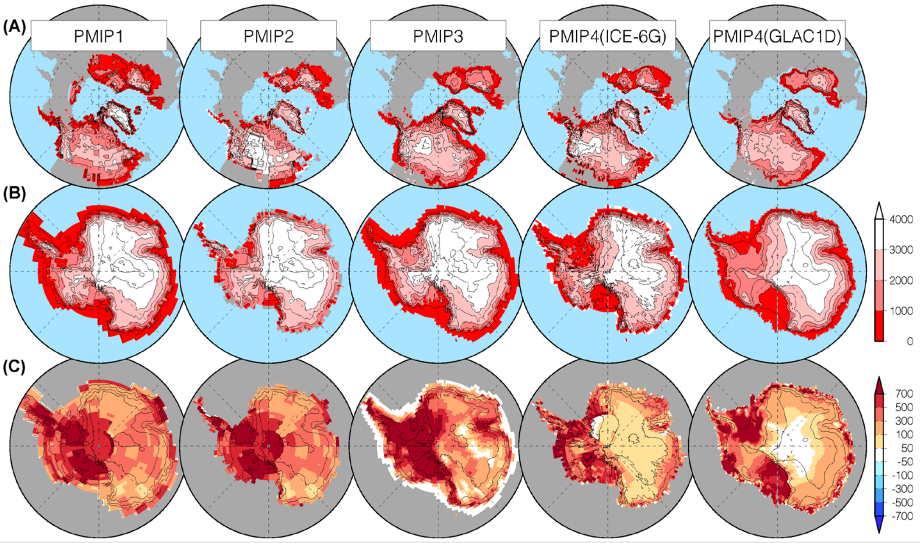

Figure 2: Evolution of the ice sheets used as boundary condition in the different PMIP phases. From the left to right: PMIP1 (ICE-4G; Peltier 1994), PMIP2 (ICE-5G; Peltier 2004), PMIP3 (Abe-Ouchi et al. 2005), PMIP4 (ICE-6G_C; Argus et al. 2014; Peltier et al. 2015), and PMIP4 (GLAC-1D; Ivanovic et al. 2016). **(A)** The altitude of Northern Hemisphere ice sheets at the LGM; **(B)** the altitude of Antarctica ice sheet at the LGM; **(C)** the altitude difference (LGM minus present day).

The recommended ice-sheet reconstruction (ICE-4G; Peltier 1994) was the same for both types of experiments. Encouraging groups to run prescribed and computed SST experiments proved to be a wise decision, as this resulted in a total of eight simulations of each type being made available with contrasting results (Fig. 1). The largest difference between the groups of PMIP simulations is clearly between the prescribed SST simulations (labelled "PMIP1f") and the computed SST simulations (labelled "PMIP1c"). Both ensemble means show global cooling, amplified from the equator to the poles, with stronger cooling over the continents than over the oceans. These two large-scale characteristics (later termed "polar amplification" and "land–sea contrast") would be analyzed in all phases of PMIP, as these features are also seen in projections of future climate and should therefore be evaluated. Another topic of analysis was the atmospheric circulation in the vicinity of the large Northern Hemisphere ice sheets, following the striking "split-jet" response found in the pioneer, pre-PMIP simulations. This feature was not systematically found in the PMIP1 experiments, but the response of the atmospheric circulation and its interaction with the oceans remains a topic of active research.

What Figure 1 does not show is that the range of the PMIP1c results was much larger than that for PMIP1f, foreshadowing the need for coupled ocean-atmosphere models (cf. Braconnot et al. this issue). The advent of coupled ocean-atmosphere general circulation models resulted in the launch of the second phase of PMIP in 2002 (Harrison et al. 2002) with an updated ice-sheet boundary condition: ICE-5G (Peltier 2004; Fig. 2). Running these experiments was technically challenging, and it remains so because it forces the climate models out of their "comfort zone" (i.e. the conditions for which the models were initially developed). It requires a long equilibration time, which is very computationally expensive for the latest generation of models. Despite these challenges, the use of these coupled models proved to be very worthwhile, as they allowed for the use of marine data for evaluation, rather than for prescribing boundary conditions. This represented a huge release of the constraints on ocean reconstructions, which did not need to cover all the world's oceans for winter and summer. New ways to compare models and marine data became available, taking into account the indicators' specificities, some of which are still being investigated today. These should help us understand why reconstructions from different indicators sometimes differ significantly (Jonkers et al. this issue).

Progress in PMIP3 and PMIP4

Simulations during the third and fourth phases of PMIP were also run with coupled models, sometimes even with interactive vegetation, dust (see Lambert et al. this issue), and/or a carbon cycle (see Bouttes et al. this issue). While PMIP2 often used lower resolution models compared to those used for future climate projections, the novelty from PMIP3 onwards was that exactly the same model versions were used for both exercises, hence allowing for rigorous comparisons of processes involved in past and future climate changes. Boundary conditions, in particular in terms of ice-sheet reconstructions, were updated for each phase (Fig. 2). Ice-sheet reconstructions for the LGM were a hotly debated topic, but during the first three phases of PMIP, a single reconstruction was chosen. For PMIP3, this reconstruction was derived from three different reconstructions (Abe-Ouchi et al. 2015; Fig 2). Choosing a single protocol was deemed important for all the simulations to be comparable. For PMIP4, however, evaluating the uncertainty in model results related to the chosen boundary conditions was deemed necessary because differences between the ice-sheet reconstructions remained quite large in terms of ice-sheet altitude (Ivanovic et al. 2016; Kageyama et al. 2017). The PMIP4 dataset should ultimately help us reach this goal (most simulations presently available use Peltier's ICE-6G_C reconstruction; Argus et al. 2014; Peltier et al. 2015).

Providing an exhaustive list of the analyses based on these simulations would require more space than is available here. Recurring topics across the four phases of PMIP encompass large-scale to global features, such as climate sensitivity; polar amplification and land–sea contrast; atmosphere and oceanic circulation, in particular the Atlantic Meridional Overturning Circulation; the comparison of model results with reconstructions for various regions; and impacts on the ecosystems. An intriguing feature is that from PMIP2 to PMIP4, even though both models and experimental protocol have evolved, the range of model results (cf. Braconnot et al. this issue regarding the multi-model results in terms of cooling over tropical land and oceans) is quite stable, and within the range reconstructed from marine and terrestrial data. This might sound satisfactory, but in fact is a call for the reduction in the uncertainty of the reconstructions, the reconciliation of reconstructions from different climate indicators, or a better understanding of the differences and a refinement of the methodology regarding model–data comparisons. This would allow us to draw many more conclusions about the LGM in terms of understanding the climate system's sensitivity to changing forcings, and in terms of impacts of climate changes on the environments.

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The last glacial ocean: The challenge of comparing multiproxy data synthesis with climate simulations

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The Last Glacial Maximum (LGM) offers paleoscientists the possibility to assess climate model skill under boundary conditions fundamentally different from today. We briefly review the history and challenges of LGM data–model comparison and outline potential new future directions.

The Last Glacial Maximum

The Last Glacial Maximum (LGM; 23,000–19,000 years ago) is the most recent time in Earth's history with a fundamentally different climate from today. Thus, from a climate modeling perspective, the LGM is an ideal test case because of its radically different and quantitatively well-constrained boundary conditions.

Reconstructions provide quantitative constraints on LGM climate, but they are often archived in isolation. Paleoclimate syntheses bring individual reconstructions together and offer a large-scale, even global, perspective on paleoclimate that is impossible to obtain from single observations. The first synthesis of the LGM surface temperature field, carried out within the Climate: Long range Investigation, Mapping, and Prediction (CLIMAP) project in the 1970s, served as boundary conditions for atmosphere-only models (CLIMAP Project Members 1976), which required full-field seasonal reconstructions. Later, with the advent of coupled ocean-atmosphere models, the information from paleoclimate archives could be used to benchmark simulations.

Since CLIMAP, the data coverage has increased tremendously and new (geochemical) proxies for seawater temperature have been developed and successfully applied. Thanks to synthesis efforts, the LGM is now arguably the time period with the most extensively constrained sea-surface temperature field prior to the instrumental period (MARGO project members 2009; Tierney et al. 2020).

Climate models largely capture the reconstructed global average LGM cooling of the oceans (Kageyama et al. 2021; Otto-Bliesner et al. 2009), thus allowing us to constrain climate sensitivity (Sherwood et al. 2020). However, the average LGM cooling emerges from a signal of marked variability (MARGO project members 2009; Rehfeld et al. 2018), a reflection of climate dynamics that cannot be resolved from the global mean. The reconstructions indicate pronounced regional patterns of the oceanic temperature change, with, amongst others, pronounced gradients in the cooling in the North Atlantic (MARGO project members 2009). It is in the spatial patterns of LGM temperature change where there are the largest differences among the individual proxies and models, as well as between the proxies and the models (Kageyama et al. 2021).

The causes—and hence implications—for these differences (and model–data mismatch in general) arise from both the reconstructions and the models. It is important to resolve the underlying reasons for the differences in order to increase the relevance of paleodata model comparison for future predictions.

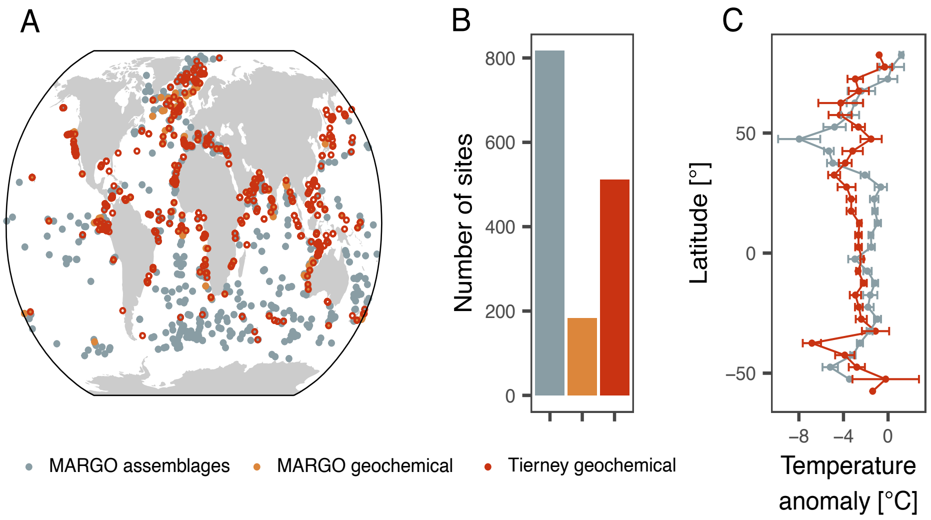

Figure 1: (A,B) Sites with LGM sea surface temperature reconstruction in the MARGO project members (2009) and Tierney et al. (2020) compilations and **(C)** binned latitudinal mean annual temperature anomaly with respect to the present day derived from assemblages-based and geochemical proxies. Errorbars represent standard errors of the mean.

Main challenges

A crucial first step to assess (any) mismatch between paleoclimate reconstructions and simulations is to quantify the uncertainty and bias of both. Without this, the reason for differences (or the meaning of agreement) will remain difficult to elucidate.

Paleoclimate records preserve an imprint of past climate that is affected by uncertainty in the chronology of the archives and in the attribution of the signal together with additional noise that may be unrelated to climate. Previous work suggests that—at least for the LGM—dating uncertainties and internal variability are not the largest source of error for the reconstructions (Kucera et al. 2005). This is likely because sediment records are averaged enough across the four millennia that span the LGM, and the dating aided by the radiocarbon technique is sufficiently reliable to identify the target time slice. Instead, the attribution of the reconstructed temperatures to specific water depths or seasons, as well as the influence of factors other than temperature on the proxy signals, remain problematic and likely explain part of the difference among proxies (Fig. 1c).

Climate model simulations, on the other hand, are physically plausible realizations of climate dynamics that are simplifications of reality, a fundamental aspect that should not be forgotten during data–model comparison. Models are generally calibrated to instrumental data so that LGM simulations are independent tests of their ability to represent a climate different from the present. Model design choices lead to differences among the simulations of LGM temperature that are on a par with differences among proxies (Fig. 2). Among these design choices, the coarse spatial resolution of climate models leads to difficulties in accurately resolving small-scale features, such as eastern boundary currents or upwelling systems: areas where the data–model mismatch tends to be large (Fig. 2). Moreover, modelers have to make choices in terms of boundary conditions (in particular ice sheets) and in the set-up of the model used (e.g. including dynamic vegetation, interactive ice sheets). And finally, most simulations of LGM climate are performed as equilibrium

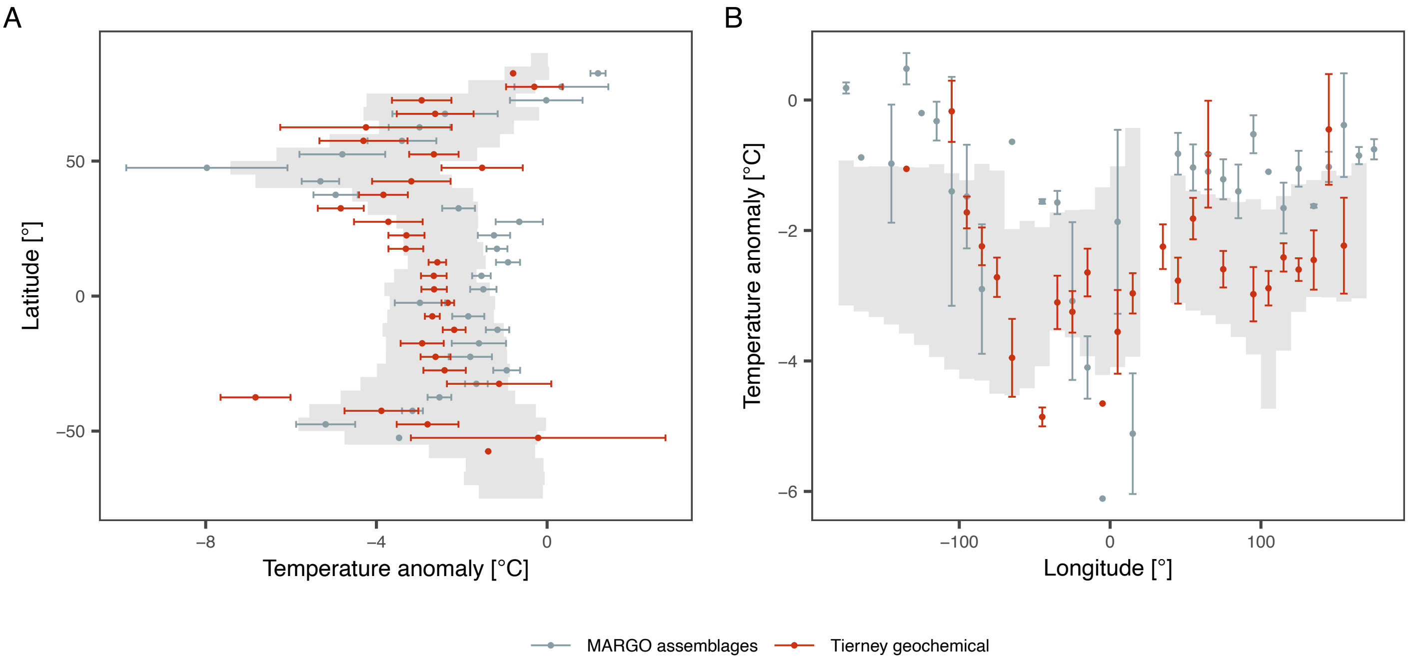

Figure 2: (A) Zonal and **(B)** tropical meridional (15°N–15°S) mean annual LGM sea surface temperature anomalies in reconstructions (colors) compared to PMIP4 inter-model spread (gray background). Reconstructions and simulations are binned at the same resolution; errorbars represent standard errors of the mean.

experiments (without history/memory), whereas in reality the LGM was the culmination of a highly dynamic glacial period.

Ways forward

Proxy attribution can be addressed directly through increased understanding of the proxy sensor. Most seawater temperature proxies are based on biological sensors, and better understanding of their ecology is likely to help constrain the origin of the proxy signal (Jonkers and Kucera 2017). Alternatively, uncertainty in the attribution may also be accounted for in the calibration (e.g. Tierney and Tingley 2018). However, neither approach explicitly considers the dependence of the proxy sensor itself on climate. Forward modeling of the proxy signal is a promising way to address this issue, but sensor models for seawater temperature proxies are still in their infancy (Kretschmer et al. 2018).

Apart from the proxy attribution uncertainties, reconstructions are spatially distributed in an uneven way. For both historical and geological reasons most of the reconstructions stem from the North Atlantic Ocean and from continental margins (Fig. 1) and despite almost half a century of focus on reconstructing the LGM temperature field, progress in filling the gaps has been slow. This is in part due to the depositional regime that characterizes large parts of the open ocean. Sedimentation rates and/or preservation in these areas are often insufficient to resolve the LGM. Therefore, it would seem that rather than aiming for a reconstruction of global mean temperature, a more fruitful approach would be to focus on areas where the reconstructions can better constrain the simulations, for instance in areas where models show the largest spread or bias.

At the same time, uncertainty, including structural uncertainty in model simulations has to be considered more explicitly. It is now more and more common to run large ensembles of model simulations, thereby sampling parametric uncertainties and/or uncertainties in scenarios, or in initial or boundary conditions. Such an approach, together with the multi-model approach that PMIP has fostered, helps to better describe the uncertainty of the model simulations, and better quantify model–data (dis)agreement. Taking uncertainty in the models and in the paleodata into account, simulations and reconstructions can be integrated through data assimilation (Kurahashi-Nakamura et al. 2017; Tierney et al. 2020). Offline approaches to obtain full field reconstructions are valuable but difficult to validate. Furthermore, such methods require some overlap between reconstructions and simulations to obtain reconstructions that are not only physically plausible but also realistic. Online data assimilation is possibly the most direct way of using the strengths of the models and the data to learn about the climate system.

Outlook

Avenues to increase the value of paleoclimate data to inform climate models would be to better exploit the multidimensionality of the paleorecord. Archives of marine climate often hold more information than just temperature. Because many archives co-register different climate-sensitive parameters, (age) uncertainty can be reduced to some extent. Thus, approaches carrying out comparison, or data assimilation, in multiple dimensions (Kurahashi-Nakamura et al. 2017) are likely to provide more constraints on the reason for model-data discrepancies.

Although the LGM time slice has proved a useful and effective way to compare models and data, the paleoclimate record is in fact four-dimensional, as it traces changes through time and space. Climate models can now increasingly simulate transient change over long periods of time. The future of climate model–data integration therefore likely belongs to timeseries comparisons (Ivanovic et al. 2016). Timeseries can be used to assess the temporal aspect of climate variability and the large-scale evolution of climate. With the increasing availability of multi-proxy/parameter data synthesis (Jonkers et al. 2020), even the prospect of four-dimensional data–model comparison is coming closer to reality.

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PMIP contributions to understanding the deep ocean circulation of the Last Glacial Maximum

Sam Sherriff-Tadano[1] and Marlene Klockmann[2]

Simulations of the Last Glacial Maximum (LGM) within PMIP significantly improved our understanding of the mechanisms that control the Atlantic Meridional Overturning Circulation (AMOC) in a glacial climate. Nonetheless, reproducing the reconstructed shallowing of the LGM AMOC remains a challenge for many models.

AMOC at the LGM

The Last Glacial Maximum (LGM; ca. 21,000 years ago) was a period within the last glacial cycle with very low greenhouse gas concentrations and maximum ice volume. The global climate was much colder than the modern climate, and the state of the Atlantic Meridional Overturning Circulation (AMOC) was very different as a consequence of the glacial climate forcings. In the modern climate, North Atlantic Deep Water (NADW), which forms in the Nordic and Labrador Seas, fills the deep North Atlantic basin. In contrast, proxy data such as carbon and neodymium isotopes, suggest that during the LGM, a large fraction of NADW in the deep Atlantic basin was replaced by Antarctic Bottom Water (AABW), which is formed in the Southern Ocean. As a result, the glacial AMOC was shallower than the modern AMOC (Lynch-Stieglitz 2017). The strength of the LGM AMOC is harder to reconstruct; proxies of AMOC strength support a glacial AMOC state ranging from weaker than or similar to today (e.g. Lynch-Stieglitz 2017). Nonetheless, the LGM provides a good opportunity to understand the AMOC response to climate changes as well as to evaluate the capability of comprehensive atmosphere-ocean coupled general circulation models (AOGCM) to reproduce AMOC states which are very different from today.

LGM AMOC from PMIP1 to PMIP4

Throughout the four PMIP phases, simulating the LGM AMOC has remained a challenge. While the respective AOGCMs tend to agree on large-scale changes in surface cooling patterns, the simulated AMOC changes differ strongly between models and PMIP phases, and most models cannot simulate the reconstructed shallower LGM AMOC. The first official LGM AMOC model intercomparison was conducted as part of PMIP2 (Weber et al. 2007); this intercomparison included three additional simulations from AOGCMs that adopted the PMIP1 protocol. These simulations are referred to as PMIP1.5 simulations. Here, we include a fourth PMIP1.5-type simulation (Kim 2004) that was not part of the original intercomparison.

In Figure 1, the results of various PMIP phases are shown. Out of nine PMIP1.5/PMIP2 models, four simulated a shallower and weaker LGM AMOC, three a stronger and deeper LGM AMOC, one simulated a stronger LGM AMOC with no changes in depth, and one a deeper and slightly weaker LGM AMOC. In PMIP3, the inter-model spread was much smaller, but fewer models agreed with reconstructions. Only one model simulated a shallower LGM AMOC, one simulated no change in depth, and all other models simulated a much deeper LGM AMOC. All models simulated a stronger LGM AMOC. In PMIP4, most models simulated a stronger LGM AMOC, while all but two models simulated very minor changes in the depth (Kageyama et al. 2021).

What have we learned from PMIP?

The PMIP ensembles have provided many plausible hypotheses regarding the mechanisms that control the LGM AMOC. While there are still open questions, it is possible to assemble some pieces of the puzzle to form a consistent picture. The PMIP1.5/PMIP2 simulations suggested that the meridional density contrast between NADW and AABW source regions plays a key role in controlling the AMOC state (Weber et al. 2007): the glacial AABW needs to become much denser than the NADW in order to generate strong enough stratification in the deep ocean, thereby inducing a shallower AMOC. Starting from there, key processes

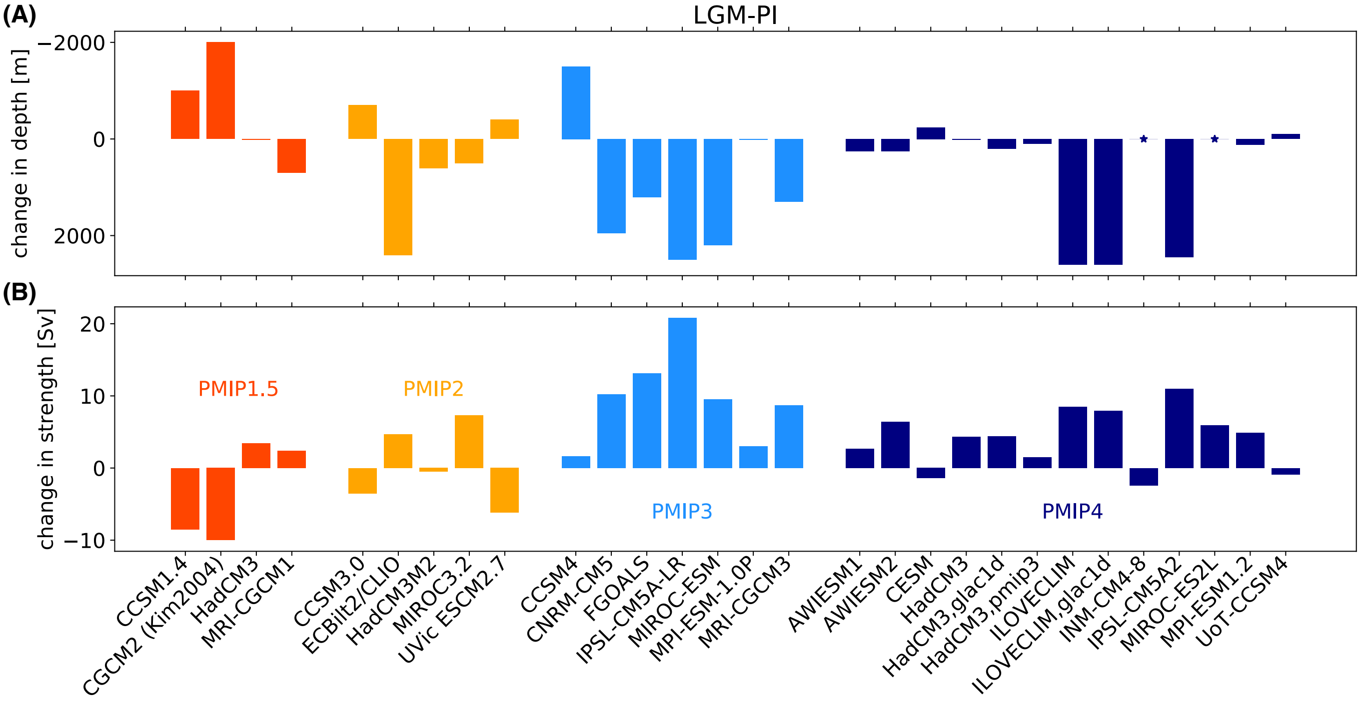

Figure 1: (A) AMOC depth and **(B)** strength at the LGM compared to pre-industrial (PI) in the PMIP generations 1.5–4. The values for PMIP1.5 and PMIP2 are taken from Weber et al (2007) and Kim (2004); values for PMIP3 and PMIP4 are taken from Kageyama et al (2021). AMOC strength is defined as the maximum transport in Sv at 30°N. AMOC depth is defined as the depth of the interface between the NADW and AABW cell at 30°N for CGCM2, PMIP3, and PMIP4, and at the Southern end of the Atlantic basin for PMIP1.5 and PMIP2. Negative values in AMOC depth and strength correspond to shoaling and weakening of LGM AMOC compared to PI. Asterisks indicate that the NADW cell covers the entire water column in both PI and LGM simulations.

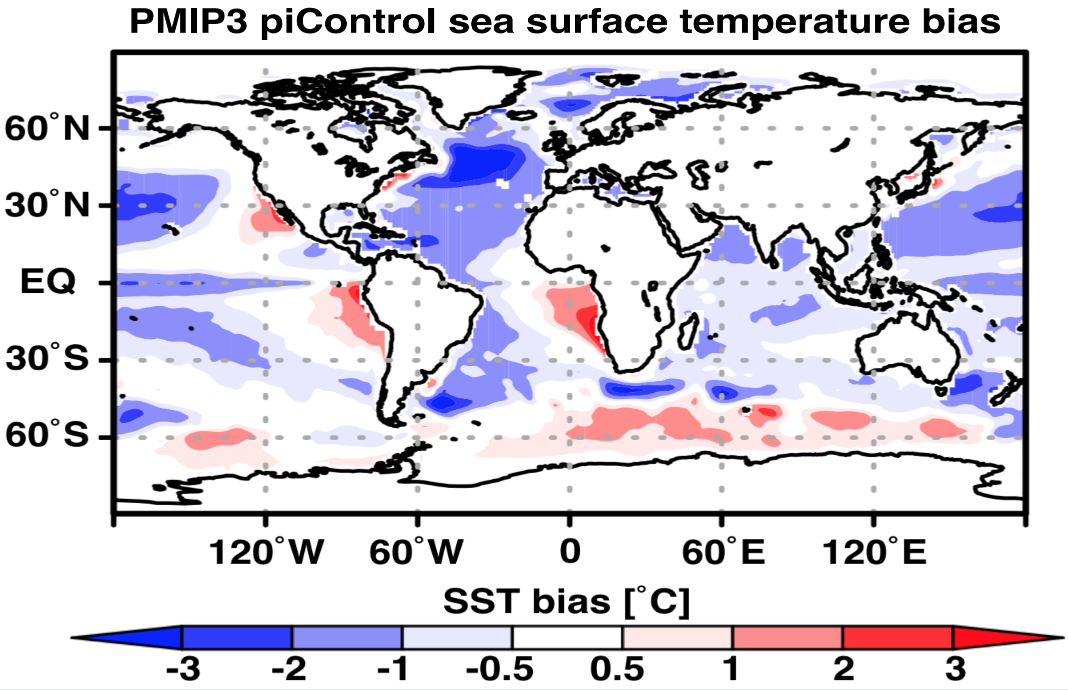

Figure 2: PMIP3 model mean annual sea-surface temperature bias in pre-industrial climate simulations compared with World Ocean Atlas 2013 (nodc.noaa.gov/OC5/woa13/woa13data.html).

that modify the meridional density gradient under LGM conditions can be identified.

In the Southern Hemisphere, buoyancy loss through sea-ice export and brine release in the Southern Ocean associated with low CO_2 concentrations are key for the formation of dense AABW (Klockmann et al. 2016). Models with a shallower LGM AMOC tend to have a very strong buoyancy loss over the Southern Ocean (Otto-Bliesner et al. 2007). An additional factor could be the duration of the spin-up: a sufficient integration time is required to account for the slow penetration and densification of the deep Atlantic by AABW (Marzocchi and Jansen 2017).

In the Northern Hemisphere, key processes are changes in the North Atlantic freshwater budget, sea-ice cover, and surface winds. Stronger LGM surface winds over the North Atlantic caused by the Laurentide ice sheet increase the density and formation of NADW and induce a strong and deep LGM AMOC (Muglia and Schmittner 2015; Sherriff-Tadano et al. 2018). Extensive sea-ice cover or increased freshwater input in the NADW formation sites reduces the buoyancy loss and leads to less dense NADW and a weaker and shallower AMOC (Oka et al. 2012; Weber et al. 2007). Depending on the model specifics, these mechanisms might compensate differently and lead to very different LGM states (Klockmann et al. 2018).

Few PMIP4 models simulate a substantial deepening of the LGM AMOC (Fig. 1). This improvement with respect to PMIP3 may imply that the models are making some progress in capturing the important processes and getting the balance right. Future analyses of the PMIP4 simulations will show whether this confidence is justified.

Discussion

The current ensemble of simulations across all PMIP phases contains 29 simulations from 26 different models. Only seven of these simulations capture the shallower LGM AMOC, and five were performed with models from the CCSM family (Fig.1). It is, therefore, reasonable to say that it remains a challenge for most AOGCMs to reproduce an LGM AMOC in agreement with reconstructions. Why is it so difficult?

There are several factors that affect the LGM AMOC, either because they affect the key mechanisms described above or through additional mechanisms. These factors are, for example, uncertainties in the ice-sheet reconstructions, the magnitude and representation of glacial tidal mixing (Peltier and Vettoretti 2014), or assumptions of the AMOC being in a quasi-equilibrium state with 21ka climate forcing (Zhang et al. 2013). The PMIP4 protocol explicitly addressed the uncertainties in the ice-sheet reconstructions by offering a choice between three different reconstructions: ICE6G, GLAC1D, and the previous PMIP3 ice sheets (Kageyama et al. 2017 and references therein). Most PMIP4 simulations were run with the ICE6G ice sheets; only two models were used for multiple simulations with different ice sheets. In these two models, the different ice-sheet reconstructions make only a small difference for the simulated LGM AMOC, but this need not be the case for other models or other ice-sheet reconstructions.

Additional problems could arise from biases in the pre-industrial control simulations. Figure 2 shows sea-surface temperature (SST) biases in pre-industrial climate simulations from PMIP3 models. Large SST biases are evident over the Southern Ocean and northern North Atlantic, where AABW and NADW are formed, respectively. A recent study with an AOGCM showed, in fact, that an improvement in modern SST biases over the Southern Ocean could help to reproduce the shallower LGM AMOC by enhancing the formation of AABW (Sherriff-Tadano et al. submitted). NADW formation areas experience large changes in surface winds at the LGM; hence, biases in this region require additional attention as well.

In the future, sensitivity experiments such as parameter ensembles, or partially coupled experiments, may provide useful information regarding the role of uncertain climate parameters and model biases in LGM simulations. Increased direct modeling of carbon isotopes and relevant tracers will be key for model–data comparisons, and to better understand and constrain the LGM AMOC, including its strength.

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Mineral dust in PMIP simulations: A short review

Fabrice Lambert[1,2,3] and Samuel Albani[4]

We review the advances in paleoclimatic dust simulations and describe recent developments and possible future directions for the paleoclimatic dust community within the Paleoclimate Modelling Intercomparison Project.

Mineral dust aerosols (hereafter "dust") are an important component of the climate system. Airborne dust particles are usually smaller than 20 µm and both scatter and absorb incoming solar radiation as well as outgoing thermal radiation, thus, directly altering Earth's radiative balance. Dust particles can also act as ice and cloud condensation nuclei altering cloud lifetime, or darken snowy surfaces after deposition, thus affecting planetary and surface albedo. Finally, dust particles are composed of various minerals, some of which play an important role in biogeochemical cycles both on land and in the ocean. This mineral makeup also determines the impact of dust on radiation and clouds (Maher et al. 2010).

Deserts and semi-arid regions are the main sources of dust to the atmosphere. They are heterogeneously distributed throughout the world, with the largest sources in the subtropics. Dust particles are entrained in the atmosphere by surface winds and reach the higher levels of the troposphere through ascending air currents, and from there they can be transported across the globe. Dust particles are removed from the air by both dry (gravitational settling) and wet (washout through precipitation) deposition processes. Local atmospheric dust concentration and surface deposition therefore depend on the distance to the source, source emission strength, wind speed and direction, and the hydrological cycle. They are also not constant throughout the year, but depend on emission event and washout frequency (Prospero et al. 2002).

Unlike well-mixed greenhouse gases, the climatic effects of dust vary seasonally and regionally and are not well represented by global averages. Close to the source regions, particle concentrations are very high, and can be associated with strong surface direct radiative effects of over 50 W/m^2. The net effect at the top of the atmosphere can be positive or negative, depending on the ratio of small and large particles, the height of the dust layers, particle mineralogy, and the albedo of the underlying surface (Albani and Mahowald 2019; Maher et al. 2010). Over micronutrient-limited regions of the oceans, dust particles are an important source of minerals like iron, and can thus modulate the strength of the biological pump and affect the global carbon cycle (Hain et al. 2014; Lambert et al. 2021).

Dust in PMIP simulations

Interest in dust as an important aerosol with significant orbital- and millennial-scale variability and potential climate feedbacks emerged in the 1970s and 1980s and soon found its way into the climate modeling community. The first global dust simulations for the Last Glacial Maximum (LGM) were performed in the early 1990s (Joussaume 1993). Over the next three decades, our understanding of the dust cycle improved, thanks to more abundant observations from modern platforms and paleoclimate records (Maher et al. 2010). This allowed for improvements in climate models and their embedded dust schemes, with new observational data, data syntheses, and model development spurring each other on (Albani et al. 2015; Maher et al. 2010; Mahowald et al. 2006).

The paleoclimate dust community has strongly focused on the LGM period, owing to the large dust flux increase marked particularly in mid- and high-latitude paleoarchives. However, only a few modeling groups have tried to simulate the LGM dust cycle, with a varying level of validation against modern and paleodata. Estimates of dust emissions, load, direct radiative effects, and impacts on the carbon cycle through iron fertilization are summarized in Figure 1. The large spread in results can mainly be attributed to differences in the representation of dust emission and deposition mechanisms, differences in boundary conditions (including vegetation), inclusion of glaciogenic (formed by glacier abrasion) dust sources, different aerosol size ranges and optical properties, and assumptions about dust-borne iron solubility and bioavailability.

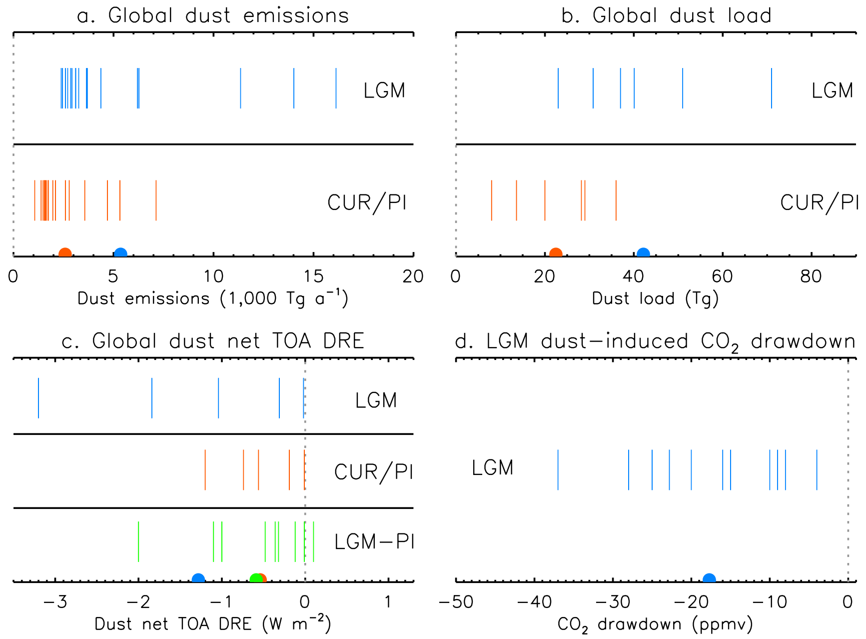

Figure 1: Synthesis of global metrics from LGM dust simulations, adapted from Albani et al. (2018). Vertical bars represent the results of individual experiments. The semi-circles on the x-axes mark the average of the respective model ensembles. The vertical gray dotted lines mark the zero value on the x-axis. CUR/PI indicates either current or pre-industrial simulations. TOA DRE stands for Top Of Atmosphere Direct Radiative Effect.

Overall, the central estimates from these simulations suggest that global LGM dust probably doubled in load compared to the late Holocene. This likely contributed about 25% (–20 ppmv) to the CO_2 drawdown through iron fertilization of the oceans and had a direct radiative forcing of –0.6 W/m^2, slightly lower than the main other forcing mechanisms (greenhouse gases: –2.8 W/m^2, ice sheets and sea level changes: –3.0 W/m^2; Albani et al. 2018). However, direct radiative forcing estimates of global dust average both positive and negative values; locally and regionally, the magnitudes can be much stronger (Albani and Mahowald 2019).

The mid-Holocene (MH) had received far less attention until recently, when it was found that marine sediment records indicated that North African dust emissions were two to five times lower during the "green Sahara" phase than during the late Holocene. These findings motivated the first efforts to simulate and reconstruct the MH global dust cycle (Albani et al. 2015). New idealized and realistic experiments quickly followed, highlighting the role of dust on the ITCZ and monsoon dynamics (e.g. Albani and Mahowald 2019; Braconnot et al. 2021; Hopcroft et al. 2019).

Although the aforementioned simulations were performed using PMIP climate models (or adaptations thereof), it was only recently that CMIP/PMIP protocols started to include dust forcings beyond the use of prescribed pre-industrial (PI) or present day (PD) fields. The importance of replacing the PI and PD fields with period-accurate fields (including additional glaciogenic sources in LGM simulations) is evidenced in Figure 2, with LGM surface dust depositions generally several orders of magnitude larger than during the PI period. Although the inclusion of glaciogenic sources in LGM simulations may not appear crucial for global radiative forcing, they are very important for local and indirect effects (Lambert et al. 2021).

The new CMIP6/PMIP4 protocol allows for dust to vary across climates, either as a prognostically emitted species, or prescribed based on previous paleoclimate simulations or reconstructions (Kageyama et al. 2017; 2018; Otto-Bliesner et al. 2017). As the first PMIP4 papers focused on dust begin to emerge (Braconnot et al. 2021), these efforts are leading to a new exciting phase. We hope that soon many more groups will start to contribute to the effort of understanding the role of dust in the climate system, both as a tracer of past changes of land-surface and atmospheric conditions, as well as an active agent affecting local, regional, and global climate in various ways.

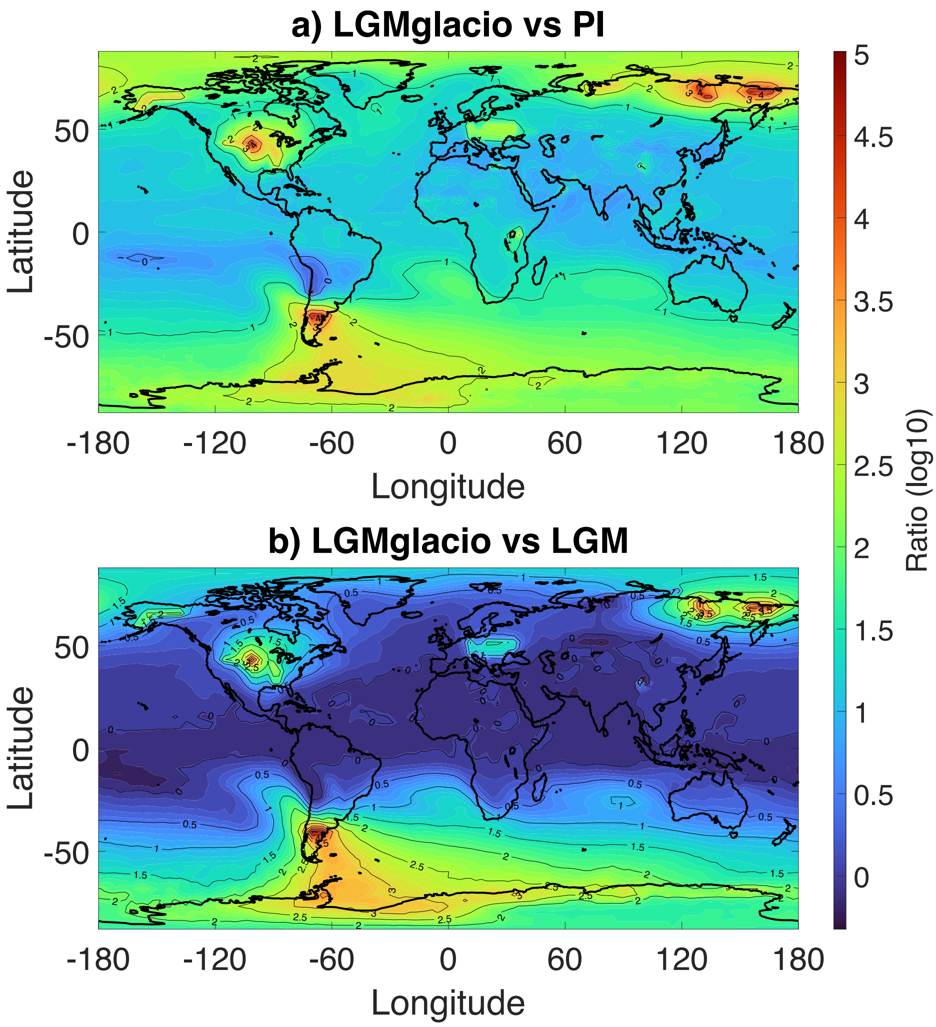

Figure 2: Simulated surface dust deposition ratios (Ohgaito et al. 2018). **(A)** Ratio of the LGM simulation including glaciogenic sources to the PI simulation; **(B)** ratio of the LGM simulations with and without glaciogenic sources (note the logarithmic ratio scale).

Future Directions

Recent studies have investigated more complex and detailed dust-climate interactions. These include the dust-vegetation-monsoon nexus (Hopcroft et al. 2019), the effects of dust on snow albedo (Albani and Mahowald 2019; Mahowald et al. 2006; Ohgaito et al. 2018), and the regional features of dust on biogeochemistry, radiative effects and forcing, as well as the dynamical response of the climate system to these forcings (Albani and Mahowald 2019; Braconnot et al. 2021; Lambert et al. 2021).

The newest generation of climate models feature developments of great interest for paleoclimatic dust simulations. These include the incorporation of more realistic particle sizes and optical properties (Albani and Mahowald 2019; Hopcroft et al. 2019) and indirect effects on clouds (Ohgaito et al. 2018), as well as coupling of dust to ocean biogeochemistry, iron processing during atmospheric transport, and explicit representation of particle mineralogy (Hamilton et al. 2019). In its latest iteration, PMIP has been expanding from the mainstay MH and LGM periods to include further equilibrium simulations and transient simulations. Transient simulations are of particular interest to the dust community to investigate the variability and timing of occasional abrupt variations recorded in dust records. These were shown to potentially affect the global carbon cycle on short timescales (Lambert et al. 2021), and additional short-term feedbacks are likely.

To meet future challenges as a community, it is important to highlight the need for interaction and cooperation between the empirical and modeling communities. We stress the need for feedback between the two for project planning. Data syntheses are an important and necessary bridge between empirical measurements and simulations. Ongoing work is expanding the existing Holocene dust synthesis (Albani et al. 2015) to provide a comprehensive dust database of timeseries of dust-mass accumulation rates, with information about the particle-size distribution, over the last glacial-interglacial cycle; it is hoped that this will address some of the needs of the paleoclimate modeling community.

Recently, a new PMIP focus group on dust was launched, with the aims to: (1) coordinate a dust synthesis from PMIP4 experiments and (2) promote the definition of the experimental design for CMIP7/PMIP5 dust experiments. The group may also provide data as a benchmarking tool and boundary conditions for future equilibrium and transient simulations, should this be aligned with the scopes of the next phase. Interested parties are encouraged to contact the authors to participate in this effort.

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PMIP-carbon: A model intercomparison effort to better understand past carbon cycle changes

Nathaelle Bouttes[1], F. Lhardy[1], D.M. Roche[1,2] and T. Mandonnet[1]

Past carbon cycle changes, especially during the Last Glacial Maximum 21,000 years ago, remain largely unexplained and difficult to simulate with numerical models. The ongoing PMIP-carbon project compares results from different models to improve our understanding of carbon cycle modeling.

PMIP-carbon

Atmospheric CO_2 concentration plays a major role for the Earth's climate as this is one of the main greenhouse gases. Moreover, the CO_2 level directly influences the ocean pH with large impacts on marine biology. Hence, understanding the carbon cycle, and its past changes, is critical. The carbon cycle at short timescales corresponds to the exchange of carbon between the main carbon reservoirs: ocean, atmosphere, terrestrial biosphere, surface sediments, and permafrost (Fig. 1). The atmospheric CO_2 concentration depends on the carbon fluxes and how much carbon is stored in the various reservoirs.

We know from proxy data that the atmospheric CO_2 level has varied largely in the past. In particular, measurements of CO_2 concentration in air bubbles trapped in ice cores indicate lower values of ~190 ppm during cold glacial periods compared to values of ~280 ppm during warmer interglacial periods (Bereiter et al. 2015 and references therein). Many studies have focused on explaining the low CO_2 during the Last Glacial Maximum (LGM), but no consensus on the main mechanisms has been reached yet. Most models do not simulate such a low value, especially when they are simultaneously constrained by other proxy data such as carbon isotope values. Nonetheless, several potential mechanisms have emerged (Bouttes et al. 2021). Firstly, the ocean is assumed to play a major role; this is the largest reservoir relevant for these timescales, meaning that any small change in its carbon storage could result in large modifications in the atmospheric CO_2 concentration. In addition, proxy data, such as carbon isotopes, seem to indicate changes in ocean dynamics and/or biological production. Besides the ocean, the sediment and permafrost reservoirs have also expanded during the LGM, helping to decrease atmospheric CO_2. Conversely, the terrestrial biosphere lost carbon at the LGM, indicating that even more carbon was taken up by the other reservoirs.

Until now, the different working groups within PMIP have mainly focused on climate without considering carbon cycle changes. A new project was recently defined as part of the deglacial working group in PMIP4 to tackle the issue of past carbon cycle changes. The objectives of this model intercomparison are to evaluate model responses in order to better understand the changes, help find the major mechanisms responsible for the carbon cycle changes, and improve models. As a starting point, the project focuses on the LGM, hence the protocol follows the main LGM PMIP4 guidelines for greenhouse gases, insolation, and ice sheets, as closely as possible (Kageyama et al. 2017). The same numerical code should be used for the pre-industrial period and the LGM, including the carbon cycle modules.

First results: Carbon storage changes in the main three reservoirs

So far, three GCMs (MIROC-ES2L, CESM and IPSL-CM5A2), four EMICs (CLIMBER-2, iLOVECLIM, MIROC-ES2L, LOVECLIM, UVic), and one ocean only GCM (MIROC4m) have been participating in PMIP-carbon. As not all models have all carbon cycle components (particularly sediments and permafrost), this first intercomparison exercise is focused on simulations with the ocean, terrestrial biosphere, and atmosphere carbon reservoirs only.

It should be noted that there are often two CO_2 variables in models: one for the radiative code—generally fixed to a prescribed value to ensure a correct climate—and another one for the carbon cycle. The latter can be prescribed to the same values as the CO_2 for the radiative code (yellow in Fig. 2a) or can be allowed to evolve freely in the carbon cycle model based on the fluxes with the other carbon reservoirs (purple and blue in Fig. 2a).

The most striking result is that in models that do not prescribe atmospheric CO_2 and

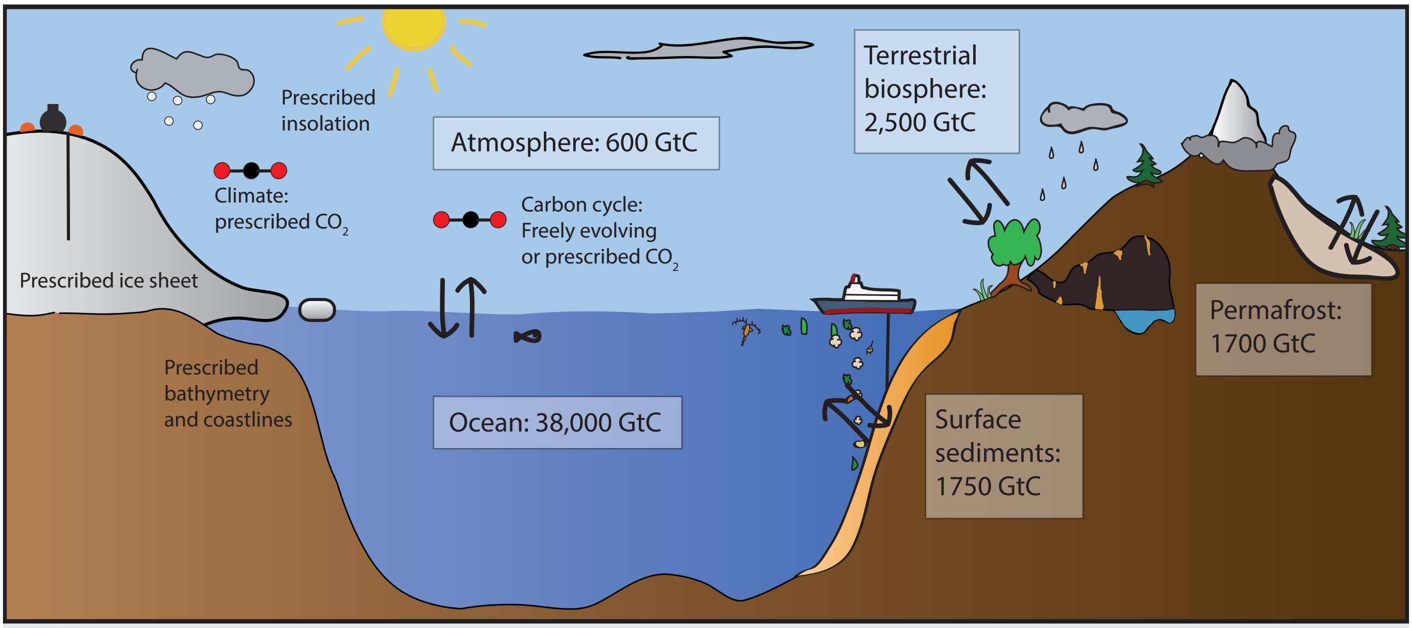

Figure 1: Schematic of the short-term carbon cycle with the main reservoirs and their estimated carbon content at the pre-industrial. The long-term processes (longer than 100 kyr) such as volcanism or silicate weathering are not considered. Also indicated are the boundary conditions imposed in climate models and the two types of simulation of atmospheric CO_2.

include the terrestrial biosphere (purple in Fig. 2a), the LGM CO$_2$ concentration is higher than during the pre-industrial, rather than lower, as indicated by the data. In the ocean-only model (blue in Fig. 2a), the CO$_2$ is lower at the LGM, but the amplitude is very small compared to the data.

In agreement with data reconstructions, the land carbon storage (vegetation and soils) decreases from the pre-industrial to the LGM (Fig. 2b) due to the colder LGM climate and larger ice sheets. The amplitude of this decrease varies between models, possibly due to differences in the terrestrial biosphere modules, and differences in the simulated climate (Kageyama et al. 2021). However, this could also result from different prescribed boundary conditions, such as coastlines and ice-sheet extents, both of which yield different land surfaces at the LGM and, hence, more or less space for vegetation to grow.

In the ocean, model results are more variable. Most models with prescribed atmospheric CO$_2$ (except LOVECLIM) indicate a loss of ocean carbon storage, at odds with the general view of increased carbon storage. In the models with freely evolving CO$_2$, the ocean stores more carbon (a similar result is seen in LOVECLIM simulations), but this effect is far too small to counteract the loss of carbon from land. This, therefore, results in atmospheric CO$_2$ values far outside of the range of the data.

The carbon storage in the ocean is the result of many competing processes. For example, on the one hand, lower temperatures increase CO$_2$ solubility, and increased nutrient concentrations due to lower sea level (of ~130 m) yields more productivity, both lowering atmospheric CO$_2$. On the other hand, the increased salinity due to sea-level change tends to increase atmospheric CO$_2$. While these mechanisms are relatively well understood, the change of ocean circulation is still a major issue in models (Kageyama et al. 2021). PMIP-carbon aims to understand these model differences and highlight missing processes in the ocean.

One result that has already emerged is the importance of the ocean volume: at the LGM the ocean volume was reduced by ~3% due to the sea-level drop, yielding a reduced ocean carbon reservoir size (Lhardy et al. 2021). This means that the ocean (by means of other processes), sediments, and permafrost have to store even more carbon to counteract this effect. For modeling groups, it also means that accounting for realistic bathymetry and coastline changes is essential; at the very least, the changes of oceanic variable concentrations such as alkalinity in models must be treated with great care.

Looking forward

In the short-term, PMIP-carbon will aim for more in-depth analyses of the ocean and terrestrial biosphere to understand the differences between models using existing (and ongoing) simulations.

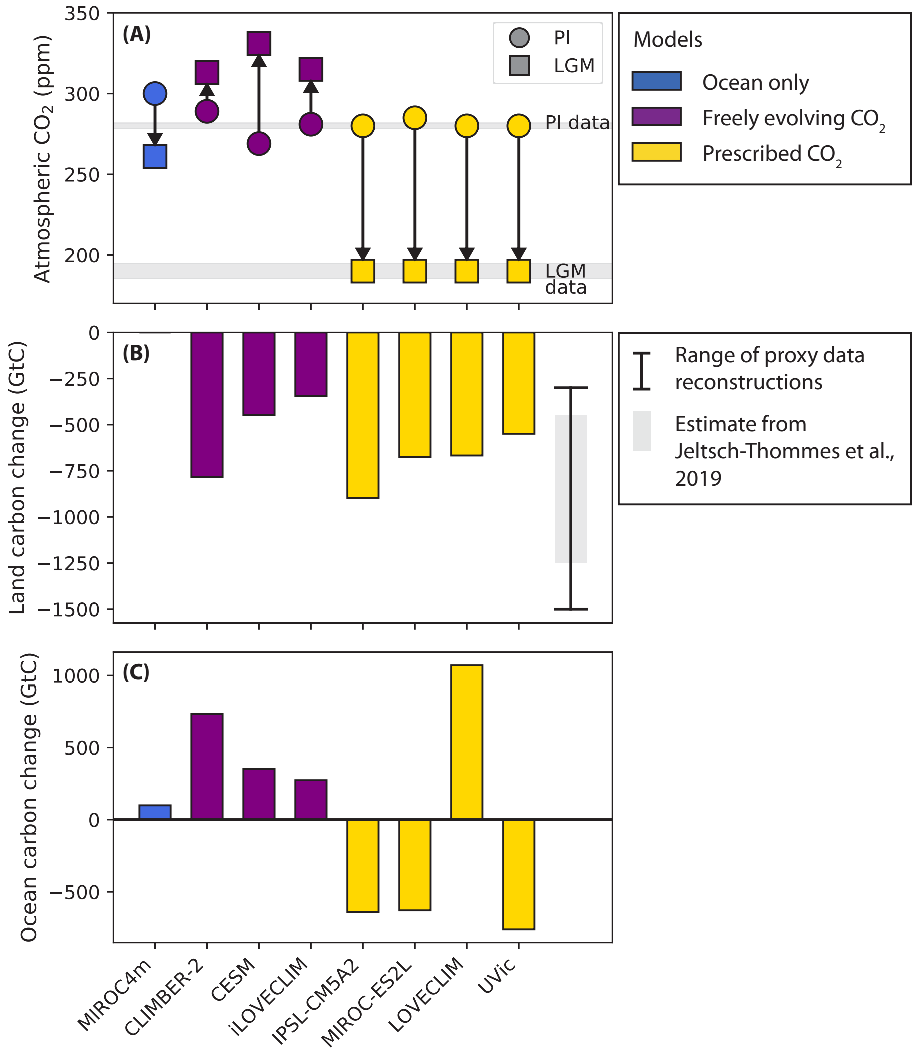

Figure 2: Carbon in three reservoirs: **(A)** Atmospheric CO$_2$ concentration (ppm), **(B)** terrestrial biosphere carbon change from PI to LGM (GtC) and **(C)** ocean carbon change (GtC). CO$_2$ data from Bereiter et al. (2015). Reconstruction of terrestrial biosphere carbon change using proxy data ranging from 300 GtC with carbon isotopes to 1500 GtC from pollen records (see Jeltsch-Thommes et al. 2019 for a more in-depth discussion).

However, the atmospheric CO$_2$ change that has to be explained is actually more than just the observed 90 ppm fall. Several changes tend to increase the CO$_2$ concentration, such as the loss of terrestrial biosphere, or the reduced ocean volume due to lower sea level. Hence, in addition to oceanic processes, other carbon reservoirs, such as sediments and permafrost, will be essential to explain the lower atmospheric CO$_2$. In the future, these additional components will be added to the protocol and their effects will be compared between models.

Finally, even if the LGM is an interesting period to study, the long-term objective of PMIP-carbon is to also compare model results during other periods such as the last deglaciation for which more challenges will arise: on top of the large glacial-interglacial 90 ppm change, the transition shows rapid changes in the carbon cycle which are not yet well understood (Marcott et al. 2014).

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Towards a better understanding of the latest warm climate: The PMIP Last Interglacial Working Group

Bette L. Otto-Bliesner[1], P. Scussolini[2], E. Capron[3], M. Kageyama[4] and A. Zhao[5]

The Last Interglacial is one of the five priorities within the CMIP6-PMIP4 initiative. Its 127 kyr BP model experiment allows for an assessment of climate model fidelity during a period of Northern Hemisphere warmth, sea-level high stand, and regional hydroclimate changes.

The main changes in forcing during the Last Interglacial (LIG) as compared to present are in the latitudinal and seasonal distribution of incoming solar radiation. Differences in the orbital configuration between the LIG and modern resulted in pronounced insolation anomalies at the Northern Hemisphere (NH) summer solstice; these anomalies are latitudinally similar but much larger than those during the Holocene (Fig. 1).

Proxy records document that these insolation anomalies altered regional hydroclimates, e.g. by enhancing the summer monsoon precipitation over North Africa and southeast Asia during the Holocene (COHMAP 1988) and during interglacials of the last 224 kyr (Wang et al. 2008). Pollen and macro-fossil evidence indicate that in the mid-Holocene, the boreal forest extended farther north than today (Prentice et al. 2000) and during the LIG (CAPE-Last interglacial project members 2006) it extended to the Arctic coast, except in Alaska and central Canada. Ice cores and proximal marine records indicate that the Greenland ice sheet survived the warmer temperatures of the LIG, though with significantly reduced extent and volume (Sime et al. 2013).

CMIP, PMIP, and IPCC

Studying the Holocene, our current interglacial, has been a cornerstone of the Paleoclimate Modelling Intercomparison Project (PMIP) since the early 1990s (see Joussaume and Taylor, this issue; Braconnot et al. this issue), and has contributed to the evaluation of climate models starting with the Intergovernmental Panel on Climate Change (IPCC) Second Assessment Report in 1995 (see Kageyama et al. this issue, p. 68). Although the LIG had been on the radar of the IPCC since the first assessment report, it gained increasing attention in the fourth and fifth assessments (AR4 and AR5) due to its relevance for future projections of Earth system responses in a warm climate state. Indeed, the LIG was elevated to the AR4 Summary for Policymakers, which included these statements: "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." Furthermore, "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)."

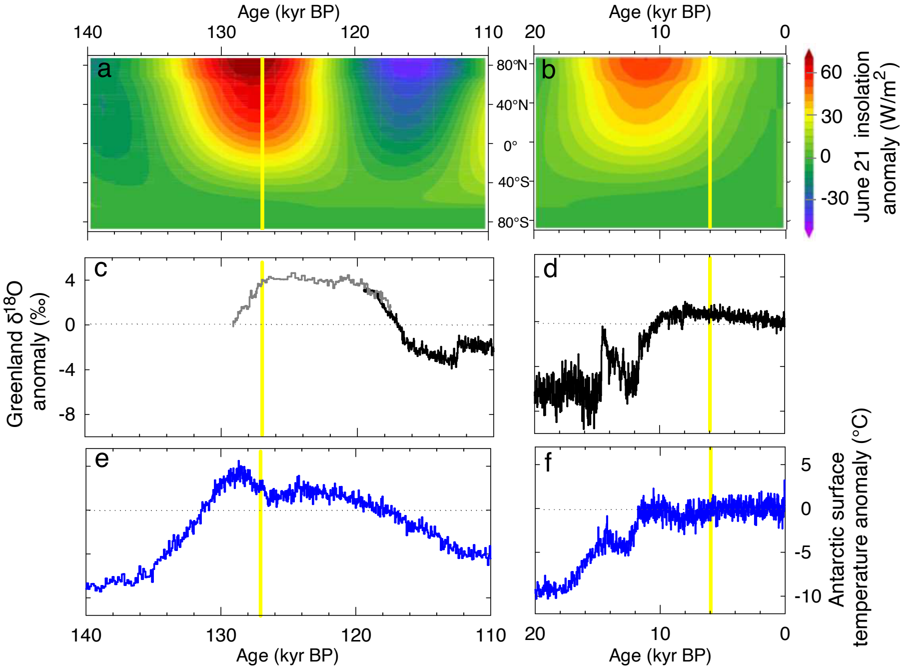

Figure 1: Insolation (Berger 1978) forcing and climate records of Antarctic surface temperature and Greenland δ^{18}O for the Last Interglacial (left) and Holocene (right). Anomalies are relative to their average value of the last 1000 years. Yellow lines indicate the periods selected for the lig127k and midHolocene simulations with the PMIP climate models. Figure modified from Otto-Bliesner et al. (2017).

The first multi-model ensemble for the LIG, as assessed in the AR5, compiled a set of 23 time-slice climate model simulations of the early LIG (130 to 125 kyr before present (BP)) by 14 models, encompassing a range of model complexities and various choices in the forcings (Lunt et al. 2013). However, the models in general underestimated the magnitude of the reconstructed temperature responses. It was, moreover, difficult to use these results to assess model reliability for simulating feedbacks for a warm climate state, as the models in this set of simulations for the LIG were mostly older and/or lower-resolution versions of the models used for the future projections in the Climate Modelling Intercomparison Project (CMIP) Phase 5 and in IPCC's AR5.

To provide more solid results, and to improve comparability with other simulations, such as of future climate, a coordinated LIG experiment was proposed as a CMIP6-PMIP4 simulation, setting a common experimental protocol for modeling groups to run with the same model and same resolution as the CMIP6 DECK (Diagnostic, Evaluation and Characterization of Klima) simulations (Eyring et al. 2016; Otto-Bliesner et al. 2017). At the "Warm extremes" workshop of the PAGES QUIGS working group in Cambridge in 2015 (pastglobalchanges.org/calendar/26910), the proxy and modeling communities identified the 127 kyr BP time slice as target for the CMIP6-PMIP4 LIG experiment. This concerted effort within both the model and data communities also led to a specific parallel effort to: (1) compile and build appropriate data time slices using ice-core and marine data and (2) provide guidance and recommendation on the use of existing data compilations to evaluate model runs (Capron et al. 2017).

Highlights of results from the CMIP6-PMIP4 lig127k experiment

Seventeen CMIP6-PMIP4 climate models completed the priority LIG experiment, called lig127k (see Otto-Bliesner et al. 2021 and Kageyama et al. 2021 for further details).

In response to the large boreal summer insolation anomalies with respect to the modern period, the NH high latitudes experience strong warming in June-July-August (JJA)

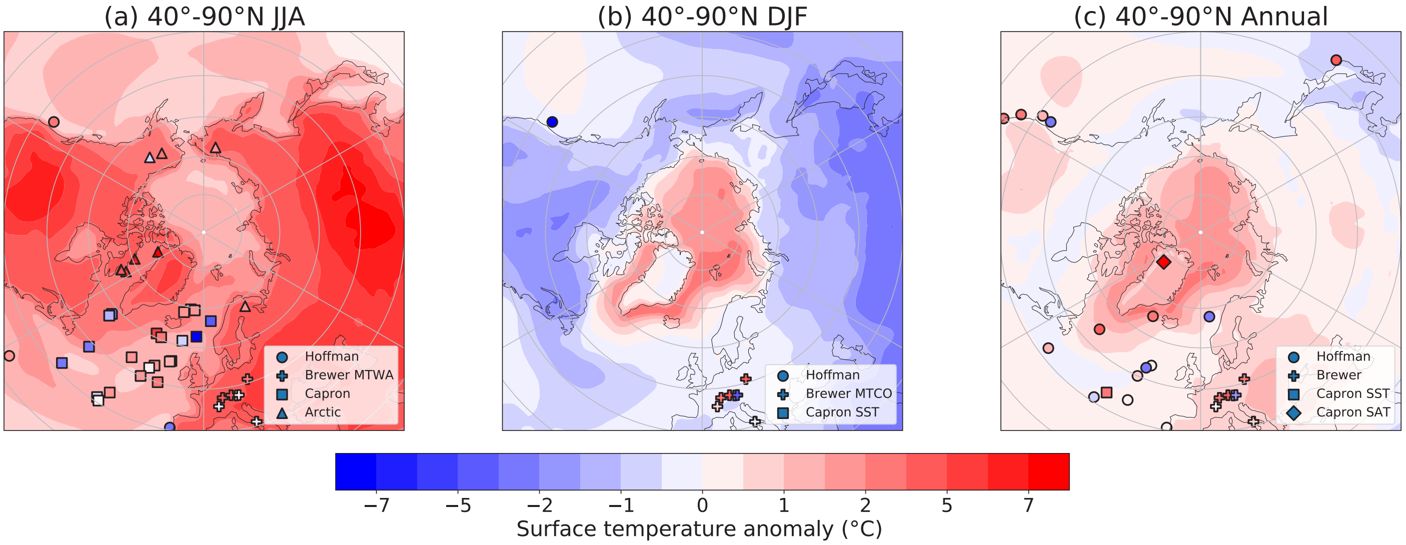

Figure 2: Comparison of results of the CMIP6-PMIP4 lig127k simulations and proxy records. Arctic (40°–90°N) surface temperature anomaly between 127 kyr BP to the preindustrial period from models (ensemble average in colors) and proxies (filled markers), doi.org/10.5194/cp-17-63-2021-supplement): **(A)** June-July-August (JJA), **(B)** December-January-February (DJF), **(C)** annual. The preindustrial reference is 1850 CE for model anomalies and for the data is 1870–1899. Figure modified from Otto-Bliesner et al. (2021).

relative to the pre-industrial (PI) simulations, with greater warming over the continents than the oceans (Fig. 2). This warming agrees well with reconstructions of summer temperatures except in the northwestern North Atlantic and Nordic seas, where marine reconstructions suggest significant cooling. One potential reason for this mismatch is that the highly uncertain meltwater flux from remnant ice sheets over Canada and Scandinavia is not included in the experiment protocol. Positive feedbacks with the cryosphere and ocean provide a "climate memory" effect that entails simulated high latitude summer warming to extend virtually year-round. The multi-model mean annual minimum sea ice extent in the Arctic is reduced by 50% relative to the PI simulations.

Precipitation simulated for the LIG exceeds that for the PI over most boreal land areas, agreeing with a significant majority of the available proxies (Scussolini et al. 2019). In particular, summer monsoonal precipitation and areal extent are enhanced over northern Africa, Arabian Peninsula, India, southeast Asia, northwestern Mexico, and the southwestern US. The opposite happens for the South American, South African, and Australian monsoons. The LIG monsoon changes are mostly of the same sign but of greater magnitude than those in the CMIP6-PMIP4 mid-Holocene simulations. Simulations of the LIG hydrology indicate potentially large changes in river discharge for several NH basins, possibly with the development of a much wider river network over North Africa (Scussolini et al. 2020).

Perspectives

Looking forward, much more could be done to understand the LIG.

Additional snapshots of the LIG and transient simulations would allow analyses of the temporal complexity of the LIG. Existing LIG compilations of temperature (e.g. Capron et al. 2017; Hoffman et al. 2017) should be extended to cover data-scarce areas of the globe, i.e. the Southern Hemisphere and e.g. the Indian and Pacific Oceans. Available terrestrial records often reflect the so-called LIG temperature optimum, which was not globally synchronous, and can hardly be associated with specific time slices during the LIG. Transient simulations would enable an integrated approach for addressing the model-to-proxy mismatch potentially due to chronological inaccuracy and bias of proxy records, and allow application of data assimilation methods. Continued development of sea-ice and hydroclimate reconstructions would provide additional metrics for comparison to model simulations.

Modeling the transition into the LIG from Termination 2 is required to understand how changes in climate and ice sheets during the preceding penultimate deglaciation (see Ivanovic et al. this issue) influenced the early LIG, e.g. the overshoot in Antarctic surface temperatures and atmospheric carbon dioxide, as well as possibly the collapse of the West Antarctic ice sheet early in the LIG. Modeling the late part of the LIG will be an important test of the ability of models to simulate the glacial inception. Other opportunities include using data and fully coupled climate-ice sheet models for simulating the transition into, during, and out of the LIG, to evaluate the feedbacks among the atmosphere, ocean, sea ice, biosphere, and ice sheets. In addition, coordination of an integrated model–data project of the earlier Marine Isotope Stage 11 interglacial would allow evaluation of the sensitivity of the Greenland ice sheet to warmth, which was more muted but lasted longer than at the LIG.

The CMIP6-PMIP4 lig127k results illustrate the potential of the LIG to inform future projections. More than half of the models simulate a LIG retreat of the August-September Arctic sea-ice edge, similar to the average August-September Arctic sea-ice edge of the last two decades. Additionally, the models that show a strong reduction in the Arctic minimum sea-ice area to LIG forcing also show it in the CMIP6 1pctCO2 coordinated experiment. Further, for several regions of the NH, observed and projected changes in atmospheric circulation and rain patterns, in turn linked to the ongoing trend in Arctic amplification of warming and the response of the polar jet stream, may have had counterparts in the LIG climate. Finally, further integrated model–data investigations are required to firmly elucidate whether the West Antarctic ice sheet was a major contributor to the large LIG global sea level and inform on its potential collapse in the future.

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PlioMIP: The Pliocene Model Intercomparison Project

Alan M. Haywood[1], H.J. Dowsett[2], J.C. Tindall[1], PlioMIP1 and PlioMIP2 participants

PlioMIP is a network of paleoclimate modelers and geoscientists who, through the study of the mid-Pliocene Warm Period (mPWP ~3.3–3.0 million years ago), seek to understand the sensitivity of the climate system to forcings and examine how well models reproduce past climate change.

Origins of PlioMIP

Building upon 20 years of geological data collection/synthesis by the US Geological Surveys' PRISM Project (Pliocene Research Interpretation and Synoptic Mapping), as well as early Pliocene climate-model studies, paleoclimate modelers and proxy-data experts gathered at the Goddard Institute for Space Studies in New York, USA, in 2007 to discuss the feasibility of a coordinated multi-model and proxy-data effort. A proposal for a PlioMIP working group within PMIP was endorsed at the 2008 PMIP meeting in Estes Park Colorado, USA (pastglobalchanges.org/calendar/128659). Through two discrete phases of work (PlioMIP1 and PlioMIP2), the project has produced, contributed, or inspired more than 100 articles in peer-reviewed literature. It has transformed our view of the Pliocene world, and underlined what the Pliocene tells us about climate and broader Earth system responses to atmospheric carbon dioxide levels akin to those of the present day.

The experimental designs for PlioMIP1 and 2 (Haywood et al. 2010; 2016) were underpinned by two generations of PRISM boundary conditions (geology.er.usgs.gov/egpsc/prism/index.html; Dowsett et al. 2010; 2016; Table 1). The 2010 PRISM3 reconstruction, used in PlioMIP1, was published at a global scale of 2° latitude x 2° longitude, and consisted of data on sea level, sea surface temperature, sea ice, deep ocean temperature, topography, vegetation, and land ice (Dowsett et al. 2010). The 2016 PRISM4 reconstruction, used in PlioMIP2, improved the global spatial resolution to 1° latitude x 1° longitude, adding soils and large lakes, and incorporated new methodologies/approaches in paleogeographic reconstruction (Dowsett et al. 2016).

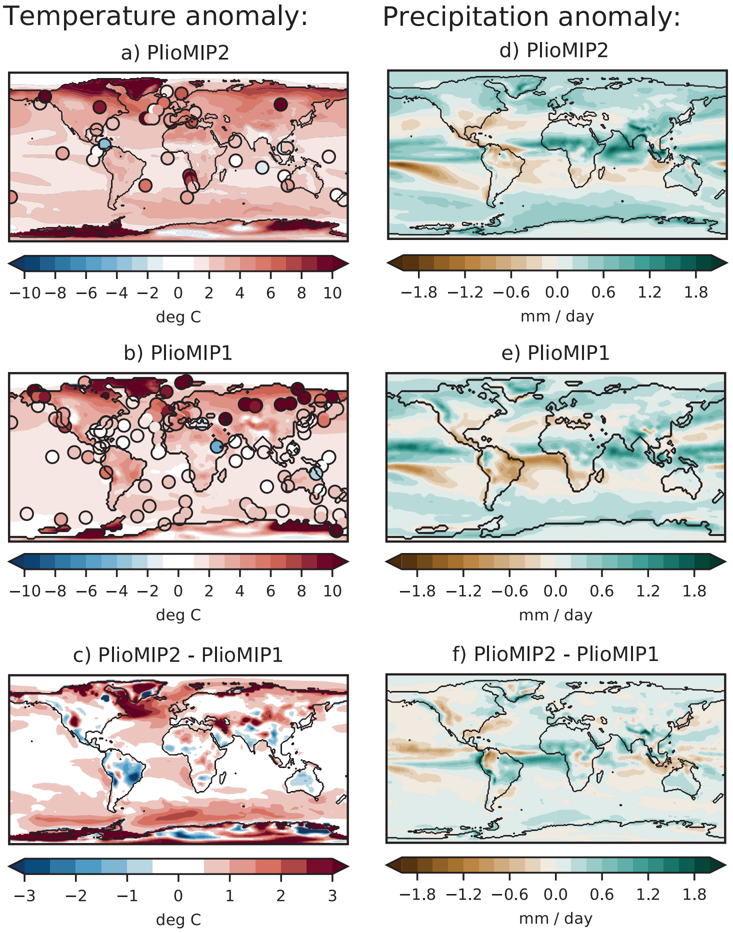

Figure 1: (A) PlioMIP2 and **(B)** PlioMIP1 multi-model annual mean surface air temperature (SAT) differences (over land) and sea surface temperature (SST) differences (over oceans) in °C, compared to the pre-industrial era. **(C)** Difference between PlioMIP2 and PlioMIP1 multi-modal means (°C). **(D)** PlioMIP2 and **(E)** PlioMIP1 multi-model annual mean total precipitation rate (mm/day) differences (compared to the pre-industrial era). **(F)** Difference between PlioMIP2 and PlioMIP1 multi-modal means (mm/day). Circles represent proxy-derived SST and SAT anomalies in **(A)** from McClymont et al. (2020) and Salzmann et al. (2013) respectively. Proxy-derived SST and SAT anomalies in **(B)** from Dowsett et al. (2010) and Salzmann et al. (2013) respectively.

PlioMIP1 outcomes (mPWP compared to the pre-industrial era)

An ensemble of eight climate models indicated that the mPWP global annual mean surface air temperature was 1.8 and 3.6°C higher than the pre-industrial baseline. Warming was predicted at all latitudes yet amplified at the poles, reducing the meridional temperature gradient (Haywood et al. 2013a; Fig. 1). A decline in Arctic sea-ice extent, with some models displaying a seasonally sea-ice-free Arctic, was predicted (Howell et al. 2016). Increased temperatures were predominantly a response to direct CO_2 forcing in the tropics and changes in albedo at high latitudes (Hill et al. 2014).

The change in meridional temperature gradient weakened tropical atmospheric circulation, specifically the Hadley circulation, a response akin to model predictions for the future (Corvec and Fletcher 2017). Mid-latitude westerly winds shifted poleward (Li et al. 2015), tropical cyclone intensity and duration increased (Yan et al. 2016) and the East Asian and West African summer monsoons strengthened (R Zhang et al. 2013; 2016). The global land monsoon system expanded poleward with increased monsoon precipitation over land (Li et al. 2018). The Atlantic Meridional Overturning Circulation (AMOC) showed no clear change (Z Zhang et al. 2013). Equilibrium Climate Sensitivity (ECS) ranged from 1.9 to 3.7°C (Hargreaves and Annan 2016). Earth System Sensitivity (ESS) was 1.47°C higher than the ECS (ensemble mean ECS = 3.4°C; ensemble mean ESS = 5.0°C; Haywood et al. 2013a). While models were able to reproduce many of the regional patterns of ocean and land surface temperature change demonstrated by proxy data, they underestimated the magnitude of warming at higher latitudes (e.g. Salzmann et al. 2013; Dowsett et al. 2013).

Creating PlioMIP2

PlioMIP1 highlighted two issues with model boundary conditions and proxy data used to verify climate models. Firstly, the PRISM3 paleogeographic reconstruction was a semi-quantitative interpretation of the available geological data. Changes in the distribution of land versus sea, as well as topography/bathymetry, result in significant regional changes to model-generated climates. A more objective and reproducible assessment, including the modeling of dynamic topography and incorporation of glacial

RECONSTRUCTION	FEATURES		MODEL EXPERIMENTS
PRISM0 Dowsett et al. (1994)	Northern Hemisphere 8x10 SST (Feb, Aug) Topography Vegetation	Time slab Ice (global)	**Goddard Institute for Space Studies (GISS) GCM** Chandler et al. (1994)
PRISM1 Dowsett et al. (1996)	Global 2x2 SST (monthly) Topography Vegetation	Time slab Sea Ice Land Ice	**National Center for Atmospheric Research (NCAR) GENESIS** Sloan et al. (1996)
PRISM2 Dowsett et al. (1999)	Global 2x2 SST (monthly) Topography Vegetation	Time slab Sea Ice Land Ice (revised)	**UK Meteorological Office (UKMO) GCM** Haywood et al. (2000)
PRISM3D Dowsett et al. (2010)	Global 2x2 SST (monthly) Topography (revised) Vegetation (revised) Verification data	Time slab DOT (mean annual, 4x5) SST (MAX - MIN) Sea Ice (revised) Land Ice (revised)	**PlioMIP1** 8 AGCMs and 8 AOGCMs Haywood et al. (2013a)
PRISM4 Dowsett et al. (2016)	Global 1x1 SST (mean annual) Paleogeography (revised) Vegetation Verification data (revised)	Time slice Lakes Soils Sea Ice Land Ice (revised)	**PlioMIP2** 17 AOGCMs/ESMs Haywood et al. (2020)

Table 1: Evolution of PRISM boundary conditions and their integration into climate models and PlioMIP.

isostatic adjustment (GIA) effects on the local expression of Pliocene sea level, was necessary (Dowsett et al. 2016). Secondly, PRISM reconstructions of sea surface temperatures (SSTs) were based on a time-slab concept that averaged warm phase SSTs over a ~260–300 kyr window. This practice was not optimal for verification of model-predicted SSTs, as models provide estimates of Pliocene SSTs in equilibrium with a set of time-specific boundary conditions/forcings (Haywood et al. 2016).

Moving beyond PlioMIP1 required an improved chronology for proxy data, and something approaching a true time-slice SST synthesis. Marine isotope stage KM5c (3.205 Myr BP) on the LR04 timescale was chosen as it represented an "interglacial event" within the mPWP, characterized by an almost identical orbital forcing to today, thus enhancing the relevance of its study in the context of future climate change (Haywood et al. 2013b). Proximity to a magnetic reversal and major benthic oxygen isotope excursions enhanced the ability to recognize the time-slice in high-resolution proxy records (Dowsett et al. 2016).

PlioMIP2 outcomes to date

Based on 16 of 17 available climate models that contributed simulations to the PlioMIP2 project, Haywood et al. (2020) determined that the range of global mean surface air temperatures increase was 1.7 to 5.2°C relative to the pre-industrial (multi-model mean 3.2°C), with warming polewards of 60°N and 60°S exceeding the global mean warming by a factor of 2.3 (Fig. 1). Sea-ice coverage was reduced by an average of 53%, with 11 of 16 models simulating ice-free summer conditions (de Nooijer et al. 2020). Later generation models tend to have an increased climate response compared to earlier generation models (Feng et al. 2020; Haywood et al. 2020), potentially related to new aerosol–climate and cloud microphysics schemes included in later models. The UK CMIP6 generation model HadGEM3 was determined to be too warm compared to available proxy data (Williams et al. 2021), with the previous generation UK model (HadGEM2) providing a better overall fit to geological data (Williams et al. 2021). Like in PlioMIP1, the PlioMIP2 ensemble indicates that the global monsoon domain expands, particularly in North Africa, Asia, and Australia (Berntell et al. 2021).

When using new time-slice SST reconstructions, there was broad agreement between data and models at the global scale, with regional differences reflecting ocean circulation and/or proxy signals (McClymont et al. 2020; Haywood et al. 2020). In the Atlantic and Pacific oceans, meridional temperature gradients reduced, while tropical zonal gradients remain largely unchanged. In the Atlantic this leads to a simulated reduction of interannual-to-decadal SST variability (Pontes et al. 2020). For the AMOC, in contrast to PlioMIP1, all models simulated an intensified mid-Pliocene AMOC, but no consistent response in the simulated Atlantic Ocean heat transport (Zhang et al. 2021). This consistent change in AMOC is potentially related to the closing of the Bering Strait/Canadian Archipelago in the PRISM4 reconstruction (Zhang et al. 2021). ENSO amplitude was reduced in the ensemble mean (–24%), with 15 of 17 individual models showing a reduction (Oldeman et al. 2021). The ensemble mean ESS is 67% greater than the ECS; which is larger than the increase of 47% obtained in PlioMIP1. An ECS range of 2.6–4.8°C accords with values presented in previous IPCC assessments (Haywood et al. 2020).

Going forward

PlioMIP2 will complete its planned analyses/publications within the next year and is beginning to address the necessary experiment planning in order to underpin a third phase of the project. This will include consideration of new CO$_2$ and CH$_4$ estimates (de la Vega et al. 2020; Hopcroft et al. 2020), uncertainties in paleogeographic reconstruction, as well as strategies to improve the availability of proxy data relevant to the PlioMIP time-slice. The project will continue to place a balanced emphasis on studies designed to improve our understanding of Pliocene climate, as well as studies which translate our knowledge of the past to better understand future climate change.

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DeepMIP: The Deep-Time Model Intercomparison Project

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DeepMIP has brought together the modeling and proxy communities, with an initial focus on the early Eocene climatic optimum, ~50 million years ago. In addition to evaluating global-scale metrics such as GMST and polar amplification, mechanisms of warmth are also being interrogated.

CO_2 reconstructions indicate that the closest analogs to potential 22nd-century CO_2 concentrations under mid-to-low-mitigation scenarios existed tens of millions of years ago, in "deep-time". The Deep-Time Model Intercomparison Project (DeepMIP; deepmip.org) is dedicated to conceiving, designing, carrying out, analyzing, and disseminating the results of an international effort to improve our understanding of these deep-time climates. Here, deep-time climates are defined as time periods prior to the Pliocene, ~5 million years ago. At its heart, DeepMIP aims to foster closer links between the paleoclimate modeling and data communities, grow communities of practice, develop and disseminate best practices, and to use this model–data synergy to:

- design, carry out, and analyze appropriate model simulations;
- create, collate, and synthesize proxy datasets; and
- evaluate model simulations, with a dual aim of learning about the past and informing the future.

History of DeepMIP

Prior to becoming part of PMIP, initial work was kick-started by the publication of several studies which independently modeled the early Eocene (~50 million years ago), a time period characterized by CO_2 concentrations ~1200–2500 ppmv, global mean temperatures ~23–30°C, and the complete absence of ice sheets. The temperature response to the high CO_2 concentrations and modified boundary conditions in the models were compared within the framework of an ad-hoc "ensemble of opportunity" (Lunt et al. 2012). Following on from this, several studies explored other aspects of these simulations, including the hydrology (Carmichael et al. 2016), implications for glaciation (Gasson et al. 2014), or the modification of model parameters (Lunt et al. 2013). However, there was a growing realization that for further progress to be made, a more formal, consistent experimental design and model intercomparison was necessary.

In 2015, in a meeting at NCAR, funded by NERC in the framework of an "International Opportunities Fund" project, the community came together to discuss such a formalization. DeepMIP was founded, and became part of PMIP. DeepMIP now has a membership of 200 scientists, with representation from the modeling as well as the marine and terrestrial proxy communities (deepmip.org/people); there have been a total of six meetings, with the most recent being online (deepmip.org/meetings).

DeepMIP activities and results so far

The first DeepMIP activity was to formally define a model experimental design for the time periods of interest. These were chosen to be the early Eocene climatic optimum (EECO), the Paleocene-Eocene Thermal Maximum (PETM), and the latest Paleocene. This experimental design was published as part of the PMIP4/CMIP6 Special Issue in GMD (Lunt et al. 2017). Following this, the time periods were more formally defined, guidelines and principles for the synthesis of proxy data and the strengths and weaknesses of various proxies were laid out, and the first version of the DeepMIP proxy database was also published (Hollis et al. 2019).

This proxy database was used to characterize the best estimates of global mean temperature in the three time periods of interest, and their uncertainties (Inglis et al. 2020). A variety of methods was applied to convert the relatively sparse proxy data into global means, ranging from a simple latitudinal-banded average, to Gaussian process regression. These different methods were compared and combined, resulting in estimates for the latest Paleocene, PETM, and

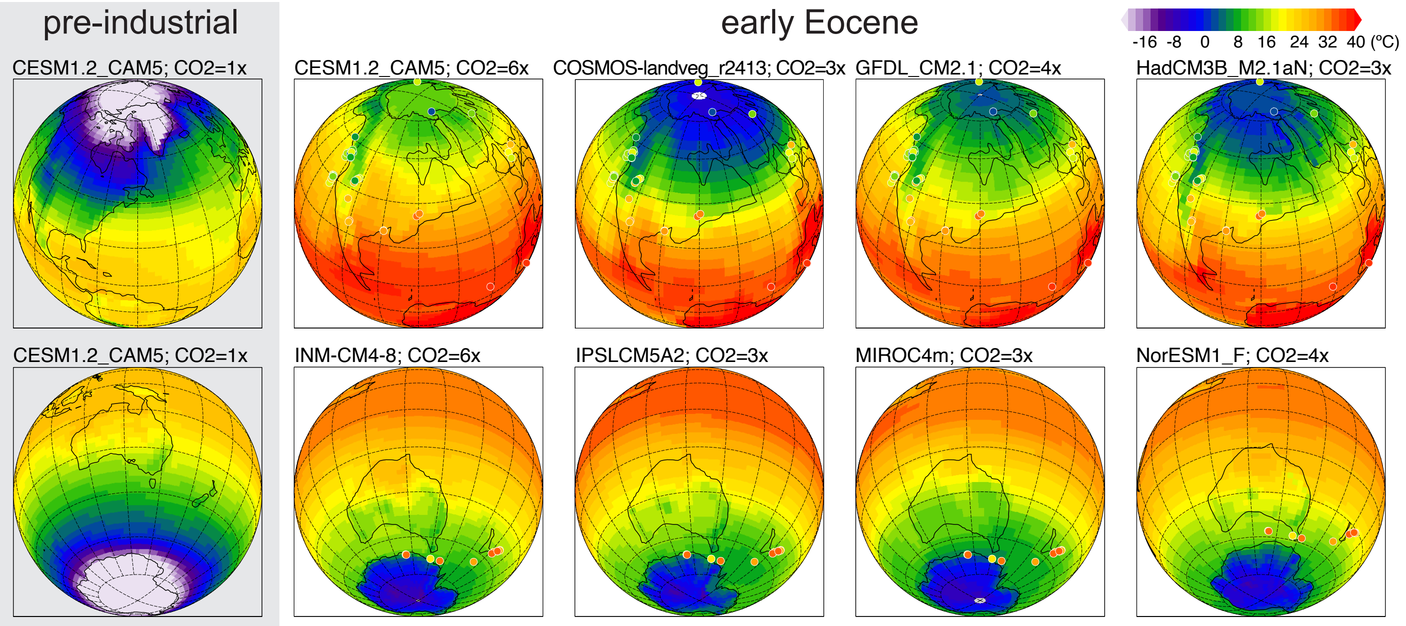

Figure 1: Modeled near-surface annual mean air temperature (°C) from eight models in the DeepMIP-Eocene (early Eocene) model ensemble, and proxy reconstructions from Hollis et al. (2019). The simulations shown here were carried out at a range of CO_2 concentrations from 840 (3x pre-industrial) to 1680 (6x pre-industrial) ppmv. Also shown is pre-industrial temperature from the CESM1.2_CAM5 model. The full model results are described in Lunt et al. (2021). The model data can be obtained from the DeepMIP model output database; see here for more info: deepmip.org/data-eocene

EECO, of 21–29°C, 26–36°C, and 22–31°C, respectively (90% confidence interval). This study also used the temperature estimates and the best existing CO_2 estimates to provide a quantification of equilibrium climate sensitivity (ECS) based on Eocene data. This resulted in ECS estimates of 1.6–8.0°C, 1.9–5.2°C, and 1.3–5.0°C for the same three time periods.

The proxy database was also used to evaluate the DeepMIP model simulations, which were presented, and their large-scale features discussed, in Lunt et al. (2021; see Fig. 1). The work showed that compared with results from previous studies of the Eocene, the DeepMIP simulations show a smaller ensemble spread in the global mean surface temperature response for a given atmospheric CO_2 concentration—this may result from the standardised experimental design and topographic/bathymetric boundary conditions.

These simulations also revealed a relatively high Eocene climate sensitivity (ECS) on average (average of 4.5°C per CO_2 doubling), compared to previous work (average of 3.3°C per CO_2 doubling). An energy balance analysis of the model ensemble indicated that global mean warming in the Eocene compared with the preindustrial period mostly arises from decreases in emissivity due to the elevated CO_2 concentration (and associated water vapor and long-wave cloud feedbacks), whereas the reduction in the Eocene in terms of the meridional temperature gradient is primarily due to emissivity and albedo changes owing to the non-CO_2 boundary conditions (i.e. the removal of the Antarctic ice sheet and changes in vegetation).

In contrast with previous work, three of the eight models examined showed results that are consistent with the proxies in terms of the global mean temperature, meridional SST gradient, and CO_2. However, at a more regional scale, the models lack skill. In particular, the modeled anomalies are substantially lower than those indicated by the proxies in the southwest Pacific (Fig. 1, lower panels); here, modeled continental surface air temperature anomalies are more consistent with surface air temperature proxies, implying a possible inconsistency between marine and terrestrial temperatures in either the proxies or models in this region.

The results from Lunt et al. (2021) and Inglis et al. (2020) have contributed to the recently published 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC AR6). Individual models that have used the DeepMIP boundary conditions have also contributed exciting results, including the finding that one of the high-ECS CMIP6 models, CESM2.1, produces a climate that is substantially warmer than indicated by the paleoproxies (Zhu et al. 2020; Fig. 2). This result is partly due to the response to the non-CO_2 forcings, which suggests that more attention is due on that subject. In addition, one of the low-ECS CMIP6 models, INMCM4-8, produces results at the low end of the proxy temperature estimates (Fig. 2). This indicates that the early Eocene may be a potentially useful tuning target for Earth system model (ESM) development, in particular if tighter constraints can be placed on the CO_2 concentration.

Ongoing and future DeepMIP activities

It is currently a very busy time for DeepMIP scientists, as several papers exploring the model ensemble and proxy data are currently in various stages of preparation. This includes studies focusing on ocean circulation (Zhang et al. submitted), Arctic sea ice (Niezgodzki et al. submitted), and the African monsoon (Williams et al. in prep), and other papers listed here: deepmip.org/publications-eocene; of these, several studies are proposing to explore the role of paleogeography and ocean gateways on regional climate. It is anticipated that many of these papers will be published in a Special Issue of Paleoceanography and Paleoclimatology, "DeepMIP in the Hothouse Earth: late Paleocene – early Eocene Climates and their lessons for the future", which is being organized by Margot Cramwinckel, Michael Henehan, and Jean-Baptiste Ladant. This work will be aided greatly by the existence of the DeepMIP model outputs database, which contains the model outputs from all eight Eocene models; see here for access: deepmip.org/data-eocene

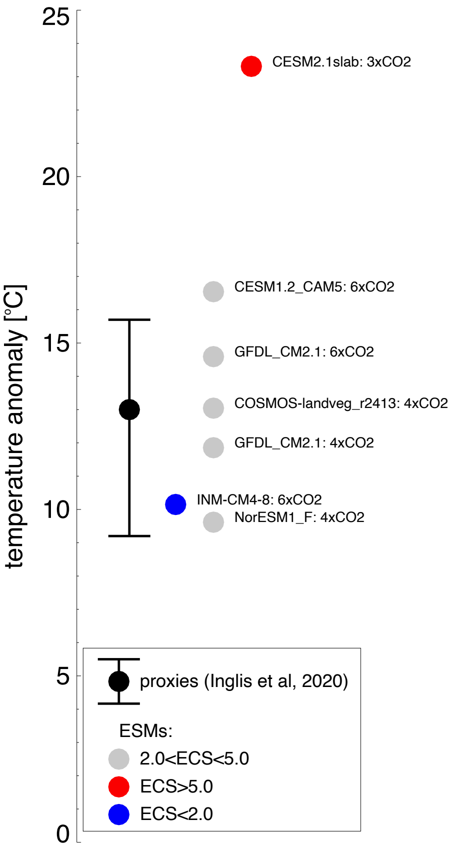

Figure 2: Modeled global-mean near-surface annual mean air temperature (°C) from those model simulations in the DeepMIP-Eocene (early Eocene) model ensemble that carried out simulations at 4x or 6x pre-industrial (consistent with proxy CO_2 estimates of Anagnostou et al. 2020), plus the 3x pre-industrial simulation using CESM2.1 (Zhu et al. 2020). Also shown is the proxy-based estimate of global mean temperature from Inglis et al. (2020).

It may be that DeepMIP will explore more time periods over the next few years. Based on experience, we expect that new time periods are best explored initially with ad-hoc ensembles of opportunity. In this regard, there has already been progress on the Eocene-Oligocene Transition (EOT; Hutchinson et al. 2021) and the Miocene (Burls et al. 2021). As such, we have already created three sub-groups within DeepMIP; DeepMIP-Eocene, DeepMIP-EOT, and DeepMIP-Miocene.

In any case, whatever happens, we will always expect DeepMIP to have a focus on integration of models and proxies, and work to bringing the modeling and data communities ever closer.

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Paleomonsoon modeling within PMIP: Recent progress and future directions

Jian Liu, L. Ning, M. Yan, W. Sun, K. Chen and Y. Qin

The recent progress on paleomonsoon modeling on various timescales within the five typical periods included in PMIP4 simulations are summarized in this paper. The remaining controversial issues and potential directions of the paleomonsoon modeling for future studies are also discussed.

During recent decades, remarkable progress has been made on monsoon variability and physical mechanisms, both by the modern and paleoclimatic communities (Fig. 1; Wang et al. 2017). However, paleomonsoon variability on different spatiotemporal scales is a complex topic requiring more studies from both proxy reconstructions and numerical modeling simulations. Phase 4 of the Paleoclimate Modelling Intercomparison Project (PMIP4) provides unique opportunities to better understand the past changes and corresponding physical mechanisms of the paleomonsoon on different timescales using updated models, more comprehensive boundary conditions, and improved experimental protocols compared with previous PMIP phases (Kageyama et al. 2018).

Last millennium

Previous paleomonsoon studies focusing on centennial changes during the last millennium (LM) have mainly compared the monsoon variability during the typical climatic periods within the LM, i.e. the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA; e.g. Jungclaus et al. 2017). Results indicate stronger (weaker) East Asian summer monsoon (EASM) and Indian summer monsoon during the MCA (LIA) due to the changes in the land–sea thermal contrast and atmospheric circulation, which were induced by total solar irradiance and volcanic eruptions. The coherent responses of monsoon systems to centennial-scale modulation of the total solar irradiance and volcanic eruptions found in both model simulations and proxy reconstructions indicate the robustness of the physical mechanisms behind this variability. However, despite the remarkable progress, it is not easy to quantitatively separate the contributions from external forcings and internal variability (Wang et al. 2017).

On the decadal timescale, monsoon variability is primarily associated with internal variability, e.g. Pacific decadal oscillation and Atlantic multi-decadal oscillation. Meanwhile, external forcings, such as volcanic eruptions, solar radiation, and land-use and land-cover change, could also influence the monsoon variability through regulating the land–sea thermal contrast, cycle of surface water, and energy balance (e.g. Qin et al. 2020). Although transient model simulations cannot exactly match the decadal monsoon phases with those found in the proxy reconstructions because models have their own initial conditions, specific events relevant to external forcings could still be reproduced through design of sensitivity experiments. Moreover, in addition to the experiments with default forcings, further experiments with different combinations of external forcings will focus on either specific periods during LM or the last two millennia in PMIP4. These will contribute to the exploration of the forcing uncertainties and the model–data comparisons on multi-scale monsoon variability (Jungclaus et al. 2017).

Mid-Holocene and last interglacial

The impacts of orbital forcing on paleomonsoon variability are examined through two groups of equilibrium simulations covering two interglacial epochs with greenhouse gas (GHG) levels similar to the pre-industrial (PI) period and the continental configurations almost identical to modern period, i.e. the mid-Holocene (MH), approximately 6 kyr BP, and the last interglacial (LIG; Otto-Bliesner et al. 2017), approximately 127 kyr BP. In general, the multi-model ensemble mean results show an enhanced Northern Hemisphere monsoon and reduced Southern Hemisphere monsoon, especially for the enhanced North African and Asian monsoons, and a weaker Australian monsoon both during the MH and LIG (Fig. 2; Brierley et al. 2020; Otto-Bliesner et al. 2021). Meanwhile, because of the larger insolation anomalies during the LIG compared to MH simulations, the changes of individual monsoon systems (e.g. areal extents and total amount of precipitation) during the LIG have a greater magnitude than those in the MH (Fig. 2).

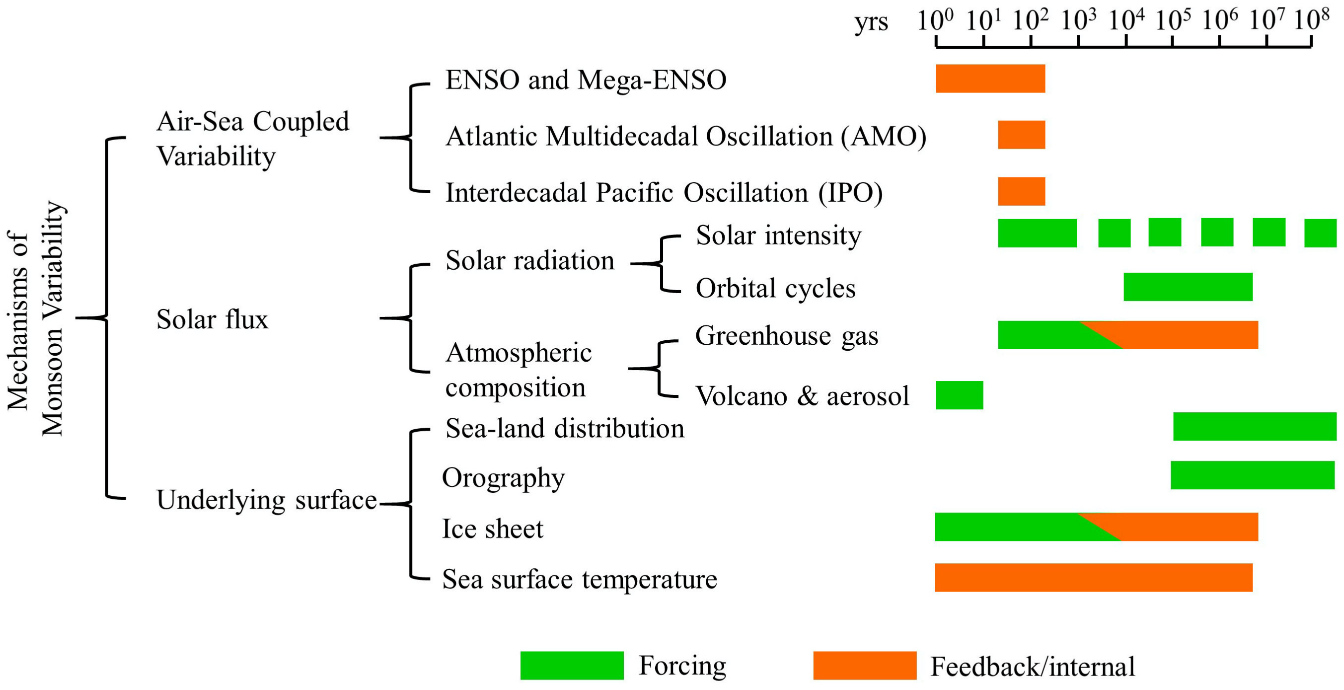

Figure 1: Mechanisms of global monsoon variability and the timescales (Fig. 6 from Wang et al. 2017).

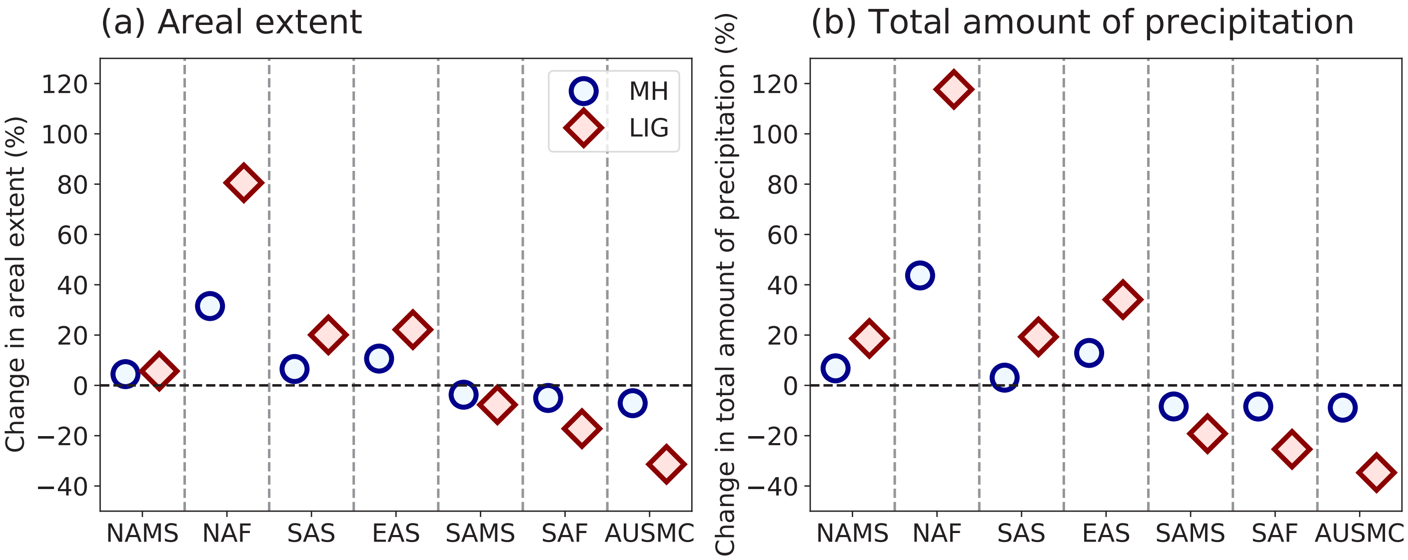

Figure 2: Multi-model ensemble mean of **(A)** relative changes of areal extents and **(B)** relative changes in total amount of precipitation in individual monsoons from PMIP4 MH and LIG simulations. The abbreviations used to identify each regional monsoon are as follows: North America monsoon system (NAMS), North Africa (NAF), South Asia (SAS), and East Asia summer (EAS) monsoon in the Northern Hemisphere and South American Monsoon System (SAMS), southern Africa (SAF), and Australian-maritime continent (AUSMC) monsoon in the Southern Hemisphere (adapted by Anni Zhao from Fig. 7 from Brierley et al. 2020 and Fig. 16 from Otto-Bliesner et al. 2021).

In addition to the aforementioned equilibrium simulations, several groups of transient simulations covering the entire Holocene have been carried out (e.g. Braconnot et al. 2019; Bader et al. 2020). These provide opportunities to investigate the characteristics and mechanisms behind multi-scale monsoon variability during the Holocene. These studies have suggested that the interannual- to millennial-scale monsoon variability could be influenced by internal variability, e.g. El Niño-like SST modes, Indian Ocean Dipole (IOD)-like SST modes, the AMOC, and external forcings, e.g. orbital parameters and GHGs (Braconnot et al. 2019; Crétat et al. 2020; Bader et al. 2020). For example, Braconnot et al. (2019) and Crétat et al. (2020) found that changes in orbital parameters cause long-term drying trends in the Indian and West African monsoons, but the Indian monsoon is more sensitive to anthropogenic GHGs, while ENSO and the IOD modulate the interannual-to-decadal Indian monsoon variability. Moreover, some extreme droughts that have been strongly associated with monsoon weakening, e.g. the 4.2 kyr BP event, may have been caused by both long-term drying trends (due to orbital forcing) and low-frequency fluctuations (due to internal variability).

Last glacial maximum

The last glacial maximum (LGM), approximately 21 kyr BP, provides an opportunity to investigate the impacts of changes in ice-sheet and continent extent on paleomonsoon variability (Kageyama et al. 2018). During the LGM, the reduction of summer monsoon precipitation in the Northern Hemisphere was twice as large as in the Southern Hemisphere. This asymmetric response is mainly caused by the moisture convergence feedback induced by the continental ice-sheet forcing rather than the reduction of moisture content (Cao et al. 2019). The multi-model ensemble mean results suggest that the lowered sea level may lead to expanded land area and thus an enhanced land–sea thermal contrast; this can further lead to a strengthened Australian summer monsoon in contrary to the weakened global monsoon during the LGM (Yan et al. 2018).

Mid-Pliocene

Generally, a robust enhancement of the West African, Indian, and East Asian summer monsoons was found during the mid-Pliocene (MP), approximately 3.2 million years ago, relative to the PI, consistent with geological reconstructions (Haywood et al. 2021). When the 11 model simulations are compared with geological records, a northwestward shift in the EASM's northern edge is captured, which is influenced by the intensification and westward extension of western Pacific subtropical high (Huang et al. 2019). Berntell et al. (2021) found that the multi-model ensemble mean in PlioMIP2 simulations shows a significant strengthening of the West African monsoon during the MP, with increased precipitation over the Sahel and Southern Sahara associated with the deepening of the Sahara Heat Low induced by GHG forcing.

Remaining controversial issues and potential directions

The progress made during PMIP4 discussed above has largely improved our understanding of paleomonsoon variability and the relevant physical mechanisms on various timescales. However, many specific issues remain poorly understood and could benefit from developments of the paleomonsoon modeling and model–data comparisons and syntheses, such as the relative influences of the polar ice-sheet development and the oceanic warm pool on global monsoon variability, further reduction of uncertainty for proxies already in use, and the development of new types of proxies that could identify certain features of the monsoon more accurately (Wang et al. 2017).

Such questions have motivated climatologists around the world and have given rise to strong collaborations between the paleoclimate reconstruction and modeling communities on future studies, on aspects of comparisons, synthesis, and fusion between proxy reconstructions and modeling simulations, through applications of isotope-enabled paleoclimate modeling and paleoclimate data assimilation, as well as other topics. Meanwhile, the paleomonsoon modeling community could also progress further with the help from the developments of the new generation of Earth system models, such as higher-resolution models and improved physical parameterizations, as well as incorporation of new findings from the paleomonsoon reconstruction communities, such as improved reconstructions of external forcings.

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Interannual-to-interdecadal variability in PMIP simulations at the local to global scale

Kira Rehfeld[1,2] and Josephine Brown[3]

Here, we outline recent insights into interannual to decadal variability of Earth's surface climate based on PMIP experiments and comparison with future climate simulations. These studies have provided new perspectives on large-scale changes of surface climate, low- and high-latitude modes of variability, and internally versus externally forced variability.

Climate variability in past, present and future

Interannual to decadal variability of surface climate variables arises through internal dynamics in the atmosphere-hydrosphere-biosphere-cryosphere system driven by the incoming solar radiation. External forcing impacts the climate system on multiple timescales. Constant adjustment of the Earth's energy budget through feedbacks and dynamics lead to changes in the global mean temperature, regional patterns, and fluctuations around the regional mean—in other words, to climate variability. Variations in the Earth's orbit (10^4–10^3 years) change the seasonal distribution of insolation quasi-periodically, while changes in solar luminosity (10^3–10^1 years) modulate the overall energy input to the system. At the same time, explosive volcanic eruptions stochastically perturb the system on seasonal to interannual timescales.

Equilibrium simulations from PMIP3 and PMIP4 allow us to examine the response of the climate system to different orbital insolation, topography, ice-sheet configurations and greenhouse-gas concentrations (Braconnot et al. 2012; Kageyama et al. 2018). Simulations for the last (pre-industrial) millennium (Jungclaus et al. 2017) have been used frequently to test the impact of solar and volcanic forcing on climate at interannual to centennial timescales. The PMIP4 working group "Past2Future: Insights from a constantly varying past" (pmip4.lsce.ipsl.fr/doku.php/wg:ptof:index) aims to improve our general understanding of climate stability through multi-model analyses of a range of climate states, focusing on large-scale patterns of change and internal modes of variability. It builds on the efforts of the PMIP3 working groups "Past to future" and "Paleovar".

Large-scale changes in simulated climate variability

The PMIP last millennium experiments have been key to improving our understanding of the role of volcanism and solar variability in driving climate variations. Studies incorporating both proxy and model data to assess mechanisms, blended reconstructions, and impacts on society draw on the considerable overlap between observations, and the dense proxy networks fostered by different PAGES working groups.

One key insight is that current climate models show too little variability locally, at individual observation locations. This was shown by Laepple and Huybers (2014), who investigated ocean surface temperature variability in CMIP5/PMIP3 last millennium simulations. At interannual timescales (2–5 years), no systematic offset between simulated regional temperature variability and observations could be found. However, on decadal to multicentennial timescales they observed a progressive increase in the underestimation of variability in gridbox-scale model surface ocean temperatures. On the other hand, the global mean simulated and reconstructed/observed temperature variability on interannual to multidecadal timescales are of similar magnitude over the last millennium (Laepple and Huybers 2014; Parsons et al. 2020) and the Common Era (PAGES 2k Consortium 2019). This consistency of simulated and reconstructed variability at the global scale, despite the lack of modeled regional variability at decadal and longer timescales, remains unexplained.

PMIP experiments targeting time periods prior to the late Holocene include a range of boundary conditions such as the land–sea mask, orbital parameters, greenhouse gas concentrations, and ice-sheet distribution. These experiments generally do not consider forcing on interannual to centennial timescales by changes in solar luminosity or explosive volcanism, as proxy-based reconstructions do not yet exist (and may not be possible given archive and proxy uncertainties). This implies that changes in interannual to multidecadal variability in these equilibrium simulations reflect the internal dynamical response of the climate system to the boundary conditions.

Interannual to multidecadal variability changes systematically across equilibrium simulations for the LGM, the mid-Holocene, and for idealized warming scenarios (abrupt4xCO2 and 1pctCO2; Taylor et al. 2012). Figure 1 illustrates the large-scale and mirroring changes between interannual to decadal temperature and precipitation variability in the LGM and 1pctCO2 cases. At the global scale, the colder climate is characterized by more variability in temperature and less in precipitation in most regions. The warming scenario is associated with increasing temperature and precipitation variability across the tropics and subtropics. Changes follow a contrasting land–sea pattern.

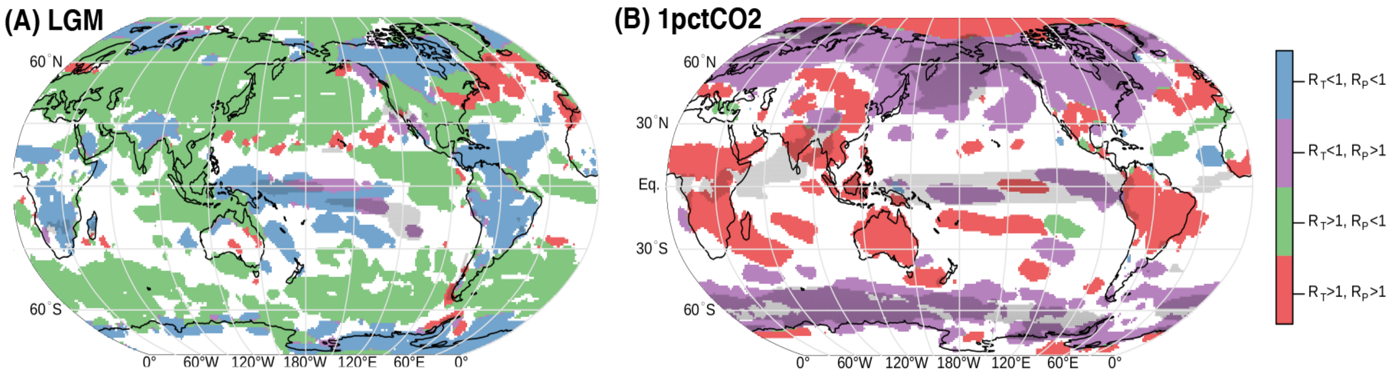

Figure 1: Temperature and precipitation variance change systematically with global mean temperature. Variance ratios ($R = \sigma_{scen}/\sigma_{pi}$ where σ_{pi} is the standard deviation of the preindustrial control simulation and σ_{scen} is the variance of {LGM,4xCO2}) were calculated from each CMIP5/CMIP6/PMIP3 model on **(A)** the last 50 years of the LGM simulations and **(B)** years 101–150 of the 1pctCO2 increase scenarios and compared to the final 50 years of the pre-industrial simulations. All simulations were linearly detrended and variance ratios were averaged. Colors classify regions with concurrent changes in temperature (R_T) and precipitation (R_P) variability. Changes of less than 5% are masked as white. Black shading indicates an increase in total precipitation by more than 0.4 mm/day in the annual mean. Visualization by J. Bühler based on data from Rehfeld et al. (2020).

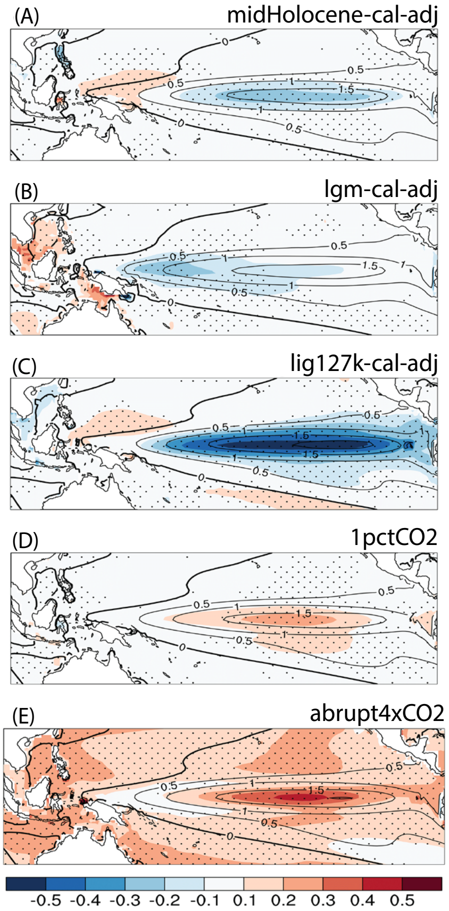

Figure 2: Changes in SST variability associated with ENSO for PMIP and CMIP experiments. The ensemble mean difference between the SST composites in each model during El Niño minus La Niña (defined as ±1 standard deviation) in the **(A)** midHolocene, **(B)** lgm, **(C)** lig127k, **(D)** 1pctCO2 and **(E)** abrupt4xCO2 experiments minus the same pattern for the piControl simulations is shown. The ensemble mean ENSO SST patterns in the piControl simulations are shown as black contours. Stippling indicates that more than two-thirds of the ensemble members agree on the sign of the change. Modified from Brown et al. (2020).

Spectral analysis showed that these general patterns hold from seasonal to multidecadal timescales across the PMIP3/CMIP5/CMIP6 model ensemble (Rehfeld et al. 2020).

Changes in modes of climate variability

Many studies have investigated changes in the El Niño Southern Oscillation (ENSO) characteristics in PMIP experiments. Zheng et al. (2008) compared multiple models for paleoclimate (PMIP2 LGM, mid-Holocene experiments) and future simulations, finding relationships between the tropical Pacific mean state and ENSO amplitude, as well as a reduced mid-Holocene ENSO variability. An and Choi (2014) compared ENSO in PMIP2 and PMIP3 mid-Holocene experiments and found a significant reduction in ENSO amplitude for PMIP2 models but only a marginal reduction in PMIP3 models due to competing processes, with weakened air-sea coupling leading to suppressed ENSO but weakening of the annual cycle over the tropical eastern Pacific supporting intensified ENSO.

Using an ensemble of PMIP3 and PMIP4 mid-Holocene experiments, Brown et al. (2020) found a consistent reduction in ENSO amplitude of 7% for PMIP3 models and 10% for PMIP4 models relative to pre-industrial ENSO amplitude. Comparison of mid-Holocene proxy records and PMIP3 simulations showed that models underestimated the reduction in ENSO amplitude compared with proxy reconstructions (Emile-Geay et al. 2016). Investigation of PMIP4 last interglacial experiments showed a stronger reduction in ENSO amplitude of around 20%, consistent with the larger seasonal insolation anomalies than the mid-Holocene experiments (Brown et al. 2020).

Simulations of ENSO in PMIP2 and PMIP3 LGM experiments showed a range of changes in ENSO characteristics (Masson-Delmotte et al. 2013). PMIP4 LGM simulations show no significant change in ENSO amplitude but reduced variability in the western Pacific SST variability, indicating a spatial shift in the ENSO pattern (Brown et al. 2020). Examination of ENSO in past cold and warm climates (as shown in Fig. 2) can provide insights into the relationship between changes in the mean state and ENSO variability (Saint-Lu et al. 2015), and may assist in constraining projections of future ENSO change.

Across the PMIP3/CMIP5/CMIP6 ensemble, ENSO indices showed increasing variability with warming, but the changes were not significant given the large intermodel spread (Rehfeld et al. 2020). Similarly, some other interannual to multidecadal modes of variability showed systematic, but weak, changes in variability with increasing global mean temperature across the PMIP3 ensemble. This included the boreal winter North Atlantic Oscillation and the Northern Annular Mode (weakly positive), amongst others. The Atlantic meridional and zonal modes showed decreasing variability with warming. For many of the other proposed modes of variability the integration length (typically 50–100 years) was insufficient to assess whether or not systematic changes are expected to occur with regional or global warming.

This general perspective of reduced temperature variability with warming at the global scale is consistent with the direction of temperature variability changes from a multi-proxy study targeting multicentennial to millennial timescales (Rehfeld et al. 2018). Proxy-based confirmation on shorter timescales will, however, require reduced age uncertainties, removal of confounding effects due to other climate variables, the environment, or the archive structure, and an expansion of the high-resolution proxy network.

Challenges and Perspectives

A series of interconnected challenges need to be tackled regarding the paleoclimate record and paleoclimate modeling, in order to further enhance our understanding of changes in interannual to multidecadal variability. Firstly, this entails testing the impact of centennial- to millennial-scale variations in the mean state on variability at these shorter timescales. On the modeling side this requires the incorporation of nonstationary elements such as ice sheets, biogeochemistry, and land surface processes, but also a reasonable understanding of the nature of the variability of the glacial ocean circulation. This could be facilitated by considering an ensemble of models of different complexity together to assess stabilizing and destabilizing feedbacks of low frequency changes on interannual variability.

Spatio-temporal shifts in modes operating on interannual to decadal timescales can be expected to occur with warming. This has been extensively studied for ENSO, where shifts in the frequency of different "flavors" or spatial patterns of ENSO may occur. Examination of PMIP mid-Holocene simulations suggested changes in the occurrence of Central Pacific versus Eastern Pacific events (e.g. An and Choi 2014; Emile-Geay et al. 2016). Shifts in the spatial pattern of ENSO in past climates therefore need to be considered when carrying out model–proxy comparisons. To evaluate the simulated variability, especially in pre-Holocene time periods, the proxy network needs further consolidation in time and space, in order to assess signal-to-noise ratios and distinguish model deficiencies (e.g. underestimated SST variability) from archive noise (e.g. from bioturbation, intermittency, or aliasing). The comparability of modeled and reconstructed signals could further be improved by forward modeling of tracer species (e.g. water isotopologs) in collaboration with PMIP/CMIP experiments, longer model integrations, and the inclusion of solar and volcanic forcings in experiments.

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PMIP Past to Future Working Group

Julia C. Hargreaves

The Past to Future Working Group enables paleoclimate information from both PMIP models and climate proxies to be used to better constrain predictions of future climate change.

Strategy

The Past to Future Working Group (P2F; pmip.lsce.ipsl.fr/working_groups/Past2Future) was formed to enable paleoclimate information from both PMIP models and climate proxies to be used to better constrain predictions of future climate change. The remit of the group is wide; in principle any spatial and temporal scales of change and any metric of the climate system may be considered. Here we mostly focus on the equilibrium response of the climate system. In this context, the most significant progress over the last few years has been made in better defining and constraining climate sensitivity. Related work focusing on variability is reported elsewhere in this issue. Paleoclimate model simulations were included in the fifth iteration of the Climate Model Intercomparison Project (CMIP5), making this the first time that ensembles of historical, paleo, and future projections were run with the same model versions. In anticipation of this, the P2F group was initiated at the 2012 PMIP3 workshop in Crewe, UK (Crucifix et al. 2012). The overarching purpose of the group was to encourage the use of paleoclimatic information to improve predictions of climate change.

As a cross-cutting group, the main focus of P2F was to facilitate research activities. The working group website was used to improve accessibility to outputs from model simulations and data from climate proxies, and to highlight relevant publications in the field. The main meeting point has been at the European Geophysical Union General Assembly, where there have been a variety of EGU sessions with a focus on Past to Future activities. There have also been several workshops with a significant Past to Future element. Connections between the Cloud Feedback Model Intercomparison Project (CFMIP; cfmip.org) and PMIP have strengthened through the activities of the working group. Joint experiments have been planned; scientists from CFMIP have given keynote presentations at PMIP (and vice-versa); and there are a number of scientists who are active in both MIPs.

The status of early research focused on combining models and data from paleoclimates to constrain predictions of future climate change is well described by Schmidt et al. (2014). This paper outlines various methodologies, illustrated by examples, each of which "uses a specific target (or targets) from a palaeo-climate reconstruction of change that is within the scope of the modelled system, defines a metric of skill that quantifies the accuracy of the modelled changes and assesses the connection to a future prediction". The P2F group promoted a very similar methodology for using the CMIP ensemble, and additionally, highlighted a number of research targets, including:

- Estimating future climate by exploring information from multiple PMIP intervals;
- Exploring divergent estimates of climate sensitivity—towards reconciliation; and
- Predicting regional climate change—going beyond climate sensitivity.

Achievements

Climate sensitivity is the equilibrium global temperature change resulting from a doubling of the atmospheric carbon dioxide concentration. Estimation of climate sensitivity has been the main focus for quantitative P2F research using statistical methods. The recent community assessment of climate

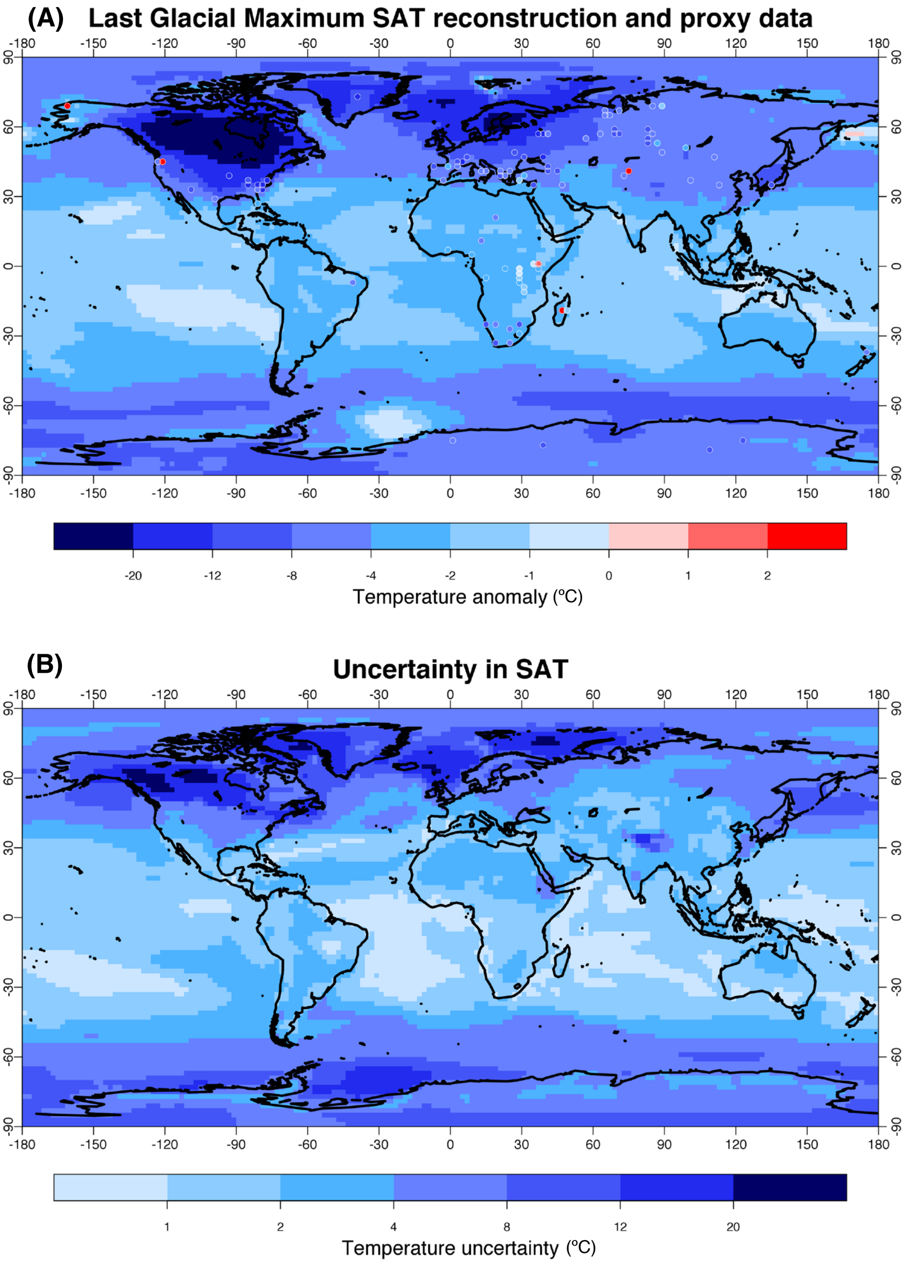

Figure 1: (A) Reconstruction of Last Glacial Maximum surface air temperature anomaly (°C) based on multi-model regression. Proxy data are represented as colored dots. **(B)** Uncertainty in Last Glacial Maximum surface air temperature anomaly (°C) from bootstrap resampling. Results presented as half-width of 95% confidence interval (Fig. 1 and 3 from Annan and Hargreaves 2013).

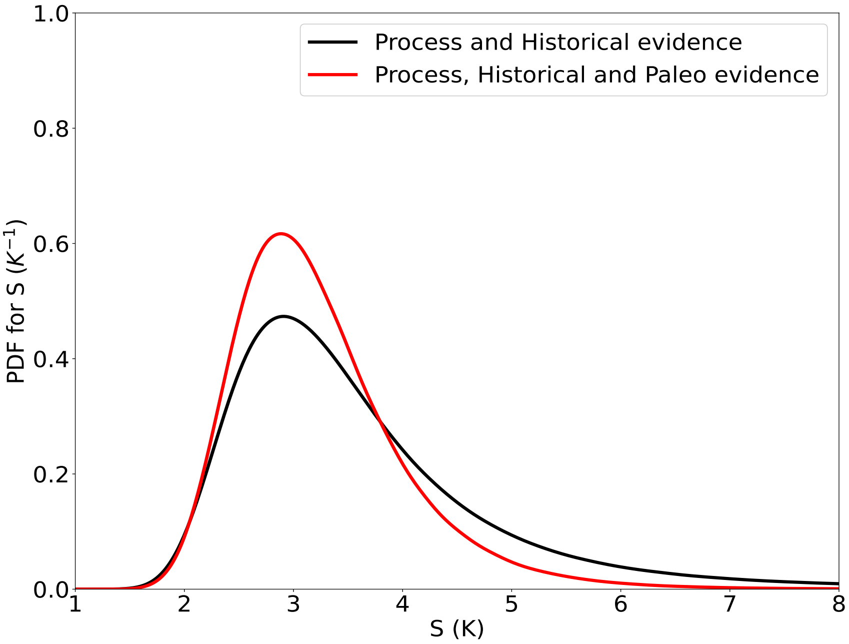

Figure 2: Estimated PDFs for climate sensitivity (S) with and without using paleo information, based on the values estimated by Sherwood et al. (2020). The baseline 66% range not including paleo information was 2.6–4.6 K. Including the paleoclimatic constraint, the range tightens to 2.6–3.9 K.

sensitivity by Sherwood et al. (2020) included a substantial paleoclimate component and involved several P2F members working alongside researchers with primary expertise in the interpretation of paleodata. Results from PMIP activities influenced almost every aspect of the paleoclimate component of the assessment.

For example, in order to estimate climate sensitivity using paleoclimates, an estimate of the large scale temperature changes for paleoclimates relative to modern is required. Figure 1 shows a reconstruction of the Last Glacial Maximum temperature anomaly that was included in the evidence for the assessment. This estimate (from Annan and Hargreaves 2013) was a result of the P2F working group activities, and combined information from the PMIP2 ensemble and from climate proxy compilations (MARGO Project Members 2009; Bartlein et al. 2011; Schmittner et al. 2011). Uncertainty estimates are critical to these kinds of assessments, and the estimated uncertainties in this reconstruction are shown in the lower sub-figure. Figure 2 shows the baseline result from Sherwood et al. (2020), and the result that would be obtained if paleoclimate information was, instead, entirely ignored. It is clear that the paleoclimatic component significantly constrains the high end of the assessed range for climate sensitivity.

The assessment also made significant progress on one of the other goals of the working group: reconciling the previously divergent estimates of climate sensitivity from different constraints, which were found to be due in part to the pattern effect (Andrews et al. 2018) and some differences in the precise definitions of climate sensitivity that had been used. An emergent constraint is the term used to describe model variables for which measurements are available which may, through use of the multi-model ensemble, be used to refine probabilistic estimates of future climate change given certain emissions forcings. Members of the working group have further developed the use of emergent constraints to estimate climate sensitivity. Initial work focused on analyzing correlations between the Last Glacial Maximum (LGM) temperature anomaly and climate sensitivity, with the mid-Pliocene considered more recently (e.g. Hargreaves et al. 2012; Hopcroft and Valdes 2015; Hargreaves and Annan 2016). Recently Renoult et al. (2020) presented a Bayesian framework for combining emergent constraints from different periods, potentially including non-paleo emergent constraints. This method makes all assumptions explicit and enables emergent constraints to be incorporated into assessments of climate sensitivity, although some caveats remain.

Progress in regional climate change has usually been more qualitative and process based (e.g. Schmidt et al. 2014; Koh and Brierley 2015; Seth et al. 2019). Large-scale changes such as Arctic amplification and land–ocean contrast may be expected to be useful for constraining future climate but direct temperature comparisons have not so far indicated robust past–future relationships in the ensembles. However, detailed analyses of the processes involved in Arctic amplification may enable particular seasons for particular paleoclimate intervals to be used as constraints (LGM: Laîné et al. 2016; mid-Holocene: Yoshimori and Suzuki 2019). There is also potential for Arctic ice extent to be used to constrain likely future Arctic sea-ice changes (Last Interglacial: Kageyama et al. 2021). The merger of P2F with Paleovar (to make P2Fvar) in PMIP4 has increased the range of spatial and temporal scales being studied (Rehfeld et al. 2020; Brown et al. 2020; D'Agostino et al. 2020), a trend which we hope to see continue.

In addition to developing the more regional focus, the simulations of the last deglaciation which have been performed within PMIP have the potential to develop towards a new P2F activity of directly paleoclimate-constrained projections, as modelers extend the deglaciation runs into the next centuries (Fieg et al. 2021).

In summary, even with relatively few scientists working primarily in this area, the group is able to use the resources of PMIP, CFMIP, and CMIP, and has been very successful in raising the profile of paleoclimate as a topic of increasing interest to a wide range of researchers.

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PaleoEcoGen: Unlocking the power of ancient environmental DNA to understand past ecological trends

Marie-Eve Monchamp[1,2], L. Armbrecht[3,4], E. Capo[5], M.J.L. Coolen[6], T. Cordier[7], I. Domaizon[8], L.S. Epp[9], C. Giguet-Covex[10], I. Gregory-Eaves[1,2], U. Herzschuh[11], L. Parducci[12], K.R. Stoof-Leichsenring[11] and J.W. Williams[13]

PaleoEcoGen is a new working group that was launched with the aim of bringing together scientists from around the world who use ancient environmental DNA (ancient eDNA) as a novel proxy to examine the response of past biological communities to environmental changes (pastglobalchanges.org/paleoecogen). We are particularly interested in exploiting the added value of these emerging ancient eDNA tools to advance our knowledge of critical transitions in Earth's Quaternary history. To this end, we aim to stimulate and enhance international ancient eDNA research by organizing topical workshops to discuss new methodologies in the field (including synthetic analyses and modeling approaches), and to coordinate research efforts for bigger picture analyses that, ultimately, will help to inform conservation efforts and future biodiversity assessments.

Changes in ecosystem dynamics can occur gradually over centuries to millennia, or abruptly (i.e. at decadal to annual timescales). Rapid changes may challenge the fitness and survival of organisms, including those that are essential for ecosystem maintenance. Even small disturbances may weaken the stability and resilience of an ecosystem (Fig. 1), and ultimately lead to "critical transitions" where the system is pushed from one equilibrium state to another (Taranu et al. 2018). These "tipping points" are often hard to predict because of the complexity of the interactions between organisms and their environment, and they imply prolonged ecosystem consequences that may not be reversible.

Critical transitions have been documented for terrestrial and aquatic ecosystems, as well as social-ecological systems, and they have been studied across many scientific disciplines (Scheffer et al. 2009; 2012). In the context of global changes, especially the "Great Acceleration" (Steffen et al. 2015), studying critical transitions has been identified as a priority in paleoecological research by the scientific community (Seddon et al. 2014). With new methodological approaches on the rise in the paleosciences, we now have the opportunity to describe past critical transitions and their effects on biological communities (Taranu et al. 2018; Capo et al. 2021).

Our working group is motivated to address two key questions:

- How can we use (sedimentary) ancient eDNA timeseries to better identify and characterize past critical transitions?
- What are the subsequent evolutionary and ecological trajectories, and which projections for future biodiversity and ecosystem change can be drawn from past critical transitions during the Quaternary?

The detailed study of critical transitions in paleoecology requires the generation of the most comprehensive view possible—of an ecosystem, its drivers, and their interactions. To meet this challenge, stratigraphic analysis of ancient eDNA is a key analytical approach because of its potential to provide new insights into: (1) the composition of biological communities across multiple trophic levels including organisms that do not fossilize; (2) species interactions within communities; and (3) the response of organisms, from individual taxa to communities, to past environmental changes (Coolen et al. 2013; Domaizon et al. 2017; Schulte et al. 2021; Liu et al. 2021). Like any other proxy, ancient eDNA has its limitations (Capo et al. 2021), but the field is now sufficiently mature to offer exciting new opportunities to expand our knowledge using paleoenvironmental data.

Upcoming activities

Our first online workshop will be in 2022 in collaboration with the sedaDNA scientific society (ercapo.wixsite.com/sedadna-society). The workshop will be dedicated to improving inclusion of African ancient eDNA researchers by offering a collaborative platform and training opportunities in molecular techniques applied to sedimentary ancient eDNA. A second workshop (in-person or online, depending on COVID-19 pandemic regulations) will focus on developing a multivariate modeling approach based on ancient eDNA temporal data (Taranu et al. 2018) to investigate the timing and magnitude of shifts in paleoenvironmental records.

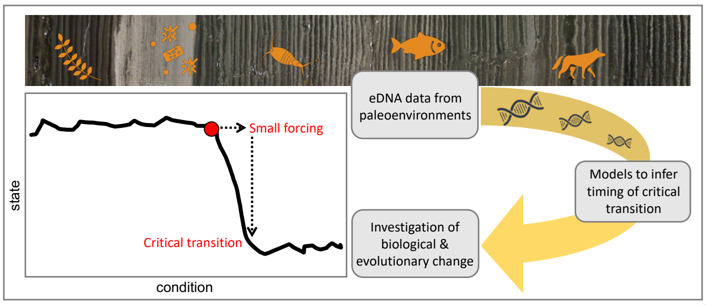

Figure 1: (Left) Schematic representation of a critical transition between two states triggered by a small forcing. (Right) Simplified workflow of the proposed approach to identify past critical transitions and evaluate subsequent biological changes based on ancient environmental DNA timeseries.

Visit our website (pastglobalchanges.org/paleoecogen) and register to our mailing list to keep up to date with our activities and find out how to get involved. PaleoEcoGen is also on Twitter: @PaleoEcoGen

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PEOPLE 3000 working group

Julie A. Hoggarth[1], C. Latorre[2], J. Freeman[3], E. Robinson[4], E. Gayo[5] and D. Bird[6,7]

Understanding what makes some socio-ecological systems (SES) more resilient to changing disturbance regimes (e.g. the length of fire season caused by abrupt climate change) is integral to explain long-term patterns in the development of human societies over the past 3,000 years. The PAGES PalEOclimate and the PeopLing of Earth (PEOPLE 3000; pastglobalchanges.org/people3000) working group explores this question by integrating archaeological data, paleoecological data, and dynamic modeling (Fig. 1) to identify regionally comparative case studies across the world.

Humans adapt to natural conditions, including variability in climate systems, over time with each generation inheriting ecological and cultural knowledge. Drawing from niche construction theory, we further argue that humans modify selection pressures in their environments that affect both humans and other species (Odling-Smee et al. 2003). As disturbances may change over time, an SES may become vulnerable when those changes extend outside of the range held within the cultural and ecological memory of a society.

More flexible systems may improve the resilience of SESs over even highly productive but rigid systems. Using radiocarbon datasets as proxies of populations, Freeman et al. (2021) explored whether systems with greater variability in production developed differing population stability patterns than those with more landscape engineering over time. They found that agricultural societies that relied on landscape engineering to intensify production and control variability of production experienced the most stability and the least severe population declines during times of environmental stress.

Scientific goals and activities

The PEOPLE 3000 working group has three primary goals: (1) to develop low- and high-precision coupled records of paleoclimate, human population, and human institutions over the last 3000 years; (2) compare changes in population, paleoclimate, and institutions from region to region; and (3) identify regionally comparative patterns to explain relationships between variation in ecosystem change, subsistence and social diversity, and the severity of social-ecological reorganization. To explore these questions, we are building a global data infrastructure for comparing patterns of human population ecology. To date, in Phase 1 of PEOPLE 3000, this has taken the form of a global radiocarbon database, compiling, and curation of over 150,000 radiocarbon dates from around the world and developing protocols for using those data (Bird et al. 2021).

PEOPLE 3000's goals in Phase 2 of the project are to integrate radiocarbon and paleoecological/ paleoenvironmental data, as well as information on social institutions, to develop coevolutionary models on carrying capacity, social integration, and data from paleoclimate and paleoecology. To date we have collected data from 17 core case study regions and will work on issues of quality control and integrating data from each region.

PEOPLE 3000 is currently seeking members from around the world. We will hold open online meetings each May to present research findings from individual members and to recruit new case studies. Visit the PEOPLE 3000 website at pastglobalchanges.org/people3000 and sign up to the mailing list to be contacted by us on our upcoming meetings and activities.

Upcoming activities

We held a hybrid meeting to wrap up Phase 1 of the project in November 2021 (pastglobalchanges.org/calendar/27099), with separate working groups meeting in individual countries and communicating over Zoom. Our first online meeting of Phase 2 will take place in May 2022, open to all PEOPLE 3000 members and interested researchers.

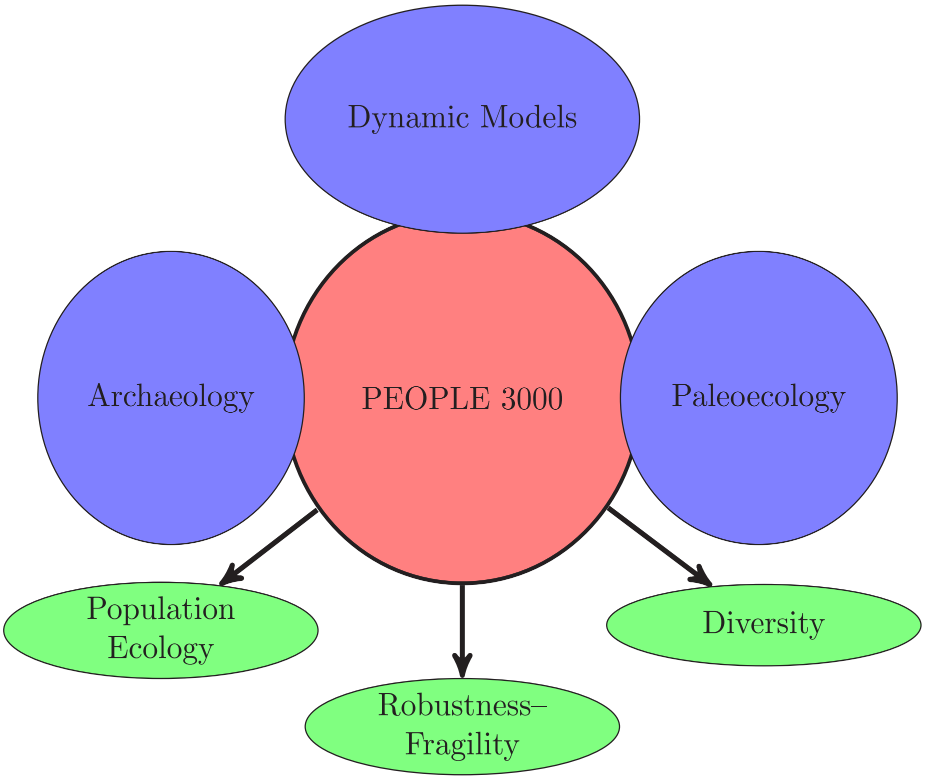

Figure 1: Conceptual diagram of PEOPLE 3000, showing the three areas of archaeology, dynamic models, and paleoecology that are integrated in the project.

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Modeling long-term human-environment feedback loops during the Holocene

Eugenia M. Gayo[1,2], M. Lima[1,3], J. Freeman[4], E. Robinson[4] and C. Latorre[2,3]

Online, 25-26 March 2021

The PEOPLE 3000 (pastglobalchanges.org/people3000) working group aims to understand how the interplay between human population growth, upscaling in social complexity, and climate variability might have driven resilience or collapse of socio-ecological systems during the Holocene. By integrating long-term timeseries for ecological, climatic, and demographic trends under common mathematical frameworks, we formally evaluate convergences/divergences in feedback loops between biophysical and social systems in different regions of the globe. We are thereby interested in exploring explanations beyond statistical correlations between human population change, climate variability, and anthropogenic land use, based on modeling theoretical climate–ecosystem–population feedback relationships.

One of the modeling approaches that we have developed to explain the trajectory of Holocene SES is based on the Population Dynamic Theory (PDT), which allows us to test empirically for the interplay between climate, ecosystem and population processes. PDT proposes that the impact of climate variability on human populations cannot be evaluated independently of demographic levels. Simply put, climatic conditions affect food production, which in turn set the carrying capacity (*k*). Clearly, unfavorable conditions necessarily affect *k* through resource limitation, but if the population/food production ratio is defining the per-capita share of resources as well as competition strength, the availability of a limiting factor will decrease regardless of the effect of climate on food production. This implies that even small changes in a relevant climate variable might trigger disproportionate impacts in population growth rates. We have begun to explore this kind of dynamic in several past populations from the Americas and Polynesia (Bird et al. 2020; Lima et al. 2020).

Our last workshop before the final PEOPLE 3000 synthesis, "Understanding long-term human-environment feedback loops through the integration of archaeology, paleoclimate and ecological models" (pastglobalchanges.org/calendar/26995) was held virtually due to restrictions of the ongoing COVID-19 pandemic. This activity aimed to expand our number of case studies by establishing collaborative strategies to integrate ecological, climate and demographic proxy data into a PDT framework for addressing the question: Does human population size and/or rates of change better correlate with climate driven changes in ecosystem structure, diversity or functionality?

Through keynote and flash-poster presentations, we discussed approaches for extracting refined paleodemographic signals from archaeological radiocarbon timeseries as well as trends for anthropogenic land-use changes from paleoecological archives. We established synergies with researchers from other complementary initiatives, e.g. LandCover6k (pastglobalchanges.org/landcover6k), Paleoclimate Modelling Intercomparison Project (PMIP; pmip.lsce.ipsl.fr) and Humans on Planet Earth (HOPE; www.uib.no/en/rg/EECRG/107501/hope) for assessing human-environment feedback loops based on the integration of our PEOPLE 3000 radiocarbon database (Bird et al. 2021) and global paleoenvironmental datasets collated previously by our collaborators.

A manuscript has been outlined that will allow us to explore relationships between technological innovations and population growth in past agrarian societies from around the world. For the case presented in Figure 1, accelerated growth rates occurred as population sizes increased in the inland Atacama Desert and the adoption of agriculture spurred on new forms of cooperation among individuals (i.e. pottery, metal-working, irrigation, pastoralism). Nevertheless, as population sizes approached the higher *k* set by agriculture, growth rates started to decrease due to the interplay between population levels and increased competition strength.

Breakout sessions on the second day were dedicated to discussing the future of PEOPLE 3000. Directions for a new Phase 2, which launched in August 2021, focus on exploring coevolutionary relationships between social organization, changes in human populations, and disturbance regimes over the Holocene. Phase 2 will broaden our number of case studies by including early-career researchers from traditionally under-represented regions in paleoscience that attended the workshop, and delve further into new computational tools available for the paleoenvironmental record (e.g. Neotoma). New collaborations with other initiatives such as LandCover6k, PMIP and HOPE will help develop novel synergies to examine mechanisms proposed to explain the variable deep histories of resilience (or lack thereof) observed in past socio-ecological systems.

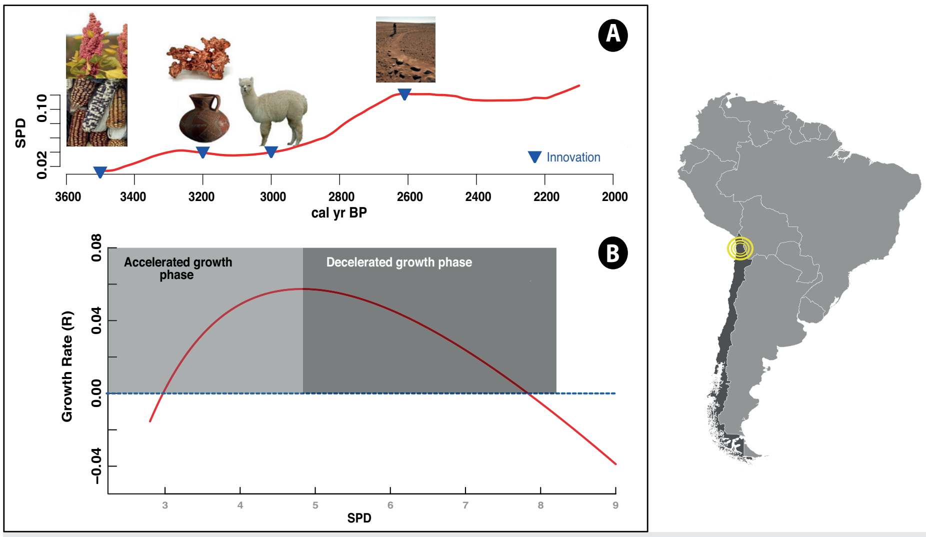

Figure 1: (A) Paleo-population levels inferred for the Atacama Desert from the summed probability distribution (SPD) of radiocarbon dates. **(B)** Population growth rates during the period 3300–2150 cal yr BP.

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COLOMBIA BIORESILIENCE Biodiversity resilience and ecosystem services in post-conflict socio-ecological systems

Socio-environmental histories and interdisciplinary perspectives on the resilience of the Andean tropical forests of Colombia

Felipe Franco-Gaviria[1] and Mónica Amador-Jiménez[2]

Online, 2-3 June 2021

This workshop on socio-environmental histories of the Colombian tropical Andean forests (pastglobalchanges.org/calendar/27028) fostered relevant academic and institutional exchanges between social and environmental disciplines. The workshop included eight invited panelists, two main speakers, eight working group moderators, eight poster presenters, and over 120 attendees each day. On average, 60 attendees participated in the breakout activities, which focused on understanding past human and landscape interactions in the tropical Andes of Colombia.

The workshop was a multidisciplinary event with 40% of academics and students from the natural sciences and 60% from the social sciences and the arts. The workshop followed a hybrid methodological concept, designed to promote interdisciplinary discussions. Over the course of two five-hour days, we held open conferences, panel discussions with experts and small discussion groups. In order to participate, it was compulsory to read articles, in advance, on environmental change issues in the Andes from journals and prestigious authors from the natural and social sciences. The breakout activity led to discussions within groups of eight people. This setting allowed for better interaction among participants, moderators, and panelists.

During the event we also experimented with "real-time illustrations" to summarize the discussions (Fig. 1). These six illustrations were widely distributed and shared among participants and the general public.

On the first day, the central theme was socio-environmental history, with the aim of understanding change and transformation in the Colombian Andes, thereby fostering a dialog between biophysical and social sciences. Introductory talks by Dunia Urrego and Henry Hooghiemstra, and the panel discussion moderated by Monica Amador, led the audience to reflect on the importance of temporal and spatial scales in studying the past. Some observations and comments led to the identification of pathways for integrating disciplines of the social and biophysical sciences into socio-environmental history. These discussions during the plenary session sparked a debate within the working groups where experts and attendees addressed possibilities of integrating knowledge, but also some of the assumptions that are made within the various disciplines regarding our interpretation of the interactions between humans and non-humans in the past (Fig. 1).

Following the same methodology, the second day was dedicated to addressing the relationships between socio-environmental history and public policy. This session began with Naomi Millner, who spoke on social aspects of socio-environmental history within the BioResilience research project (blogs.exeter.ac.uk/bioresilience), followed by Sonia Archila who presented a multi-species perspective on socio-environmental history. The panel of experts moderated by Nicolás Loaiza and Mónica Amador encouraged the interdisciplinary discussion on how a placed social and environmental history could be a tool to manage natural resources and integrate policymakers and stakeholders.

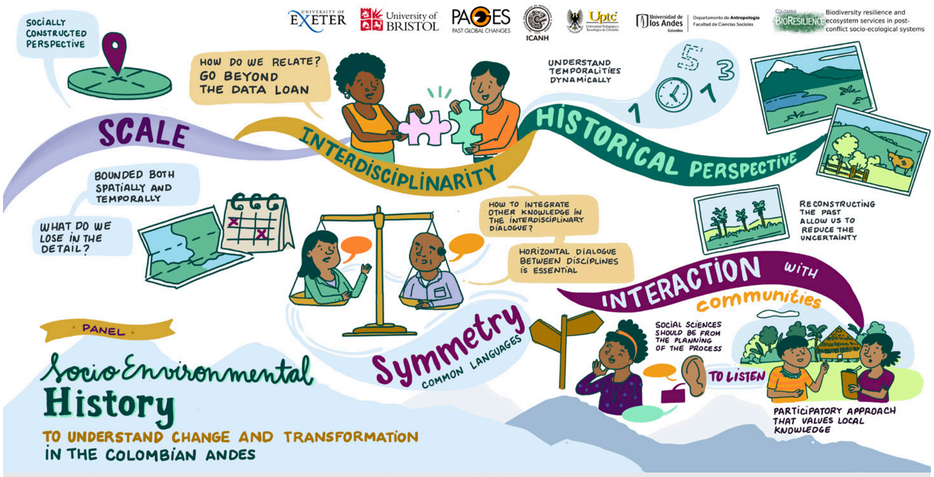

Figure 1: A real-time illustration made at the meeting following working group discussions on integration frameworks that could bring social and natural sciences together.

For the plenary session with experts, the discussions highlighted the importance of integrating knowledge between different academic disciplines and local communities to improve our understanding of the long history of the territories. Extending historical projections of the landscapes could allow us to determine when laws were formulated and understand the public policy of each territory. All the presentations and discussions were recorded and transcribed, and will be synthesized into a document that condenses the meeting's outcomes. This will form the basis for an academic article on interdisciplinarity in socio-environmental reconstruction and history in the Andes.

After the workshop, discussions have continued between organizers and national institutions, such as the National Institute of Anthropology (ICANH), to give continuity to these working groups in socio-environmental history. The organizing committee is aiming for a second integration meeting, in person, in 2022. The planned outcomes after the first workshop are to publish (1) video recordings for the two sessions, (2) graphic summaries created in real-time, and (3) an interdisciplinary paper gathered from the different workshop discussions.

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Research. Innovation. Sustainability.

Past global changes as indicators for future changes and strategies for sustainability

Marie-France Loutre[1], P.A. Gell[2], K.J. Meissner[3] and B. Vannière[4]

Online, 15 June 2021

PAGES organized a session during the hybrid Sustainability Research & Innovation Congress 2021 (SRI2021; pastglobalchanges.org/calendar/26956), a joint initiative of Future Earth and the Belmont Forum, which was led by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Future Earth Australia.

International reports on climate, biodiversity and ecosystems, such as the Intergovernmental Panel on Climate Change (IPCC) and Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES), describe the unprecedented changes that the Earth system has experienced over the last few decades. While the data are clear, it is difficult for a human being to identify these changes and their potential consequences—partly because our individual memory is short, and partly because on a daily or annual basis we experience much larger changes and quickly adapt and get used to new conditions. In other words, we struggle to identify the baselines of changes and how these baselines shift with time. Therefore, it is important to identify reference points for the most recent changes, or at least to be aware of how humans are shaping the climate and ecosystems.

Human-induced climate change is altering some of the processes that underlie modes of climate variability that can have major impacts on societies. Short observational records make it difficult to understand the full range of natural climate variability and to robustly detect recent changes in these modes of variability. Nerilie Abram reviewed paleoclimate evidence for changes in the El Niño-Southern Oscillation, Indian Ocean Dipole and Southern Annular Mode during the last millennium. She discussed how unusual some of these phenomena have been over recent years and gave perspectives on the likely future of these systems (Fig. 1a).

Michael Reid described the deep history of human impacts on aquatic ecosystems. He highlighted how paleoecological reconstructions can provide avenues to determine impacts on ecosystems caused by human activities, including activities that took place long before the establishment of systematic ecological monitoring. He stressed the importance of understanding the relative and interactive effects of multiple stressors and showed, with an interesting example from the Murray-Darling Basin in Australia, the need to address all stressors, not just the most recent ones (Fig. 1b).

Threats to property and people linked to floods are becoming more and more important, in particular because of increasing population densities in areas prone to flooding. Furthermore, the magnitude, frequency, and timing are changing, thus exacerbating the issue. Extreme flooding can be documented through historical, botanical, and geological records. Bruno Wilhelm reviewed how these archives record floods and the information they can provide (Fig. 1c). He then showed how the flood risk assessment can be improved with these records and discussed avenues for improvement. Flood management and mitigation plans should take this information into account.

Simon G. Haberle provided a long-term perspective on the 2019-2020 Australian Bushfire Crisis. The paleoecological records from pollen and charcoal show an increase in fire activity during times of past climate change – particularly during transitions from cooler to warmer climates. The presence of humans on the Australian landscape for at least the last 65,000 years appears to have mediated past climate impacts on fire regimes and fire sensitive ecosystems through Aboriginal fire management practices. The cessation of these landscape management practices across much of Australia with the start of European colonization more than 200 years ago induce a shift from low but persistent levels of burning to a much more variable fire regime pattern (Fig. 1d).

The session concluded with a fruitful panel discussion. The importance of past climate and ecosystem reconstructions was discussed, especially in light of their capacity to improve risk assessments related to current and future changes. The need to improve communication channels between past global change experts and policy makers or other end users, such as insurance companies, was also highlighted. Overall, this session successfully brought together experts from different areas of the climate system and ecosystems to discuss changes, transitions, and resilience of vital systems upon which our well-being depends.

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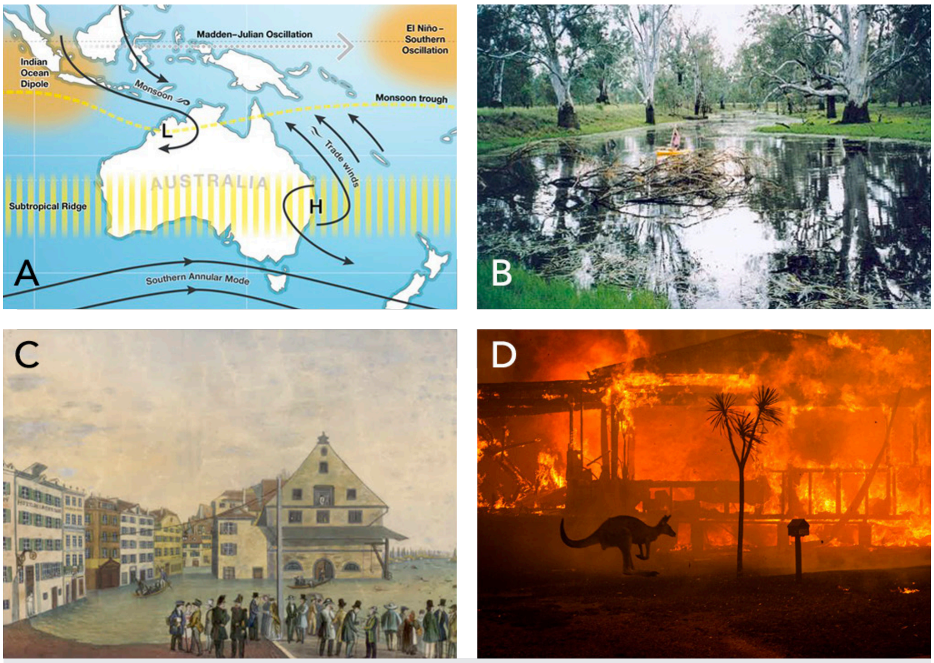

Figure 1: Illustration of the four topics discussed during this session. **(A)** Modes of climate variability; **(B)** human impacts on aquatic ecosystems; **(C)** flood and **(D)** fire hazards.
Image credits: **(A)** Australian Government, Bureau of Meteorology; **(B)** Peter Gell; **(C)** Meteoschweiz (Gasthaus zur Krone, Basel; Staatsarchiv Basel-Stadt, BILD13, 323); **(D)** Matthew Abbot (Lake Conjola, 31 Dec 2019; matthewabbott.com.au/PHOTOJOURNALISM/Black-Summer/1).

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Beyond paleoclimate ping pong

Nils Weitzel[1], C. Brierley[2], J. Bühler[1], M. Chevalier[3], B. Ellerhoff[1], V. Skiba[4] and K. Rehfeld[1,5]

Heidelberg, Germany, and online, 5-7 July 2021

A key question of the paleoclimate community is how paleoclimate data can be used to evaluate long-term predictability in climate models. How can we improve estimates of past climate variability and our understanding of the state and timescale dependency of Earth's climate? "Ping pong" serves as a metaphor to describe the back-and-forth in comparing paleoclimate data with model simulations. This is a core challenge in climate research, which requires a better understanding of proxies as well as the consequences of neglected or poorly simulated processes in climate models.

To address this question, this Climate Variability Across Scales (CVAS; pastglobalchanges.org/cvas) workshop (pastglobalchanges.org/calendar/26970) brought together a diverse pool of ~60 scientists, ranging from early-career scientists to experienced experts from various fields and different working groups, including CVAS, Speleothem Isotopes Synthesis and AnaLysis (SISAL; pastglobalchanges.org/sisal), 2k Network (pastglobalchanges.org/2k), and the PAGES-endorsed Paleoclimate Modelling Intercomparison Project (PMIP; pmip.lsce.ipsl.fr). One half participated online and the other half gathered at the "Internationales Wissenschaftsforum" in Heidelberg, Germany. Keynote talks focused on climate variability on different temporal and spatial scales, best practices for the joint use of models and proxies, the role of paleoclimate in future predictions, and the state of the art in the analysis and interpretation of various proxy types. Discussions resulting from these presentations continued in three working groups.

The first group discussed philosophical questions regarding the design and impact of data–model comparison studies, summarized in Figure 1. Among these were what insights into climate can be gained from data–model comparison, and how both sources of information can be leveraged. The importance of formulating a clear hypothesis prior to the comparison was stressed, as well as the need to explain experimental choices and assumptions such that the scope and limitations of the respective analysis are clearly defined. Consequently, techniques for a rigorous treatment of uncertainties are required and due to various uncertainties on both sides, data and models are not necessarily expected to "agree".

The second group formulated a research project based on the recommendations from the first group. Inspired by the keynote talks, the group decided to study the temperature–hydroclimate relationship in the tropics and test the hypothesis of positive covariability between the two. The participants identified suitable databases (e.g. PAGES2k Consortium 2017; Konecky et al. 2019; Comas-Bru et al. 2020) for a multi-archive and multi-proxy approach. Comparison against isotope-enabled simulations (e.g. Bühler et al. 2021) is planned. Key questions that the group identified include whether emerging isotope-enabled simulations facilitate more robust data–model comparisons, and how multiple archives and simulations can be used to understand the underlying mechanisms controlling the covariability of hydroclimate and temperature.

The third group started with the conundrum of reported agreement of global mean temperature variability in models and proxies on decadal-to-centennial scales (e.g. Neukom et al. 2019), whereas reconstructed local surface temperature variability is higher than in simulations (e.g. Laepple and Huybers 2014). The group reviewed the literature, with a focus on the spatial and temporal scales of interest. Finally, the group collected and assessed potential reasons to explain the conundrum, including effects from an overestimation of spatially uncorrelated variability in temperature reconstructions, misspecification of the spatial correlation structures in models, and the suppression of variability by climate field reconstruction methods. The group plans to expand the literature review and develop research protocols to quantify the contributions of identified potential explanations.

For most participants, the workshop was the first experience with a hybrid conference format, and the feedback was quite positive. We emphasize the importance of an appropriate technical infrastructure on site and the prior set-up of a clear workshop structure. The use of a virtual communication platform and shared working documents helped to connect virtual and on-site participants.

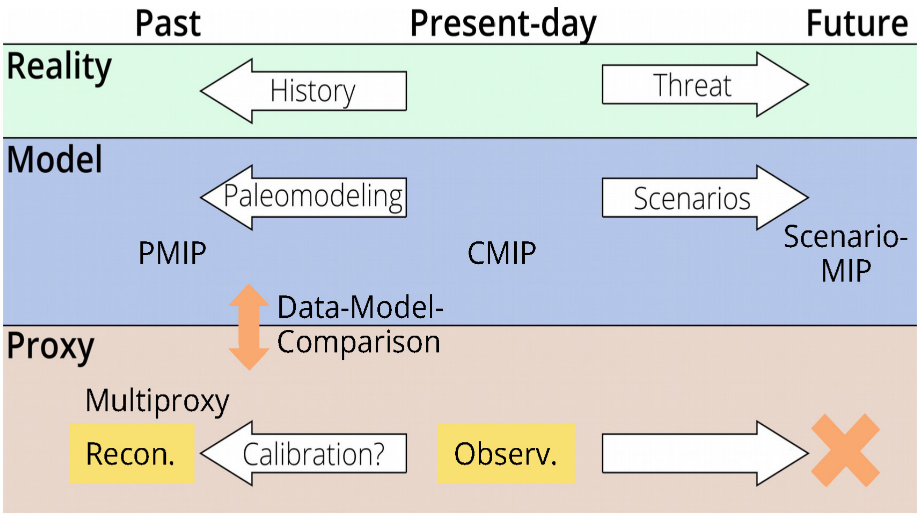

Figure 1: Key components and challenges of data–model comparison. The relevant tools, variables, intercomparison projects, and challenges (in orange) are illustrated with respect to the targeted time ranges. The workshop specifically addressed the overarching question of how paleoclimatology can contribute to solving research questions on future climate scenarios.

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