Revised PMIP proposal for CMIP FastTrack

Contacts: Masa Kageyama, Chris Brierley, Louise Sime, Christian Stepanek

In 2020 members of the international sea ice and paleo modelling communities came to together to tackle the long-standing puzzle of what drove Arctic warmth and a complete retreat of Arctic summer sea ice 127 000 years ago (*Guarino et al., 2020*). Whilst it has been known for some time that stronger spring insolation (up to +70 Wm^{-2}) at high northern latitudes drove Arctic land summer temperatures 4 °C higher than in the pre-industrial era, prior to 2020 climate model simulations failed to capture the intense summertime polar warmth, because they were unable to correctly capture sea-ice changes in response to the strong insolation forcing. Here, following on the success of a UK CMIP6 model to rapidly capture this complete ice loss (Figure 1), we propose a protocol to enable the CMIP community investigate whether CMIP7 models are capable of accurately simulating the sea-ice free Arctic that last occurred 127 000 years ago. The results of this form of test have already been shown to map directly how models respond to CO2 forcing in a warmer world (*Guarino et al., 2020; Kageyama et al., 2021; Otto-Bliesner et al. 2021a,b; Diamond et al., 2021*)

Background

The Last Interglacial 119 000 to 130 000 years ago preceded our warm Holocene Interglacial. The atmospheric CO_2 concentration at 127 000 years ago was 275 ppm (precisely measured from gas bubbles in ice cores). Compared to the preindustrial, the global mean temperature was 0.5-1.5°C warmer (*IPCC AR6 WG1 Chap. 2*), the Arctic was around 4°C warmer in summer (*Sime et al., 2023*), and the Greenland and Antarctic ice sheets were in a similar configuration (*Otto-Bliesner et al., 2017*). The seasonal contrast in polar regions was much larger than today due to differences in the Earth's orbital parameters that are also precisely known (e.g. *Otto-Bliesner et al., 2017*).

There is already a major paleoclimate community effort focused on 127 000 years ago. The conventional PMIP-defined experiment *lig127k* (CMIP6 controlled vocabulary) was run by 15 CMIP6 models (*Otto-Bliesner et al., 2021a*) and has been involved in more than 80 peer-reviewed published papers. That experimental protocol requires changes in the distribution of incoming solar radiation across seasons and latitudes (controlled in most models via three orbital parameters) and the concentration of greenhouse gases. No changes in prescribed vegetation or topography and land-sea mask are required. This simulation is therefore directly equivalent to the piControl, from which the initial conditions can be taken and the anomalies are computed, except in the prescription of a slightly changed atmospheric gases and orbital parameters - making it straightforward to set-up.

Here we propose **a 100 year-long simulation, which starts from the *piControl* and abruptly imposes observed values for the insolation distribution and greenhouse gases**. It focuses on the impact of the strong insolation anomaly on sea ice (up to 70 Wm^{-2} in the Arctic). This run length is justified as the Arctic sea ice response can be reached within 30 years (Fig. 1). This proposal mimics *abrupt-4xCO2* and could be used for process-based comparison of past and future forcings. Furthermore, if modelling groups choose to extend the simulation, their work will comply with the *lig127k* protocol.

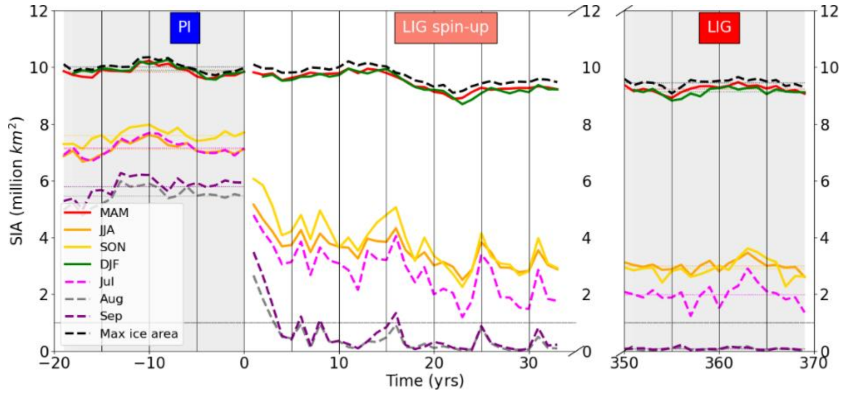

Figure 1. The loss of Arctic sea-ice during the lig127k spin-up, for HadGEM3 (Diamond et al., 2021). Comparison of seasonal Arctic sea-ice area between *piControl* (left), the proposed experiment (middle) and the equilibrated state of *lig127k* (right).

How do you envisage the experiment will be used?

The proposed simulation is easy to set-up and short to run, being equivalent to a 100 year long piControl. We thus anticipate all centres would be able to run the simulation. Whilst we ask for a 100 year length simulation, Figure 1 demonstrates that for groups for which 100 years is challenging even a 30-year simulation may be sufficient to test the sea ice response to the radiative forcing of 127 000 years ago. New sea surface, sea ice, and summer temperature datasets from the Arctic have recently been published for 127 000 years ago by *Kageyama et al*. (2021), *Sime et al.* (2023), and *Vermassen et al.* (2023), yielding excellent data for evaluating simulations. Model centres can use these datasets to explore the accuracy of their model's sea ice response. Furthermore, the institutes of the authors above have the will and capacity to immediately fully utilise the proposed experiments results to support the research done in the framework of PMIP and analyse them in conjunction with other CMIP FastTrack experiments such as *abrupt-4xCO2* or *1pctCO2*, with *piControl* as reference. This would include in-depth analysis of sea ice changes following Diamond et al. (2021).

Beyond these initial uses, the proposed experiment can be employed to address other questions which are highly relevant to future climate change. As well as helping with the identification of processes leading to this Arctic warming and sea ice loss, it offers a chance to examine how a predominantly high latitude climate forcing translates into climate signals at lower latitudes – in particular via the interplay between the direct response to the radiative forcing and the subsequent feedbacks of the climate system in terms of ocean and atmosphere circulation. Model results can, and would, also be compared to a variety of climate reconstructions from ice sheets, ocean and continental realms, documenting changes in temperature, sea ice and features of the hydrological cycle such as monsoons - in collaboration with experts on interglacial reconstructions, such as from the Quaternary Interglacials (QUIGS) PAGES group.

If model centres are willing to extend their simulations of this proposed experiment it would allow additional studies looking at equilibrium climate change, including climate sensitivity, long-term AMOC changes, and the stability of tipping elements in a warmer climate, such as quantifying the ice-sheets' response to simulated warmth using ice sheet models. It has been shown that the PMIP4 lig127k simulations see the most robust changes in ENSO properties for any PMIP or DECK simulation (*Brown et al.*, 2020), suggesting that *lig127k* is also particularly useful towards understanding modes of internal variability in a climate state different from today. Therefore, we see this proposed simulation will bridge the gap between CMIP and PMIP and lead to further synergies in model intercomparison and validation across time scales.

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Scientific reception of the lig127k modelling protocol

Here we present a selection of, in our opinion important, research items that have employed results from the PMIP *lig127k* simulation, proving utility of the modelling protocol that is proposed here in a revised form. Analyses are still ongoing, and this publication list is therefore not final. More scientific work, that refers to the *lig127k* modelling protocol, is referenced at a collection of publications that are related to the work of the PMIP Interglacials work group (https://www.pmip-interglacials.de/publications/publications-by-first-author/).

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What can build off it?

The *lig127k* protocol is published:

Otto-Bliesner, B. L., Braconnot, P., Harrison, S. P., Lunt, D. J., Abe-Ouchi, A., Albani, S., Bartlein, P. J., Capron, E., Carlson, A. E., Dutton, A., Fischer, H., Goelzer, H., Govin, A., Haywood, A., Joos, F., LeGrande, A. N., Lipscomb, W. H., Lohmann, G., Mahowald, N., Nehrbass-Ahles, C., Pausata, F. S. R., Peterschmitt, J.-Y., Phipps, S. J., Renssen, H., and Zhang, Q.: The PMIP4 contribution to CMIP6 – Part 2: Two interglacials, scientific objective and experimental design for Holocene and Last Interglacial simulations, Geosci. Model Dev., 10, 3979–4003, https://doi.org/10.5194/gmd-10-3979-2017, 2017.

The proposed experiment would benefit from a formal protocol description and further preliminary results (after Diamond et al., 2021). We would start work on this imminently.

Why was this chosen from above other PMIP experiments

Various reasons led to us initially choosing *lig127k* as a candidate for the CMIP7 fast track simulations. Here we have revised this to propose a much shorter simulation that still benefits from many of the same advantages, but requires substantially less computing resource. The Simplicity of set up, clarity of purpose, being a model setup that has proven very successful for studying model output in a paleoclimatic framework, and availability of a relatively rich geologic and glaciologic archive: The Last Interglacial (*lig127k*) is at the moment the interglacial time slice most relevant for a future warmer Arctic for which an official PMIP protocol already exists. An important asset is quantity and distribution of existing climate reconstructions. While earlier warm periods like Miocene and Eocene may also be relevant for future warm climates (given the present-day concentrations of greenhouse gases), they have a sparse network of climate reconstructions, and interpretation of their climate in the context of a future warmer world is complicated by differences in land surface conditions and in particular of the continental configuration.