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Last Interglacial Arctic sea ice as simulated by the latest generation of climate models

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The 16 models that simulated the Last Interglacial climate as part of the CMIP6/PMIP4 exercise consistently produce a smaller Arctic summer sea-ice area compared to the pre-industrial period, but their reduction ranges widely (28–96% of the pre-industrial area). Causes for these differences need further investigation.

Why are we interested in changes in the Arctic sea ice during the Last Interglacial?

The Last Interglacial (LIG, 129-116 kyr before present (BP)) is characterized by a strong insolation forcing leading to an Arctic land summer warming of 4–5°C relative to the pre-industrial period (PI; Guarino et al. 2020). The increase in surface temperatures has been associated with changes in Arctic sea ice potentially comparable in magnitude to those projected for the near future (Guarino et al. 2020). Simulations of the LIG climate, thus, provide a tool to study the processes and feedbacks related to current Arctic sea-ice loss and polar warming. The high availability of sea-ice proxy data, compared to previous interglacial periods, also makes the LIG a good case study to evaluate the ability of climate models to simulate sea ice during periods warmer than today. In recognition of the importance of the LIG in our understanding of climate change, it was formally included as a target period in the latest Paleoclimate Modelling Intercomparison Project (PMIP4). The joint experimental protocol differs primarily from the PI experiment in the astronomical parameters and greenhouse gas concentrations (Otto-Bliesner et al. 2017). The LIG PMIP4 experiment, thus, represents a reference point for discussions of model reconstruction of Arctic sea ice for this period.

What have we learned from the CMIP6/PMIP4 LIG experiment?

The Arctic sea ice, simulated by the 16 climate models that run the LIG experiment, was analyzed by Kageyama et al. (2021). Figure 1 shows the multi-model mean (MMM) for the winter (DJF), summer (JJA) and annual sea-ice concentration. The larger sea-ice retreat relative to the PI appears in summer when the insolation anomaly reaches its maximum. During this season, the Greenland, Barents and Chukchi seas experience the most significant ice loss. The minimum monthly MMM at the LIG is equal to $3.2 \pm 1.5 \times 10^6$ km^2, which represents a decrease of about 50% compared to the PI. Three models (HadGEM3-GC3.1-LL, CESM2, and NESM3) simulate an above-average retreat of the sea-ice edge in summer relative to the PI, with a total sea-ice area close to, or less than, 1×10^6 km^2. However, of these three, only HadGEM3-GC3.1-LL and CESM2 have a realistic representation of the PI Arctic sea-ice seasonal cycle. The HadGEM3-GC3.1-LL model shows the largest sea-ice retreat, with the Arctic Ocean becoming ice-free at the end of summer (Guarino et al. 2020). On the other end of the spectrum, the INM-CM4-8, GISS-E2-1-G and FGOALS-g3 models simulate large sea-ice areas greater than 5×10^6 km^2 at the end of summer. This disparity between models is also found in winter. During this season, the maximum monthly MMM is equal to $16.0 \pm 2.6 \times 10^6$ km^2, with most models simulating a slight increase compared to the PI. However, the ACCESS-ESM1-5, EC-Earth3-LR and INM-CM4-8 models show a reduced sea-ice area relative to the PI.

What is the cause of inter-model differences?

There are many characteristics of climate models that can lead to variable results, including differences in model physics and chemistry, discretization scheme and numerical resolution, parameterization of subgrid-scale processes, and tuning parameters. Given that these aspects of models and their feedbacks are interlinked non-linearly, it can be problematic to attribute specific differences in results to specific differences in process representation. However, some progress has been made. The large spread of sea-ice reduction in the PMIP4 models has been linked to differences in surface albedo and optical properties of clouds, which directly impact the surface radiation balance (Kageyama et al. 2021), as illustrated for the IPSL-CM6A-LR and HadGEM3-GC3.1-LL models in Figure 2.

An indepth analysis of processes explaining the LIG-PI difference in Arctic sea ice in the IPSL-CM6A-LR model highlighted the predominant influence of ice-air heat exchange on sea-ice melt, compared with ice–ocean heat exchange (Sicard et al. 2022). The specific sea-ice model formulation is also crucial. The large sea-ice loss in the HadGEM3-GC3.1-LL model has been attributed to

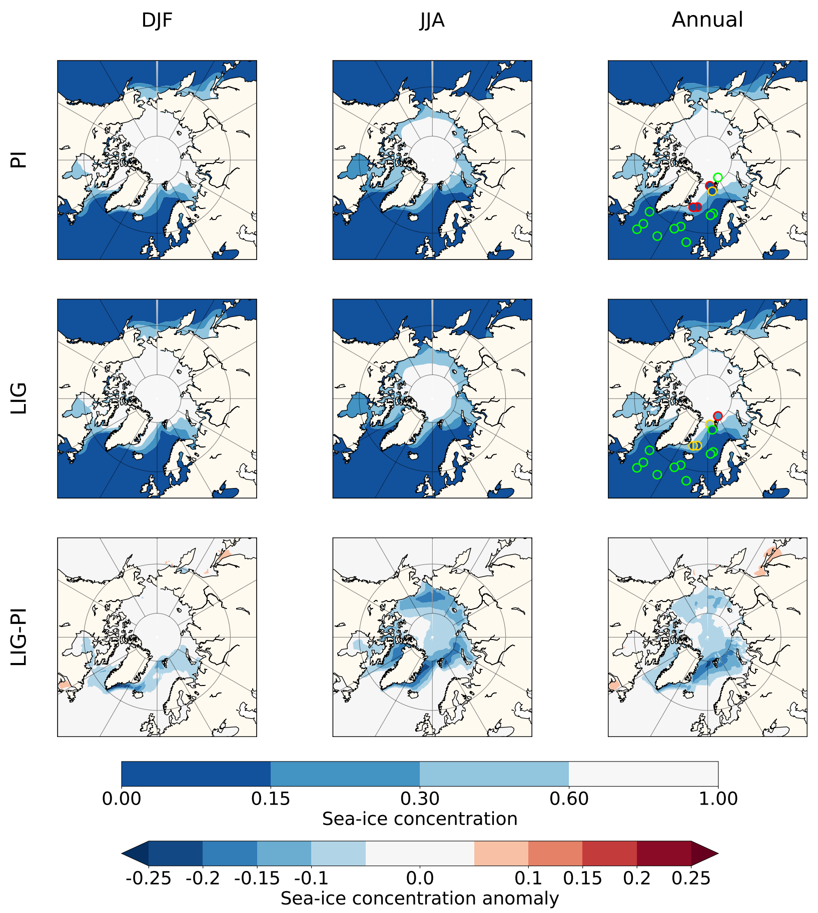

Figure 1: Multi-model mean of the Arctic sea-ice concentration for the pre-industrial (PI) and Last Interglacial (LIG) periods and LIG-PI differences. Results are plotted for winter (DJF), summer (JJA) and the annual average. The fill color of the symbols corresponds to the observed values at sites where proxy data are available for the LIG (see Kageyama et al. (2021) for more details on the sea-ice data synthesis). For the PI, a dataset obtained from different satellite and in-situ observations is used (Reynolds et al. 2002). The color of the symbol outline indicates the number of models simulating the observed sea-ice cover: green for nine or more models, yellow for five to nine models and red for five or fewer models. Adapted from Kageyama et al. (2021).

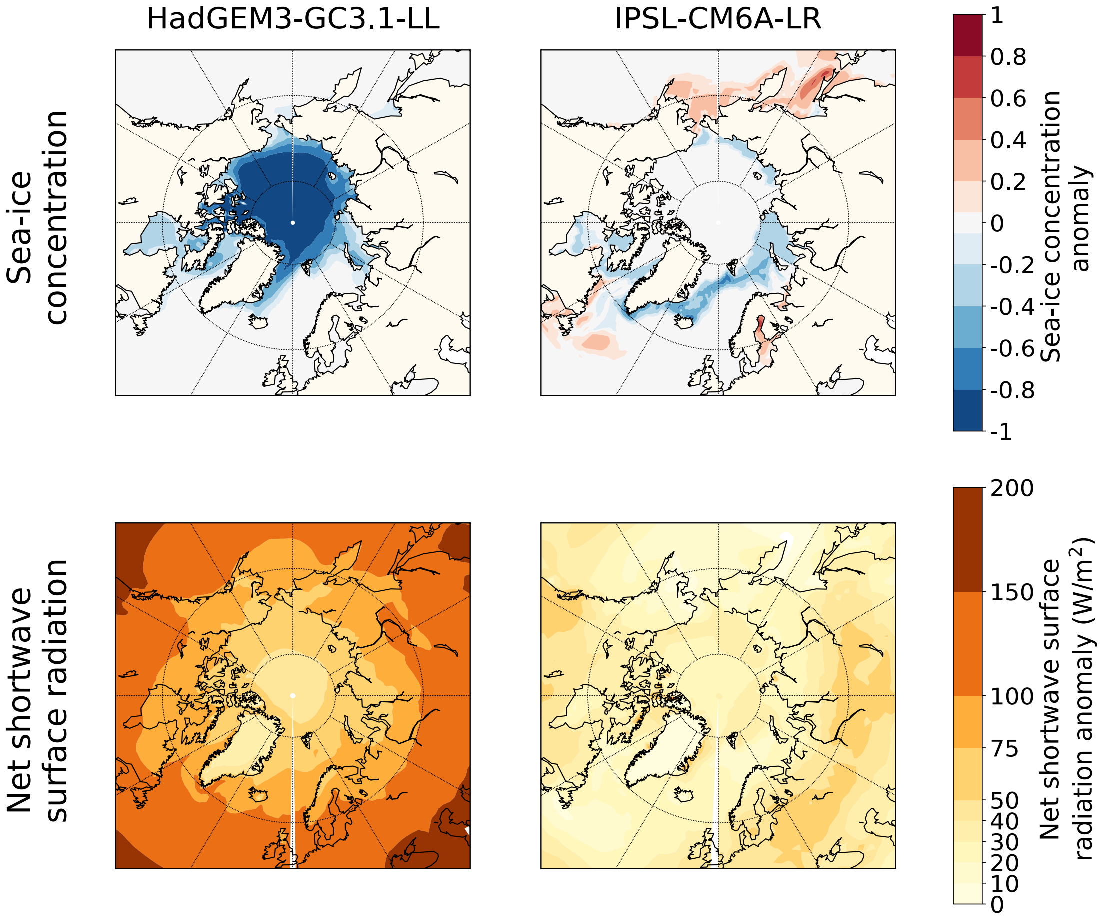

Figure 2: LIG-PI differences of the summer sea-ice concentration (top) and net shortwave surface radiation (W/m^2, bottom) simulated by the HadGEM3-GC3.1-LL and IPSL-CM6A-LR models.

the advanced melt-pond scheme included in its sea-ice model (Guarino et al. 2020). Specifically, the formation of melt ponds and leads allow the surface to absorb more incident solar radiation and, thereby, encourage more sea-ice melt (Diamond et al. 2021). Models with explicit representation of melt ponds seem to simulate particularly low LIG sea-ice area during summer (Diamond et al. 2021) and can also capture the summer warming observed in LIG continental records (Guarino et al. 2020).

Comparison with the new sea-ice data analysis

To allow for a model–data comparison, the PMIP4 synthesis paper on LIG Arctic sea ice includes an updated sea-ice data compilation (Malmierca-Vallet et al. 2018; Kageyama et al. 2021). This data synthesis is based on a set of marine records collected in the Arctic Ocean, Nordic seas, and northern North Atlantic. Models realistically capture annual sea-ice concentration in the North Atlantic region and the Norwegian Sea during the LIG, but generally simulate too much ice close to the sea-ice edge in the Greenland Sea and at the two northernmost sites in the central Arctic (Fig. 1). However, there are still significant uncertainties related to the sea-ice data in the central Arctic so that no strong conclusions can be drawn from it (Kageyama et al. 2021).

Conclusions and way forward

CMIP6 climate models that have run the LIG experiment all show a substantial reduction in the summer sea-ice area in the Arctic at 127 kyr BP (Kageyama et al. 2021). However, models disagree on the magnitude of this decline. Given the spread among model results and uncertainties in LIG Arctic proxy reconstructions of sea ice and temperature, it is therefore currently difficult to determine whether the Arctic Ocean experienced ice-free conditions during the LIG. Investigations so far have emphasized the importance of atmosphere–ice relevant processes, such as melt-pond formation or cloud optical properties, which are also crucial in determining radiation fluxes over sea ice (Guarino et al. 2020; Kageyama et al. 2021; Diamond et al. 2021; Sicard et al. 2022). Interestingly, ocean–ice fluxes have not yet been shown to be particularly significant, and have received less attention in the last few years compared to atmosphere–ice fluxes.

Ongoing work by the authors of this article and their groups aim to make further progress towards our understanding of LIG Arctic sea ice through several avenues. In a series of papers in preparation, we are investigating (1) the utility of proxies of LIG Arctic summer air temperatures to reconstruct sea ice (Sime et al. 2022); (2) the role of the LIG wind field, sea-ice transport, and Arctic ocean circulation in explaining reduced LIG sea ice (Sicard and de Boer, in prep); (3) the correspondence between LIG Arctic sea-ice loss, and that found in the CMIP6 transient simulation in which the atmospheric CO_2 concentration increase at a rate of 1% per year (Eyring et al. 2016; Sicard and de Boer, in prep); and (4) the sensitivity of Arctic sea ice to the parameterization of meltponds for the LIG, and in the near future (Diamond et al. in prep).

Following the CMIP6/PMIP4 exercise, a flurry of papers has provided new insights on the state of the Arctic sea ice during the LIG, raising with them new and challenging scientific questions. With the targeted modeling studies, alongside ongoing work on sea-ice reconstructions, the future looks promising for further breakthroughs in our understanding of LIG Arctic sea ice, and how it relates to our future.

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