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Key Points:

- The oceanic region north of Greenland is most resilient to sea-ice loss under both Last Interglacial solar forcing and future CO₂ forcing
- Close to ice margins, wind and ocean heat transport processes impact winter sea-ice distribution differently depending on the forcing

Supporting Information:

Supporting Information may be found in the online version of this article.

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Similarities and Differences in Arctic Sea-Ice Loss During the Solar-Forced Last Interglacial Warming (127 Kyr BP) and CO₂-Forced Future Warming

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Abstract Based on a 7-member global circulation model ensemble from CMIP6/PMIP4, we compare the regional distribution of Arctic sea ice between a simulation representing the Last Interglacial (LIG) climate, with solar-forced warming, and an idealized future CO₂-forced simulation with a similar annual sea-ice volume. The two simulations feature small but robust differences in the Central Arctic and Baffin Bay during summer, and larger differences at the sea-ice margins in the sub-Arctic Atlantic and North Pacific sectors during winter. Our results indicate that, under both forcings, sea ice persists north of Greenland until late summer, suggesting that the assumption that this region is the “Last Ice Area” is robust and holds for other climate states. However, we show that processes influencing sea-ice distribution in winter, such as Atlantification and sea-ice drift, differ and need to be further investigated.

Plain Language Summary The Last Interglacial (LIG; 129–116 Kyr before present) represents the most recent period with Arctic summer temperatures significantly higher than during the pre-industrial era. This warming results from higher insolation than today in the Arctic, and is associated with changes in Arctic sea ice that are potentially comparable in magnitude to those projected for the near future. Therefore, the LIG climate represents a good testing ground for investigating processes responsible for sea-ice loss. Here, we compare the distribution of the Arctic sea-ice concentration for solar-forced LIG warming and CO₂-forced future warming in climate simulations. The aim is to determine whether the decline in Arctic sea ice follows a similar spatial pattern for two distinct forcings when focusing on periods with similar sea-ice volumes. The main differences occur in winter, close to ice margins. They are related to changes in wind intensity over the Greenland and the northern Bering Seas, and differences in Atlantic Water temperatures, which regulate ice melting in the Barents Sea. In summer, sea-ice cover in Baffin Bay experiences the greatest changes due to differences in circulation regime. As suggested by previous studies, the region north of Greenland is the most resilient to the disappearance of Arctic sea ice.

1. Introduction

As global climate is changing due to rising greenhouse gas concentrations, the Arctic region is warming at least three times more than the rest of the world, with dramatic consequences for the cryosphere (Fox-Kemper et al., 2021; Rantanen et al., 2022). Observations of sea-ice cover report a clear decreasing trend in Arctic sea ice in all seasons and all regions since the first satellite measurements in 1979 (Wang et al., 2022). Pan-Arctic sea-ice area decline has been strongest in summer, with September ice-loss rates as high as 12.8% ± 2.3% per decade relative to a 1981–2010 mean (Meredith et al., 2019). Climate projections indicate that the Arctic is likely to experience ice-free conditions at the end of summer at least once before 2050 (Fox-Kemper et al., 2021). However, owing to internal variability, differences between climate models, and scenario uncertainties, there is still no consensus on when a permanent transition to seasonal sea ice will occur, with timings ranging from 2035 to 2100 (Docquier & Koenigk, 2021a; Karami et al., 2023; Notz & SIMIP Community, 2020).

To make progress in our understanding of sea-ice processes, the focus has turned to the Last Interglacial (LIG; 129–116 Kyr before present; Otto-Bliesner et al., 2017). While some proxies have been interpreted to point to perennial sea ice in the central Arctic (Cronin et al., 2010; Kremer et al., 2018; Stein et al., 2017), other studies suggest it was seasonally ice-free during the LIG (Sime et al., 2023; Vermassen et al., 2023). This period, also sometimes called Marine Isotope Stage 5e (MIS 5e) or the Eemian, has been extensively analyzed through proxy

reconstructions and has been the focus of targeted experiments of the Paleoclimate Modeling Intercomparison Project (PMIP4; Kageyama et al., 2018), in its contribution to CMIP6. The 16 climate models that have run the CMIP6/PMIP4 LIG experiment simulate a substantial reduction in the summer minimum sea-ice area with a multi-model mean (MMM) equal to $3.2 \pm 1.5 \times 10^{-6} \text{ km}^2$. This represents a decrease of approximately 50% compared to the pre-industrial (PI) period (Kageyama et al., 2021). The range of simulated sea-ice loss is large, varying between 30% and 96% of the PI concentration. However, models that have a seasonally (nearly) ice-free Arctic reproduce continental surface air temperature (SAT) reconstructions more accurately, suggesting that this is a more likely climate state at the LIG (Sime et al., 2023). Differences between models have so far been attributed to differences in albedo feedback, cloud effects on the incident solar radiation, and possibly oceanic and atmospheric heat transports (Diamond et al., 2021; Guarino et al., 2020; Kageyama et al., 2021; Sicard, de Boer, & Sime, 2022; Sicard, Kageyama, et al., 2022). The spatial distribution of the remaining late summer sea ice at the LIG also exhibits variations across models, with maximum concentrations found alternatively in the Lincoln Sea north of Greenland, the Central Arctic, or the Beaufort Sea north of Canada. A comparison with an Arctic sea-ice proxy synthesis shows that models realistically capture annual sea-ice concentration in the North Atlantic region and Norwegian Sea during the LIG, but generally simulate too much ice close to the sea-ice edge in the Greenland Sea (Kageyama et al., 2021). Unfortunately, sites where semi-quantitative sea-ice reconstructions exist in the Central Arctic Ocean are scarce and often lack either the temporal resolution or age model confidence to unequivocally identify MIS 5e (Kageyama et al., 2021; Razmjooei et al., 2023; Vermassen et al., 2023).

Today, summer sea-ice loss occurs primarily at sea-ice margins, in particular in the East Siberian, Chukchi, Kara, and Beaufort Seas (Onarheim et al., 2018). CMIP6 models support the assumption that the region from the western Canadian Arctic Archipelago to the northern coast of Greenland is the last area of the Arctic to lose its perennial ice cover (Notz & SIMIP Community, 2020; Wei et al., 2020). For lack of evidence, proxy reconstructions of sea ice often assume that if the region north of Greenland is ice-free in the past, then so is the rest of the Arctic (Detlef et al., 2023; Vermassen et al., 2023). However, it remains unclear whether this “last bastion,” now commonly referred to as the “Last Ice Area” (Moore et al., 2019), assumption is robust during previous warm periods. The CMIP6/PMIP4 LIG simulations suggest similarities between processes responsible for sea-ice loss during the LIG and the near future (here referred to as the next 50–100 years), showing a correlation between the total sea-ice area during these two periods among the models (Kageyama et al., 2021). However, the distribution of sea ice is influenced by winds, atmospheric heat fluxes, and ocean heat transport, all of which could differ between LIG solar-forced warming and future greenhouse warming. In particular, the radiative anomalies of LIG solar forcing and future greenhouse forcing have very different seasonal expressions (see Figure 1 in Otto-Bliesner et al., 2017 and Figure S1 in Supporting Information S1). To evaluate whether the LIG can be used as an analog for a future climate state in the Arctic, it is necessary to better constrain the spatial pattern of sea-ice loss for these periods. Here, using a 7-member global circulation model ensemble from CMIP6/PMIP4, we investigate the similarities and differences in the Arctic sea-ice distribution in two simulations: a time-slice simulation representing the climate 127,000 ago (127 Kyr BP) and a transient CO₂-forced experiment depicting a future with a similar annual sea-ice volume to the LIG experiment.

2. Materials and Method

As part of PMIP4, a total of 16 models produced the LIG experiment, but this study is limited to the seven models which also had idealized future warming experiments (see details below) and for which we had access both to the sea-ice thickness and sea-ice concentration variables on the Earth Grid System Federation (ESGF) database (<https://esgf-node.llnl.gov/projects/esgf-llnl/>, last downloaded on 08th May 2023). Sea-ice concentration refers to the areal fraction of a given model grid cell that is covered by sea ice, independent of the thickness of that ice (SIMIP; Notz et al., 2016). We analyzed seven CMIP6/PMIP4 models (see Table S1 in Supporting Information S1). Model outputs were interpolated on a 1° grid using the Climate Data Operators (CDO; Schulzweida, 2022) to compute the multi-model mean, referred as MMM hereafter. For calculations across the Arctic, we used the region between 60°N and 90°N.

The LIG has been studied within PMIP since its phase 3 but in PMIP4 (phase 4), a common experimental protocol has been established (Otto-Bliesner et al., 2017). The recommended experiment is a time-slice experiment representing the climate 127 Kyr BP (*lig127k*). The LIG climate was mainly different from that of the PI period because of variations in the Earth's orbital parameters. At 127 Kyr BP, the obliquity and eccentricity were higher

Table 1

Overview of the 10-Years Period of the *IpctCO2* Simulation Selected for Each Climate Model, and the Associated Atmospheric CO₂ Concentration and Surface Warming

Climate models	Time period of the <i>IpctCO2</i> simulation used here	Corresponding mean atmospheric CO ₂ concentration (ppm)	Corresponding sea-ice volume loss (10 ³ km ³)	Arctic warming from PI (°C), for LIG (left) and <i>IpctCO2</i> run (right)	
ACCESS-ESM5-1	56–66	514	−9.19 (−43%)	1.51	3.11
CESM2	42–52	447	−14.18 (−47%)	0.53	2.62
GISS-E2-1-G	42–52	447	−8.10 (−36%)	1.01	2.20
IPSL-CM6A-LR	44–54	456	−12.32 (−42%)	0.49	2.23
MIROC-ES2L	32–42	405	−6.85 (−24%)	0.10	2.15
NESM3	09–19	322	−3.77 (−22%)	0.32	1.45
NorESM2-LM	50–60	484	−11.38 (−43%)	0.31	2.36

than they are today, and the perihelion was located near the summer solstice. This orbital configuration results in an amplified seasonal cycle in the high latitudes of the Northern Hemisphere compared to today (Figure S1 in Supporting Information S1). The CMIP6/PMIP4 LIG simulations were forced by prescribed orbital parameters according to Berger and Loutre (1991, 1999). Greenhouse gas forcing was globally uniform with greenhouse gas concentrations close to those of the PI period. The atmospheric concentration of CO₂ (Bereiter et al., 2015; Schneider et al., 2013), CH₄ (Loulergue et al., 2008; Schilt, Baumgartner, Schwander, et al., 2010) and N₂O (Schilt, Baumgartner, Blunier, et al., 2010; Schilt, Baumgartner, Schwander, et al., 2010) were derived from Antarctica ice cores and aligned with the Antarctic Ice Core Chronology 2012 (AICC2012; Bazin et al., 2013). To prevent artificial biases in the analysis due to the phase lag in the LIG seasonal cycle compared to present day (Bartlein & Shafer, 2019; Joussaume & Braconnot, 1997; Timm et al., 2008), we adjusted the LIG monthly outputs using the PaleoCalAdjust algorithm (Bartlein & Shafer, 2019).

The LIG experiment is here compared to an idealized simulation of the future climate for which the annual Arctic sea-ice volume is similar. Specifically, we use the CMIP6 DECK *IpctCO2* experiment (Eyring et al., 2016), a transient experiment in which the atmospheric CO₂ concentration increases at a rate of 1% per year. This gradual increase achieves a quadrupling of CO₂ after 140 years, but the climate system is still highly transient. Compared with the PI experiment, only the atmospheric CO₂ forcing is modified. The boundary conditions and solar forcing are identical (Table S2 in Supporting Information S1). The continuously increasing CO₂ leads to rising temperatures and shrinking Arctic sea-ice cover, with a rate of sea-ice reduction depending on the model. In each model, we select a period in the *IpctCO2* experiment for which the annual-averaged Arctic sea-ice volume is similar to that in its LIG experiment. To identify such a period, we compute the 10-year running average of sea-ice volume for each model and choose the time when this mean is closest to the equilibrium value for the LIG. In the MMM, these conditions are reached at a CO₂ atmospheric concentration around 440 ppm. However, the variation across the models is large (Table 1). For example, the NESM3 model has a much larger seasonal cycle than most of CMIP5/6 models (Shen et al., 2021), which is amplified under LIG climate forcing. It also has the highest effective climate sensitivity (ECS; Otto-Bliesner et al., 2021) and the highest sensitivity of the Arctic sea-ice area to the rise in global mean surface temperature (Notz & SIMIP Community, 2020). This results in the fastest reduction in Arctic sea-ice volume from its annual PI state to its annual LIG state under the *IpctCO2* forcing, compared to other models. It reaches its LIG Arctic sea ice already at a CO₂ value of about 320 ppm, which is far below the present-day CO₂ concentration of about 420 ppm.

3. Differences in Sea-Ice Patterns

Figures 1a–1c show the *IpctCO2*–*lig127k* differences of annual, winter (DJF), and summer (JJA) MMM sea-ice concentrations over the Arctic. In the following, we report only the differences between the CO₂-forced and LIG simulations, which have the same sign in at least five of the seven models. We consider such differences as robust.

The amount and spatial distribution of Arctic sea ice are determined by a complex interplay between dynamic processes, such as sea-ice transport forced by winds and ocean currents, and thermodynamic processes, such as

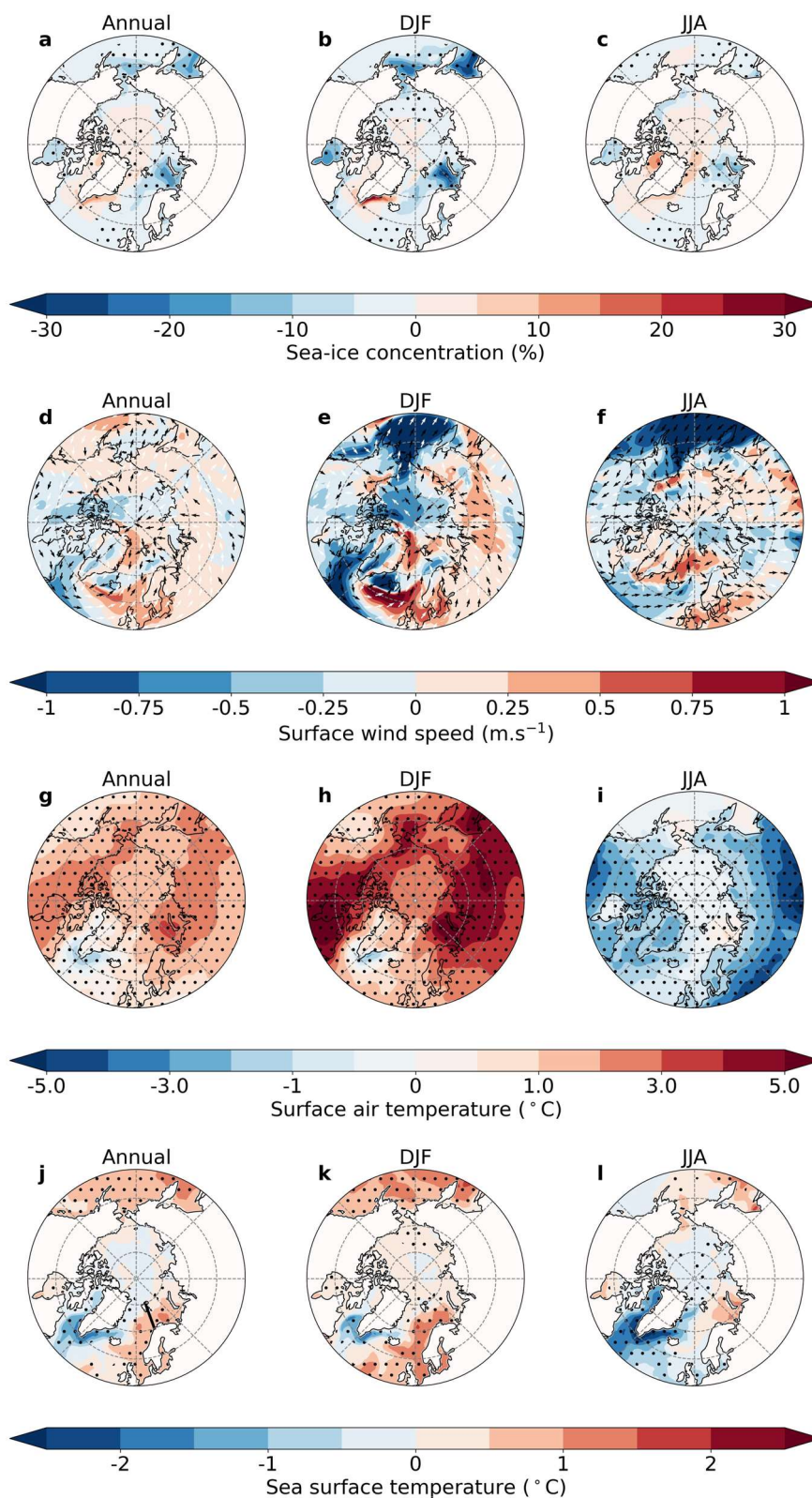


Figure 1.

sea-ice growth and melting. Although a comprehensive analysis of these processes in the seven models for both periods and all seasons is beyond the scope of this study, we address the main drivers of the observed results. On an annual average, the MMM sea-ice concentration differs most between the CO₂-forced and LIG simulations (i.e., more than 10% and the same sign in 5/7 models at least) close to the sea-ice margins outside the Central Arctic (Figure 1a). These areas include the water surrounding Greenland, the Barents Sea, the Bering Sea, and the Central Arctic, and are discussed individually below.

On both sides of Greenland, the annual MMM sea-ice concentration points to more ice in the CO₂-forced experiment than in the LIG simulation (Figure 1a). Over Greenland, the sea level pressure (SLP) is higher in the CO₂-forced simulation (Figure S4 in Supporting Information S1) and drives an anomalous anticyclonic circulation around the island. In particular, northerly winds northeast of Greenland are stronger, and northerly winds southwest of Greenland are weaker (Figures 1d and 1e). In the CO₂-forced simulation, surface winds push more ice along the East Greenland shelf break farther south, where ice tends to accumulate. Analogously, on the western side, there is a weaker southward sea-ice export, resulting in an accumulation of ice in northern Baffin Bay. Furthermore, these differences in sea-ice concentration are associated with changes in surface air temperature (SAT, Figures 1g–1i). Under CO₂-forcing, the Arctic receives less solar radiation during summer than in the LIG (Figure S5 in Supporting Information S1), mostly due to differences in the orbital configuration (Figure S1a in Supporting Information S1). This leads to lower SAT over Greenland. Katabatic winds from cooler Greenland further enhance the negative differences in sea surface temperature (SST) in the surrounding ocean, in particular in the south (Figures 1j–1l). These cooler SST and SAT together contribute to the thermodynamic forcing that leads to more sea ice in the CO₂-forced scenario than in the LIG.

The mechanisms described above are valid in the MMM, in the sense that they describe robust signals (in >4/7 models). However, these mechanisms are not strong in all the models (Figures S4–S8 in Supporting Information S1) and the signal in the MMM can be dominated by a few individual models. For example, the ACCESS-ESM1-5 and IPSL-CM6A-LR models have the largest differences in annual sea-ice concentration southeast of Greenland compared to the other models, whereas GISS-E2-1-G does not show large differences between the simulations (Figure S8 in Supporting Information S1).

The other areas where sea-ice concentration shows clear differences between the simulations are the Barents and Bering Seas. In both regions, the MMM sea-ice concentration is lower in the CO₂-forced experiment, with differences reaching up to 20% locally. In the Barents Sea, the spatial pattern of the differences is similar in the summer and winter, but changes are smaller in summer (Figures 1a–1c). Unlike over the Greenland Sea, surface wind differences between the two experiments are small (from -0.25 to 0.25 m.s⁻¹, or non-significant) and therefore, have less direct impact on sea ice (Figures 1d–1f). Here, sea-ice concentration is mainly influenced by thermodynamic processes. Under CO₂-forced conditions, the models generally simulate higher sea surface temperatures in the Norwegian and Barents Seas than during the LIG (Figures 1j–1l). This surface warming is maximum in winter, with differences in temperature exceeding 1°C along the Norwegian coast. This signal follows the inflow of Atlantic Water (AW) to the Arctic through the Barents Sea. It extends to the deeper layers, as illustrated by the vertical distribution of the differences in ocean temperatures through the Barents Sea Opening (see section in Figure 1j) between northern Norway and southern Svalbard (Figure 2, for all models except NESM3). Therefore, the lower sea-ice concentrations in the CO₂-forced simulations compared to the LIG are likely a result of the stronger bottom melt at the base of the sea-ice layer. Indeed, bottom melting is stronger than surface melting over the Barents Sea in all four of the models where these outputs are available (not shown here). These results are in line with previous studies showing that increased northward ocean heat transport leads to sea-ice reduction in the Barents Sea through more bottom melt (Årthun et al., 2012, 2019, 2021; Docquier & Koenigk, 2021b; Koenigk & Brodeau, 2014). Further, larger ocean heat transport and sea-ice loss generate stronger upward heat fluxes into the atmosphere, cooling and densification of the water and thereby mixing and strengthening of the warm Atlantic layer in the Arctic.

Figure 1. Multi-model ensemble average differences in (a)–(c) sea-ice concentration (%), (d)–(f) surface wind speed (m.s⁻¹), (g)–(i) surface air temperatures (°C) and (j)–(l) sea surface temperatures (°C) between the CO₂-forced and Last Interglacial (LIG) experiments. Results are plotted for annual, winter (DJF) and summer (JJA) averages. Warmer colors toward red imply higher values for the CO₂-forced simulation compared to the LIG simulation. On figures (a–c, g–i, and j–l), stippling denotes robust results that is, at least 5/7 models agree on the sign of the changes. On figures (d–f), arrows show the direction of the surface wind in the LIG experiment. The wind direction does not change substantially between the two experiments, except in summer (see Section 3, Figures S2 and S3 in Supporting Information S1). The color of the arrows characterizes the degree of robustness of the wind intensity differences between both simulations. Black arrows are for robust changes. White arrows are for non-robust changes.

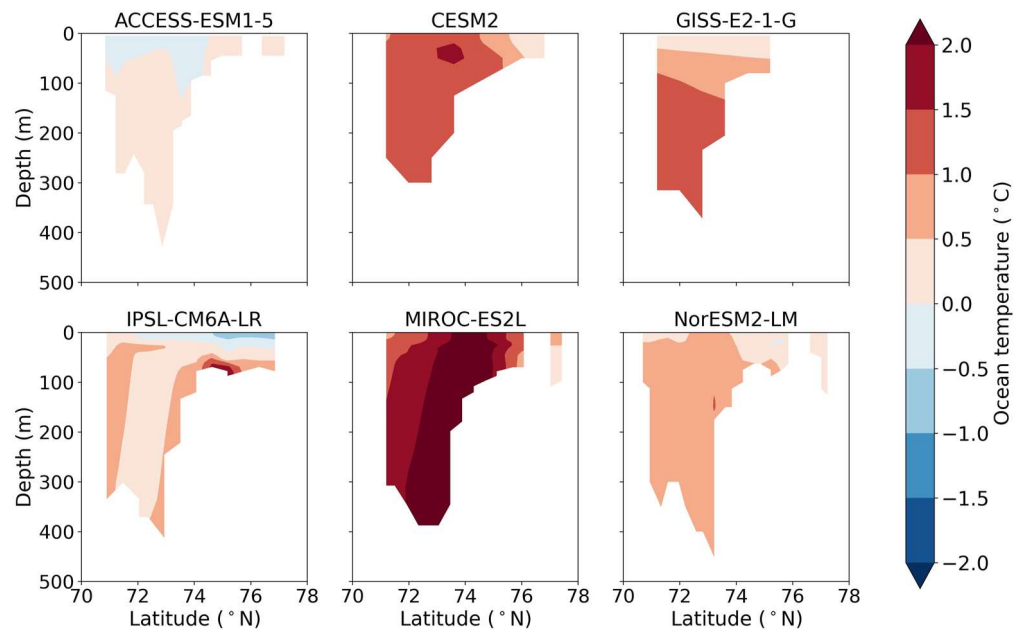


Figure 2. Vertical distribution of the $1pctCO_2-lig127k$ differences in annual ocean temperature field ($^{\circ}C$) through the Barents Sea Opening. Potential temperature is plotted for each model, except for IPSL-CM6A-LR for which the conservative temperature is shown. The location of the vertical section is indicated in Figure 1j.

There is a strong inter-model spread in the magnitude of sea-ice retreat in the Nordic and Barents Seas. First, this seems to be related to the position of the sea-ice edge. For example, the ACCESS-ESM1-5 and IPSL-CM6A-LR models simulate smaller differences in annual sea-ice concentration (Figure S8 in Supporting Information S1) and SST in the Barents Sea relative to the other models (Figure S7 in Supporting Information S1). For these models, sea ice recedes north of the Barents Sea in both simulations compared to other models with the sea-ice edge located at the junction between the Kara and Barents Seas. Second, previous analyses of ocean temperature and salinity profiles have shown that climate models widely diverge in their representation of Arctic hydrography (Khosravi et al., 2022; Shu et al., 2019) with some models, such as ACCESS-ESM1-5, simulating non-realistic AW core depth and very low AW core temperature compared to the Polar Science Center Hydrographic Climatology 3.0 database (Khosravi et al., 2022). Moreover, the GISS-E2-1-G model displays minimal variations in sea-ice concentration in the Atlantic sector. This is probably a consequence of the distinctive SLP anomaly pattern. The presence of a negative anomaly centered on the Bering Sea, and a positive anomaly centered on the North Atlantic, north of Scotland, contribute to retaining ice in the Kara Sea and Baffin Bay but does not significantly influence the atmospheric circulation east of Greenland. Also, the magnitude of the Atlantic Meridional Overturning Circulation (AMOC) affects ocean heat transport and sea-ice distribution in the Barents Sea. The models analyzed here show different AMOC strength and structure (Weijer et al., 2020), which can explain the large inter-model spread.

In the northern Bering Sea, sea ice is only present during cold months, while the sea-ice cover retreats into the Chuckchi Sea in summer (Figures S2 and S3 in Supporting Information S1). Consequently, major differences in sea-ice concentration between the two simulations appear in winter, and the winter signal prevails over the annual average (Figures 1a–1c). Here, winter sea-ice formation and extent are influenced by northerly winds and SAT. Under CO_2 -forced conditions, weaker northerly winds transport less sea ice and cold air from higher latitudes to the Bering Sea than during the LIG (Figure 1e). As a result, the sea-ice concentration is reduced relative to the LIG simulation (Figure 1b), and the sea surface temperatures are higher in the Pacific sector (Figure 1h).

Finally, the differences in the Central Arctic are of interest. In winter, this region remains completely ice-covered in both the LIG and CO_2 -forced experiments. Contrary to the signals at the sea-ice margins, differences in sea-ice concentration are very small during this season. The rest of the year, although the MMM sea-ice concentration in the Central Arctic is only slightly higher under CO_2 forcing than during the LIG (less than 5%), this is a robust feature in annual mean (Figure 1a) and in JJA (Figure 1c). This is of particular interest because late summer is

the time that will first become ice-free in the future. In the CO₂-forced simulation, larger sea-ice concentration is caused by lower SAT. This is particularly pronounced in summer when insolation is weaker than during the LIG, leading to colder surface conditions that help maintain the sea-ice. Summer differences in the Central Arctic sea-ice concentration may also be related to a stronger convergence of ice due to changes in surface winds. In particular, while the wind direction over most of the Arctic remains constant between the two climate states, surface winds in the Laptev Sea off-shore sector change from a northerly direction in the LIG experiment to a southerly direction in the CO₂-forced experiment (Figures S2 and S3 in Supporting Information S1).

4. Discussion and Conclusion

The LIG orbital forcing induces a seasonal and spatially inhomogeneous insolation anomaly from the PI period, whereas greenhouse gas forcing does not differ across latitudes and seasons (Yin & Berger, 2012). We can expect this to affect the spatial distribution of the Arctic sea-ice cover. Not surprisingly then, the seven models analyzed here all simulate different sea-ice distributions in the LIG simulation (*lig127k*) compared to an idealized CO₂-forced (*1pctCO2*) experiment. The main differences appear in the sub-Arctic Atlantic and North Pacific sectors. In the Greenland Sea, Baffin Bay, and Bering Sea differences in sea-ice concentration are a response to atmospheric forcing, in particular to changes in atmospheric circulation as evidenced by the SLP anomaly patterns and surface wind variations. A positive SLP anomaly over Greenland/North Atlantic leads to more ice in the Greenland Sea and the Baffin Bay, while a negative anomaly over North Pacific results in less ice in North Bering Sea. In the Barents Sea, the CO₂-forced simulation has also less sea ice relative to the LIG. This is associated with higher upper ocean temperatures due to warmer AW inflow through the Barents Sea Opening. Models simulating weaker annual northerly winds in the Greenland Sea under CO₂ forcing are also models with a weaker AW inflow into the Barents Sea (ACCESS-ESM1-5 and IPSL-CM6A-LR). In contrast, models showing stronger northerly winds over the Greenland Sea in the CO₂-forced experiment also have an amplified AW inflow over the Barents Sea (CESM2, MIROC-ES2L, NESM3, and NorESM2-LM). This link between wind intensity in the Greenland Sea, on the western side of the Nordic Seas, and AW inflows to the Barents Sea, on the eastern side of the Nordic Seas, has been previously analyzed in nine climate models by Muilwijk et al. (2019). By modifying the SLP in the Greenland Sea region, they found that stronger winds over the Greenland Sea enhance cyclonic circulation in the Nordic Seas and increases the northward transport of AW volume and heat through the Barents Sea Opening. This suggests that both the dynamic and thermodynamic differences in Arctic sea-ice distribution, highlighted here, could be primarily driven by changes in SLP.

These regional differences in Arctic sea-ice distribution stem from different surface warming levels compared with the PI period. For the same annual sea-ice volume, the rise in SAT over the Arctic is much higher in the CO₂-forced experiment than during the LIG (Table 1). There may be several explanations for this finding. On the one hand, the CO₂-forced simulations are not in equilibrium, which means they may already have reached the LIG sea-ice volume at lower CO₂ concentrations if they had had the time to equilibrate. It may also be a response to the higher sea-ice loss in the Barents Sea (and to lesser extent the Bering Sea) in the CO₂-forced simulation, allowing more heat release from warmer waters to the overlying atmosphere in winter. Furthermore, we note that most of the differences between the two simulations occur in winter, suggesting that the LIG is a closer analog to a future with similar summer surface temperatures than a future with similar annual surface temperatures (Figure S1 in Supporting Information S1).

The CMIP6 models have biases in representing the AW layer in the Arctic (Heuzé et al., 2023). They also generally underestimate Arctic polar amplification in warmer climates (Burls & Sagoo, 2022; Rantanen et al., 2022). Given these model discrepancies, it is of particular interest when all or most of the models point to a consistent difference between the LIG solar-forced and CO₂-forced simulations. One such finding is that the AW inflow to the Arctic is warmer in the CO₂-forced experiment than it may have been during the LIG. Planktonic species with a present-day AW habitat, that are not found in Holocene sediments, exist in sediments from across the Central Arctic during past interglacials (Cronin et al., 2019; Nørgaard-Pedersen et al., 2007; O'Regan et al., 2019; Vermassen et al., 2023). While discussions on age models persist, it can be debated whether these species may have inhabited the Arctic during the LIG alone, or were also present during previous interglacials. However, the existing evidence suggests a higher degree of Atlantification during past interglacials compared to the Holocene (Vermassen et al., 2023). Currently, the Atlantification process is still largely limited to the eastern Eurasian Basin (Barents-Kara-Laptev Seas) in the high Arctic realm (Muilwijk et al., 2023; Polyakov et al., 2020).

Therefore, a rigorous comparison of stratification and circulation in the Arctic Ocean is needed to interpret oceanic influences on the simulated Arctic sea ice and LIG sea-ice reconstructions. This work is to be carried out in a follow-up study.

With regard to the sea-ice conditions during the LIG, it is not yet clear whether the Central Arctic had seasonal or perennial ice cover. Most of the models analyzed in this study simulate a retreat of the sea-ice edge to the north coast of Greenland and the Canadian Arctic Archipelago at the end of summer (Figure S9 in Supporting Information S1). This would imply that this region could also have been the “Last Ice Area” during the LIG. However, the LIG model-data comparison with SAT proxies (Sime et al., 2023) and the possible presence of Atlantic zooplankton (Vermassen et al., 2021) together argue that the Arctic may have experienced ice-free summers during the LIG. While the debate is not yet settled, if these recent studies suggesting a near ice-free Arctic are correct, then the models are overestimating both summer (Figure S9 in Supporting Information S1) and winter (Figure S10 in Supporting Information S1) sea-ice cover during the LIG. Given that there is a correlation among these models between the summer sea-ice area in the *lig127k* and *1pctCO2* simulations (Kageyama et al., 2021), the future sea-ice loss projected by the CMIP6 models may also be underestimated.

The LIG sea-ice volumes are reached in the models at CO₂ concentrations ranging from 332 to 514 ppm (Table 1). The models in the lower range thus suggest that the real world may have already surpassed the state of the Arctic during the LIG, whereas others indicate that we are approaching this state or may reach it in the coming decades. CO₂ levels suggested by NESM3 (332 ppm) and MIROC-ES2L (405 ppm) are unrealistically low, maybe because these models have difficulty capturing LIG-PI summer SAT over land (Sime et al., 2023) and/or because they simulate an Arctic sea ice sensitivity out of range (Notz & SIMIP Community, 2020). Moreover, these estimations have been made by implicitly assuming that model biases are stationary or vary predictably under CO₂ and solar forcing, which does not always seem the case. Comparison of model biases under LIG and future warming is thus necessary. Lastly, future CO₂ simulations that are designed to equilibrate at climate states with the same sea ice as the LIG, as opposed to the equivalent transient simulation here, would allow a more rigorous analysis of the differences between the LIG and CO₂-forced warming and their driving processes.

Data Availability Statement

The CMIP6 data used for this study are freely available from the Earth System Grid Federation (ESGF; <https://esgf-node.llnl.gov/search/cmip6>).

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