

Paleoceanography and Paleoclimatology®



RESEARCH ARTICLE

10.1029/2025PA005247

Key Points:

- In Last Interglacial simulation, the North Atlantic subpolar gyre is consistently stronger than in pre-industrial and future scenarios
- No clear Arctic Atlantification is simulated at 127 ka, unlike future scenarios with similar annual Arctic sea-ice volume
- Last Interglacial and future scenarios both show similar spatial patterns of surface salinity differences in the central Arctic Ocean

Supporting Information:

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

Correspondence to:

M. Sicard,
M.A.Sicard@leeds.ac.uk

Citation:

Sicard, M., de Boer, A. M., Coxall, H. K., Koenigk, T., Karami, M. P., Navarro Labastida, R. G., et al. (2026). Variations in Arctic Ocean dynamics and hydrography under 127 ka last interglacial conditions and future warming. *Paleoceanography and Paleoclimatology*, 41, e2025PA005247. <https://doi.org/10.1029/2025PA005247>

Received 17 JUN 2025

Accepted 11 MAR 2026

Author Contributions:

Conceptualization: Marie Sicard, Agatha M. de Boer

Formal analysis: Marie Sicard

Funding acquisition: Agatha M. de Boer

Investigation: Marie Sicard, Agatha M. de Boer

Methodology: Marie Sicard, Agatha M. de Boer

Project administration: Agatha M. de Boer

Supervision: Agatha M. de Boer

Writing – original draft: Marie Sicard

Variations in Arctic Ocean Dynamics and Hydrography Under 127 ka Last Interglacial Conditions and Future Warming

Marie Sicard^{1,2,3} , Agatha M. de Boer^{1,2} , Helen K. Coxall^{1,2} , Torben Koenigk^{2,4} , Mehdi Pasha Karami⁴ , René Gabriel Navarro Labastida⁴, Martin Jakobsson^{1,2} , Matt O'Regan^{1,2} , and Flor Vermassen^{1,2}

¹Department of Geological Sciences, Stockholm University, Stockholm, Sweden, ²Bolin Center for Climate Research, Stockholm, Sweden, ³School of Earth and Environment, University of Leeds, Leeds, UK, ⁴Rosby Centre, Swedish Meteorological and Hydrological Institute, Norrköping, Sweden

Abstract Using outputs from eight Coupled Model Intercomparison Project Phase 6/Paleoclimate Model Intercomparison Project phase 4 models, we compare the hydrography and surface ocean circulation in the Arctic and sub-Arctic regions across three climate states: the pre-industrial (PI; 1850 CE), the Last Interglacial (LIG; 127 ka BP), driven by strong summer insolation in the high latitudes of the Northern Hemisphere, and an idealized future scenario forced by increasing atmospheric CO₂ concentration. Insolation forcing at 127 ka causes an anomalous cyclonic circulation over Greenland and surrounding seas, which enhances the Baffin and Labrador currents, while slightly weakening the East Greenland Current relative to PI. These changes affect sea-ice and water export on both sides of Greenland. Most models also simulate a strengthened North Atlantic Subpolar Gyre (SPG) and increased volume transports through Fram Strait and Barents Sea Opening. However, this does not always correlate with a larger heat transport into the Arctic. In contrast, under increased CO₂ forcing, the SPG weakens, but more heat is carried toward the Arctic compared with the PI and LIG simulations. Consequently, temperatures of the surface and subsurface waters are higher in the Eurasian Basin and sea-ice decline in the Barents Sea is more pronounced in the idealized future experiment. These changes closely resemble the ongoing Arctic Atlantification, whereas evidence for a similar process in the LIG simulation is less clear.

Plain Language Summary The Last Interglacial (LIG; ~129–116 thousand years ago) was the most recent period before today with significantly higher surface temperature in the Arctic region than those of the pre-industrial (PI) era. This warming was driven by stronger summer insolation relative to today and further amplified by regional sea-ice feedbacks. Because sea-ice changes during the LIG may have been comparable in magnitude to those projected for the near future, this period provides a valuable reference for understanding how the Arctic system responds to rising surface temperatures. In this study, we use climate model simulations to compare Arctic and sub-Arctic oceanic conditions during the early LIG (127,000 years ago), the PI period, and an idealized future scenario driven by increasing atmospheric CO₂ concentration. Our results show that differences in the climate forcing, that is, solar radiation during the LIG versus rising CO₂ in the future, lead to contrasting wind patterns, which in turn alter surface ocean circulation and the transport of water and sea ice differently. Notably, in the idealized future experiment, the Arctic Ocean is more influenced by sub-Arctic and Atlantic water masses than in the early LIG simulation.

1. Introduction

In recent decades, anthropogenic warming has been pushing the Arctic toward a new state. Ongoing transformations include a dramatic reduction in Arctic sea-ice cover (AMAP, 2021; Stroeve & Notz, 2018; Wang et al., 2022), alterations of freshwater and heat budgets (Solomon et al., 2021; Timmermans & Marshall, 2020), changes in oceanic circulation and deep convection (Timmermans & Marshall, 2020), among others (Druckemiller et al., 2021; Meredith et al., 2019). These processes are deeply interconnected and their variations remain poorly understood, partly due to the logistical difficulties of accessing and observing the central Arctic Ocean, especially regions under perennial sea ice, and the challenges of accurately simulating its dynamics in climate models (Athanasé et al., 2025; Heuzé et al., 2023; Khosravi et al., 2022).

© 2026. The Author(s).

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Writing – review & editing: Agatha M. de Boer, Helen K. Coxall, Torben Koenigk, Mehdi Pasha Karami, René Gabriel Navarro Labastida, Martin Jakobsson, Matt O'Regan, Flor Vermassen

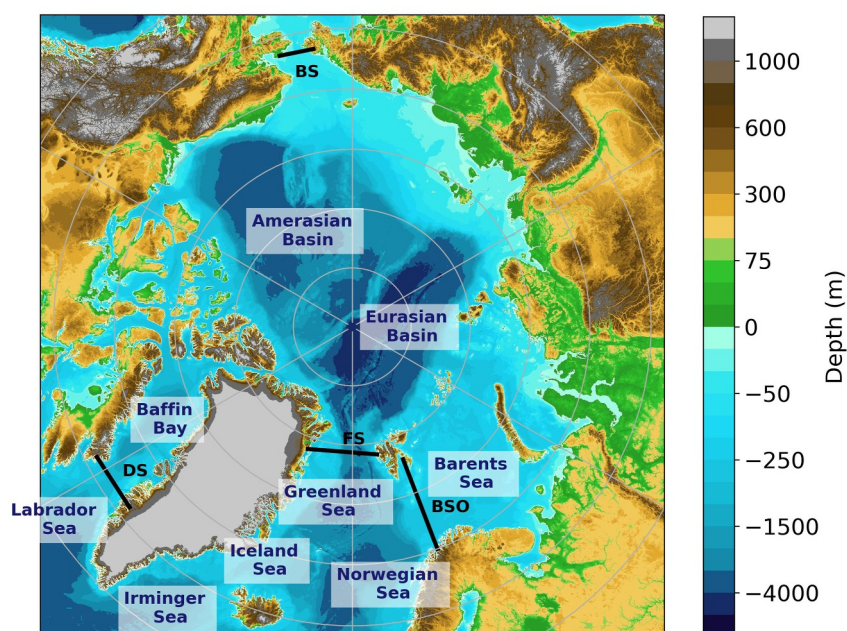


Figure 1. Map of the Arctic and sub-Arctic regions highlighting the locations of key seas and basins mentioned in this study. Thick black lines indicate the four main Arctic gateways: Bering Straits (BS), Barents Sea Opening (BSO), Fram Strait (FS) and Davis Strait (DS). The bathymetry is based on Version 4.2.13 of the International Bathymetric Chart of the Arctic Ocean (IBCAO; Jakobsson et al., 2020).

The study of past warm periods provides a unique opportunity to investigate the response of the Arctic to varying boundary conditions and warming rates. The Last Interglacial period (LIG; ~129,000 to 116,000 years ago) represents the most recent time, prior to the current interglacial, when Arctic surface temperatures exceeded those of the pre-industrial era (PI; 1850 CE). Moreover, the higher sea level provides clear evidence for reduced ice sheets and glaciers in polar regions (Dyer et al., 2021). Despite progress, the hydrography and sea-ice conditions of the central Arctic during the LIG remain debated largely due to dating uncertainties and conflicting proxy perspectives (Vernal et al., 2013; Razmjooei et al., 2023). Interpretations range from larger than modern to considerably reduced Arctic sea-ice cover at the interglacial onset (Kageyama et al., 2021; Nørgaard-Pedersen et al., 2007; Stein et al., 2017; Vermassen et al., 2023). The Arctic Ocean is connected to the sub-Arctic via four main gateways: the Fram Strait, Barents Sea Opening (BSO), Bering Strait, and Davis Strait (Figure 1). Sea ice drift and water exchanges through these gateways influence the hydrography of the Arctic Ocean through heat and freshwater transports. Analyzing these fluxes provides additional insight into Arctic oceanic conditions. For example, proxy evidence from marine sediment cores documents repeated periods of more pronounced influence of warm Atlantic Water (AW) during past interglacials compared to the Holocene (Vermassen et al., 2023). AW inflows are a good indicator of changes in oceanic circulation and stratification, and contribute to sea-ice loss. In the sub-Arctic region, the properties and circulation of water masses are better constrained thanks to higher-resolution and more accurately dated marine records. Analysis of sediment cores reveals that different parts of the sub-Arctic did not experience the onset of LIG warming simultaneously. The eastern Nordic Seas, Fram Strait and Gardar Drift record a delayed warming of several millennia after peak insolation forcing (Eynaud et al., 2004; Ezat et al., 2024; Steinsland et al., 2025; Van Nieuwenhove et al., 2011; Zhuravleva, Bauch, & Spielhagen, 2017). In contrast, the central and western Nordic Seas, the subpolar North Atlantic, and the Labrador Sea experienced the strongest warming during the early LIG (Bauch, 2013; Bauch et al., 2012; Eynaud et al., 2004; Irvali et al., 2012, 2016; Penaud et al., 2008; Rasmussen, Oppo, et al., 2003; Rasmussen, Thomsen, et al., 2003; Steinsland et al., 2023; Zhuravleva, Bauch, & Van Nieuwenhove, 2017). This spatio-temporal pattern has been attributed to variations in large-scale surface ocean circulation and associated heat transport, particularly changes in the extent of the North Atlantic Subpolar Gyre (SPG) through the LIG (Irvali et al., 2012, 2016; Steinsland et al., 2023; Zhuravleva, Bauch, & Van Nieuwenhove, 2017). For example, during the early LIG (128–126.5 ka), a stronger and more expansive SPG facilitated the advection of warm AW into the subsurface layer of the Labrador Sea, while cold polar waters transported by the East Greenland Current (EGC) dominated the surface.

At the same time, North Atlantic Deep Water (NADW) formation and northward heat transport likely weakened due to freshwater input to the Nordic Seas, associated with the melting of the Greenland Ice Sheet (Galaasen et al., 2014) and/or Arctic sea-ice (Ezat et al., 2024). However, some uncertainties remain. For example, paleoceanographic studies often assume modern-like oceanic circulation when interpreting proxy data, whereas it is not certain that ocean circulation during the LIG followed the same patterns.

Simulations of the LIG provide valuable insights into Arctic and sub-Arctic interactions within a global context, offering a framework that can help to interpret the signals preserved in proxy records. As part of the Coupled Model Intercomparison Project Phase 6 (CMIP6) and the Paleoclimate Model Intercomparison Project Phase 4 (PMIP4), a dedicated LIG experiment was designed to capture the climatic response to orbital and greenhouse gas forcings at 127 ka. This interval coincides with the peak insolation and is characterized by a topography of the Greenland ice sheet that is believed to be very close to its PI configuration. Previous analyses of this simulation have highlighted the strong impact of insolation on the Arctic sea-ice cover (Crow & Prange, 2025; Diamond et al., 2021; Guarino et al., 2020; Kageyama et al., 2021; Sicard et al., 2023; Sime et al., 2023) and its associated effects, including amplified surface warming in summer (Guarino et al., 2020; Sicard et al., 2022; Sime et al., 2023), increased precipitations (Sime, Sivankutty, et al., 2025), extended warming into autumn (Sicard et al., 2022), and altered sea-ice growth (Sicard et al., 2022; Sime, Diamond, et al., 2025). Although previous studies have mainly addressed Arctic sea-ice changes, key aspects of the Arctic Ocean and surrounding sea hydrography and circulation remain underexplored, despite proxy evidence for significant changes during the early LIG.

This study aims to address these gaps by providing a comprehensive analysis of the Arctic and sub-Arctic regions during the early LIG and comparing the results with an idealized future scenario. Section 2 describes the numerical experiments and diagnostics used to assess gyre dynamics and water transports. In Section 3, we present the results, focusing on changes in temperature, salinity, surface circulation, and mixed-layer depth during the early LIG. Section 4 compares the effects of LIG insolation forcing with those of increased atmospheric CO₂ concentration in the near future, while Section 5 discusses the implications of these findings and their consistency with proxy reconstructions. Finally, Section 6 summarizes our main findings.

2. Methods

2.1. Description of the CMIP6/PMIP4 Simulations

Three time periods are studied, each corresponding to a CMIP6/PMIP4 experiment: piControl (Eyring et al., 2016) for PI, lig127k (Otto-Bliesner et al., 2021) for the early LIG, and 1pctCO₂ (Eyring et al., 2016) for idealized future conditions. The list of models and simulation DOIs is provided in Table S2 in Supporting Information S1.

The piControl simulation is a time-slice experiment for the year 1850 and serves as the reference. For each model, we use the first ensemble member when multiple members were available. The lig127k simulation corresponds to a snapshot of the climate 127,000 years ago (Kageyama et al., 2018; Otto-Bliesner et al., 2017). It is characterized by a perihelion near the boreal summer solstice, high orbital eccentricity and obliquity (Berger & Loutre, 1991), while greenhouse gas concentrations were close to those of the PI period. Full experimental details are provided in Otto-Bliesner et al. (2017) and the main boundary conditions are summarized in Table S1 in Supporting Information S1. Only the last 100 years of the piControl and lig127k simulations are used. Following what was previously done in Kageyama et al. (2021), we analyze the 1pctCO₂ experiment to explore potential links between the LIG and future Arctic warming. In this experiment, atmospheric CO₂ increases by 1% per year from PI levels, while other atmospheric components remain fixed. This experiment has been mainly selected for its simple forcing relative to CMIP6 emission-based scenarios. For each model, we identified the period when the 10-year running mean of annual Arctic sea-ice volume matches that of the lig127k simulation, using the same time windows as in Sicard et al. (2023). As HadGEM3 was not included in that study, we determined the corresponding period as years 43–53 of the 1pctCO₂ simulation following the method in Sicard et al. (2023). The piControl, lig127k and 1pctCO₂ experiments are hereafter referred to as “PI,” “127k” and “idealized future” respectively.

Sixteen climate models completed the 127k experiment. However, we only selected those for which most of the required oceanic outputs are available, for all three periods, on the Earth System Grid Federation (ESGF; <https://esgf-node.llnl.gov/projects/esgf-llnl/>, last accessed 09 November 2025). This reduces the ensemble to eight models, although the number varies between six and seven for some analyses, depending on data availability (Table S3 in Supporting Information S1).

Model horizontal grids were interpolated on a 1° grid using the Climate Data Operators (CDO; Schulzweida, 2022) when the multi-model mean (MMM) is needed. Bilinear interpolation was applied to atmospheric fields, whereas distance-weighted interpolation was used for ocean variables, because it proved to better handle discontinuous fields. Vertical model levels were linearly interpolated onto the 33 levels of the Polar Science Center Hydrographic Climatology (PHC3) data set.

In the following, we define the Arctic and sub-Arctic regions as the area between 60°N and 90°N . Regional analyses were also performed with a focus on the Eurasian and Amerasian basins (Figure 1), as well as the Arctic-Atlantic sector, including the Labrador Sea, subpolar North Atlantic, and Nordic Seas.

2.2. Computation of the Barotropic Streamfunction

The barotropic streamfunction $\Phi(x,y)$ is a useful tool for identifying changes in ocean gyres and surface ocean circulation. Here, This was estimated as the cumulative sum of the depth-integrated zonal velocity component $U(x,y)$ along the latitudes or meridional velocity component $V(x,y)$ along the longitudes:

$$\begin{aligned}\Phi_u(x,y) &= \int_{y_{\text{south}}}^y U(x,y) dy \\ \Phi_v(x,y) &= \int_{x_{\text{west}}}^x V(x,y) dx\end{aligned}\quad (1)$$

Depending on the model grid, $\Phi_u(x,y)$ or $\Phi_v(x,y)$ were alternatively computed. The value at the southern South Africa reference point was then subtracted to minimize the influence of inter-model differences in Antarctic Circumpolar Current strength and to better isolate changes in the flow north of this region.

2.3. Computation of Volume, Heat, and Freshwater Transports

To evaluate how exchanges with the North Pacific and North Atlantic influence Arctic water properties and sea-ice cover, volume (OVT), heat (OHT) and freshwater (FWT) transports were computed using monthly sea water velocity, potential temperature, and salinity. All the calculations are done on the original model grid as follows:

$$OVT = \int_{x1}^{x2} \int_{-H}^0 v(x,y,z) dx dz \quad (2)$$

where $v(x,y,z)$ is the three-dimensional velocity (m.s^{-1}) normal to the section, and $x1$ and $x2$ are the western and eastern boundaries respectively.

$$OHT = \rho_0 C_p \int_{x1}^{x2} \int_{-H}^0 v(x,y,z) [T(x,y,z) - T_{ref}] dx dz \quad (3)$$

where ρ_0 is the reference density of seawater ($1,025 \text{ kg.m}^{-3}$), C_p is the heat capacity of seawater ($3,850 \text{ J.kg}^{-1} \cdot ^\circ\text{C}^{-1}$), $T(x,y,z)$ is the three-dimensional temperature ($^\circ\text{C}$), and T_{ref} is the reference temperature set to 0°C .

$$FWT = \int_{x1}^{x2} \int_{-H}^0 v(x,y,z) [S_{ref} - S(x,y,z)]/S_{ref} dx dz \quad (4)$$

where $S(x,y,z)$ is the three-dimensional salinity (psu), and S_{ref} is the reference salinity. S_{ref} is defined as 34.8 psu, which corresponds to the mean Arctic Ocean salinity (Aagaard & Carmack, 1989) and is commonly used in Arctic multi-model studies.

To ensure consistent comparison between simulations, the same reference temperature and salinity are applied across all models and time periods. The choice of T_{ref} and S_{ref} influences the absolute magnitude of transports across a gateway, but the relative changes and variability are not affected by this choice.

3. Key Properties of the Arctic Ocean During the Early Last Interglacial

3.1. Arctic Ocean Hydrography

In the Arctic, models generally simulate higher sea surface temperatures (SST) at 127 ka compared with the PI period (Figures 2a–2c). The largest differences occur around Greenland with a maximum southeast of the island. This surface warming is directly related to the retreat of the sea-ice edge (Figures 2g–2i and Figure S1 in Supporting Information S1), as reduced albedo enhances the oceanic absorption of solar radiation. South of Greenland, however, changes in SST extend beyond the region of sea-ice retreat, indicating additional drivers.

Across the central Arctic and surrounding seas, the SST changes are consistent between models, except in the Norwegian Sea and northern North Atlantic, where the AW circulates.

At deeper depth, oceanic waters are on average cooler than PI conditions in both the Eurasian and Amerasian basins (Figures 3a and 3b respectively). Maximum cooling occurs between ~1,000 and 2,000 m, where Arctic deep waters are typically found. Above this layer lies the AW. In climate models, the AW layer can be identified by finding the maximum temperature between ~150 and 1,000 m (Khosravi et al., 2022), also called the Atlantic Water Core Temperature (AWCT). The depth of the AWCT is defined as the Atlantic Water Core Depth (AWCD). In the Eurasian Basin, the AWCT decreases, on average, by ~0.2°C at 127 ka relative to the PI period. However, not all models agree on this cooling (Figure S3 in Supporting Information S1). Three models (ACCESS, HadGEM3, and NorESM2) simulate a warming, and one (CESM2) shows little differences from PI. The AWCD ranges from 370 to 900 m in the PI experiment, and from 230 to 900 m in the 127k simulation. Two models indicate shoaling of the AW layer (GISS and NorESM2), whereas other models either show no change or a deepening. This shoaling is associated with warming only in NorESM2.

In the Amerasian Basin, the simulated changes are generally similar in magnitude to those in the Eurasian Basin (Figure S4 in Supporting Information S1).

In terms of sea surface salinity (SSS), the Amerasian Basin experiences a marked freshening in the 127k simulation, whereas changes in the Eurasian Basin are not consistent across models. The largest SSS differences occur north of the Canadian Arctic Archipelago (CAA), within the Beaufort Gyre region (Figure 2f), where salinity locally decreases by more than 1 psu. Such changes typically reflect variations in freshwater sources, including the precipitation-minus-evaporation ($P-E$) budget, sea ice, river discharge, and Pacific Water (PW) inflows, and/or from freshwater redistribution within the Arctic Ocean (Timmermans & Toole, 2023). We further examined $P-E$ and runoff changes, but limited data restricted the analysis to a few models, so results should be interpreted cautiously. In the 127k experiment, changes in $P-E$ budget are larger over land than over oceanic areas (Figure S7 in Supporting Information S1). Over the Arctic Ocean, the $P-E$ budget is on average higher compared with the PI experiment. The spatial distribution of river runoff changes varies among models, but most of them indicate stronger inputs to the Beaufort, Chukchi, and East Siberian seas in the 127k experiment (Figure S8 in Supporting Information S1). However, these changes do not explain why the largest surface freshening occurs north of the CAA, suggesting that freshwater redistribution by ocean currents and/or sea-ice transports likely plays a dominant role.

South of Greenland, more saline waters lay at the surface compared with PI. These changes in SSS are associated with higher SST (Figures 2c and 2f) and a reduced sea-ice cover (Figure S1 in Supporting Information S1). They could come from differences in the properties and/or volume of waters transported by the EGC, Baffin Current, and Irminger Current, which converge in this region. Outside the regions north of the CAA and south of Greenland, models do not always agree on the sign of SSS changes relative to PI. In particular, model responses to 127 ka forcing diverge in the Nordic Seas, a key region where sea water properties influence deep water formation. The MMM salinity profiles in the Eurasian and Amerasian basins are broadly similar between the PI and 127k experiments (Figures 3c and 3d). The largest changes are found in the surface layer of the Amerasian Basin, consistent with the patterns shown in Figure 2f. At greater depths (>200 m), salinity differences are minor, typically within ~0.1 psu or less in both basins, with the most pronounced changes simulated by the IPSL model (Figures S5 and S6 in Supporting Information S1).

Overall, changes in SST and SSS are relatively robust, as they are directly influenced by changes in sea ice, and all models consistently simulate summer sea-ice loss at 127 ka in these regions. At greater depths, however, models

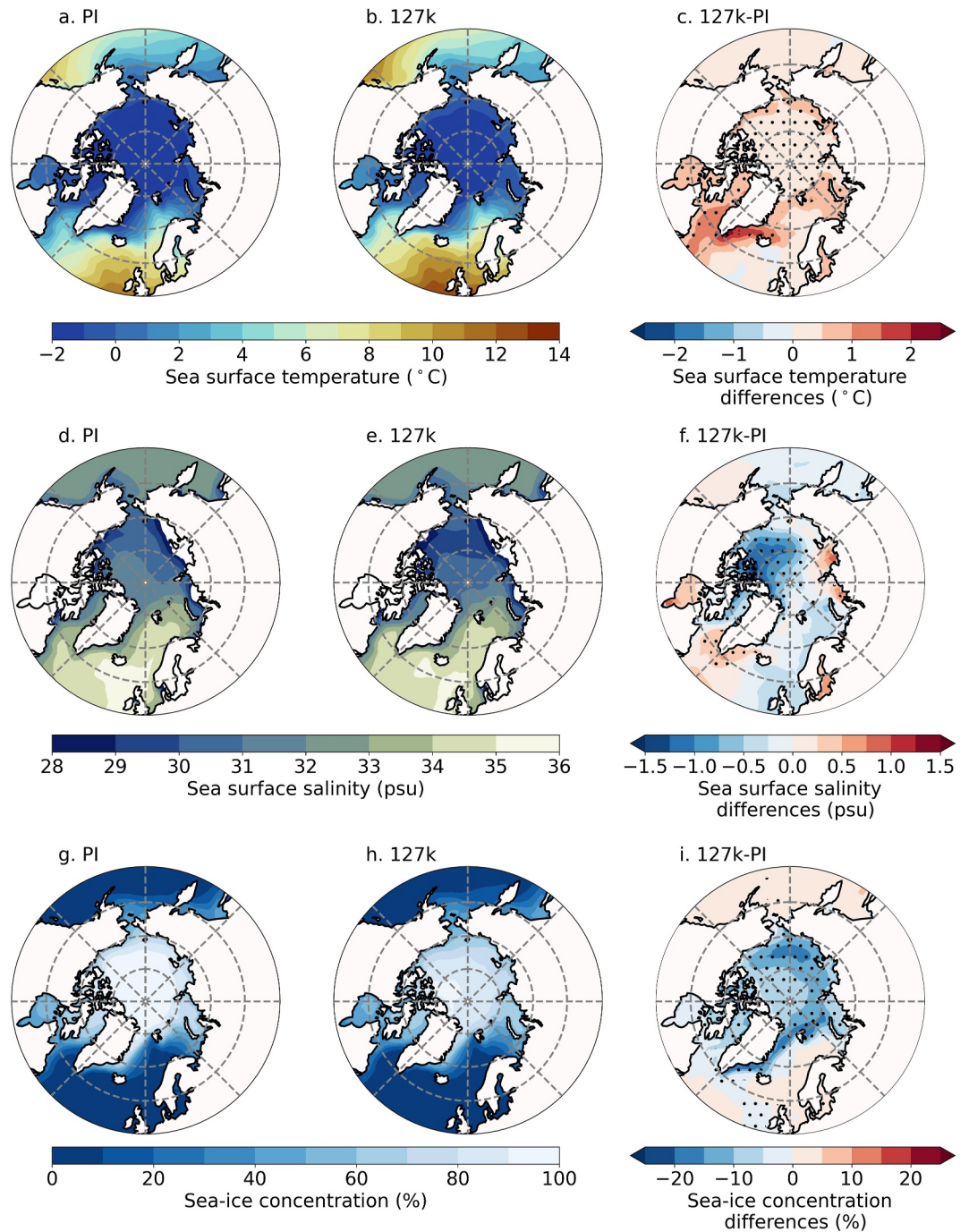


Figure 2. Multi-model mean of annual surface conditions for the pre-industrial (PI), Last Interglacial (127 ka), and their differences: (a–c) sea surface temperature (°C), (d–f) sea surface salinity (psu), and (g–i) sea-ice concentration (%). In panels (c), (f), and (i), dots mark regions where at least six of the eight models agree on the sign of change between the 127k and PI simulations, indicating robust differences.

show less agreement in salinity and temperature differences relative to PI, particularly within the AW layer. This may reflect differences in model responses, but it could also arise from variations in deep-ocean equilibrium, as the AW layer typically adjusts over multi-centennial timescales, while deeper layers require even longer model integration times to stabilize.

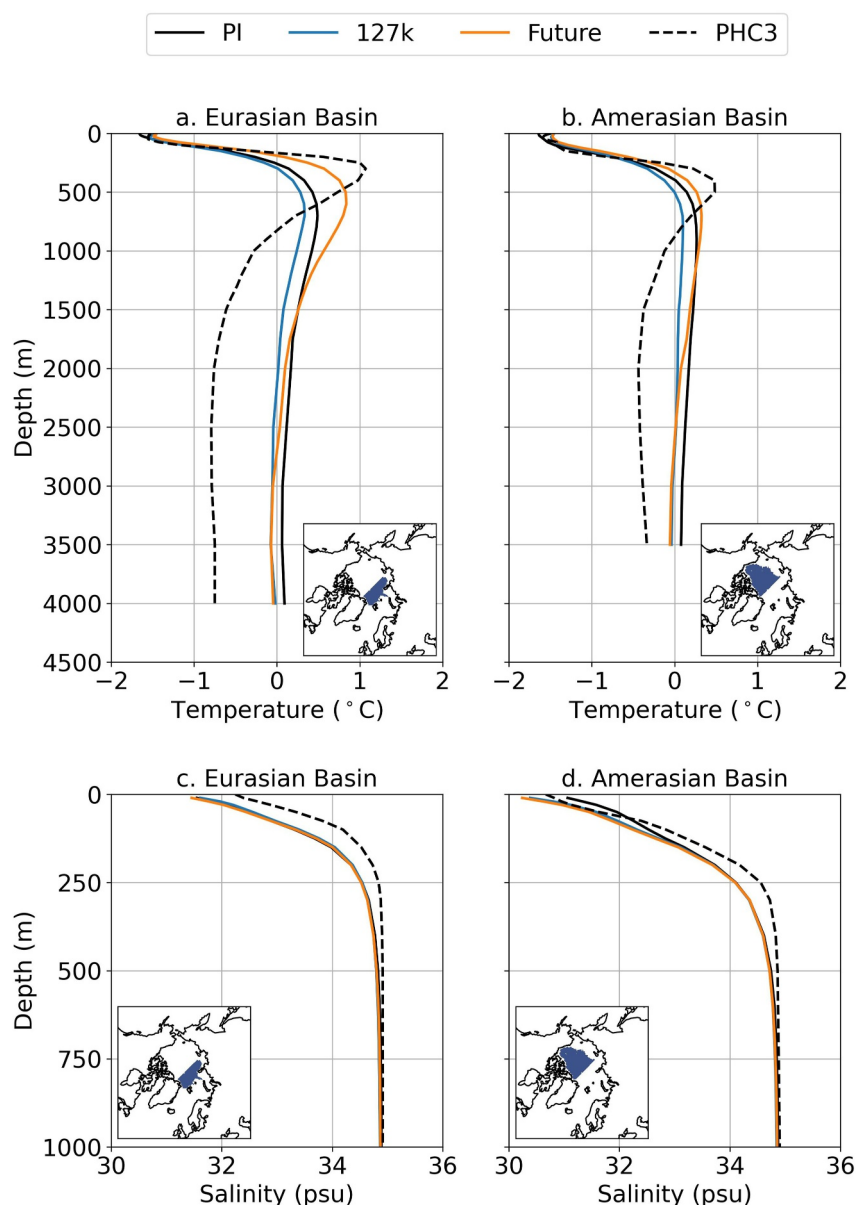


Figure 3. Annual ocean temperature (°C) and salinity profiles (psu) for the Eurasian and Amerasian basins. The black dashed line indicates the Polar Science Center Hydrographic Climatology (PHC3; Steele et al., 2001). Solid lines represent the annual multi-model mean: black for the pre-industrial period, blue for the Last Interglacial (127k), and orange for the idealized future experiment (Future).

3.2. Oceanic Circulation in the Arctic and Sub-Arctic Regions

Despite the sometimes coarse resolution, the models simulate an Arctic Ocean circulation for the PI era that resembles the observed circulation in the historical period, with its main features well represented (Figure 4a): the Bering Current in the North Pacific sector, the TransPolar Drift, the Beaufort Gyre in the Amerasian Basin, and strong surface currents in the Baffin, East Greenland, and North Atlantic sectors of the Arctic Ocean.

At 127 ka, the overall circulation pattern resembles that of the PI, but its strength differs (Figures 4b and 4c). There are no major differences in surface current speed in the central Arctic between the 127k and PI simulations, except a slight intensification at the surface of the Beaufort Gyre (Figure 4c), which is not representative of the overall slowdown of the Beaufort Gyre highlighted by changes in the barotropic streamfunction (i.e., velocities integrated over the whole water column) on Figure 4f. Larger differences can be observed west of Greenland,

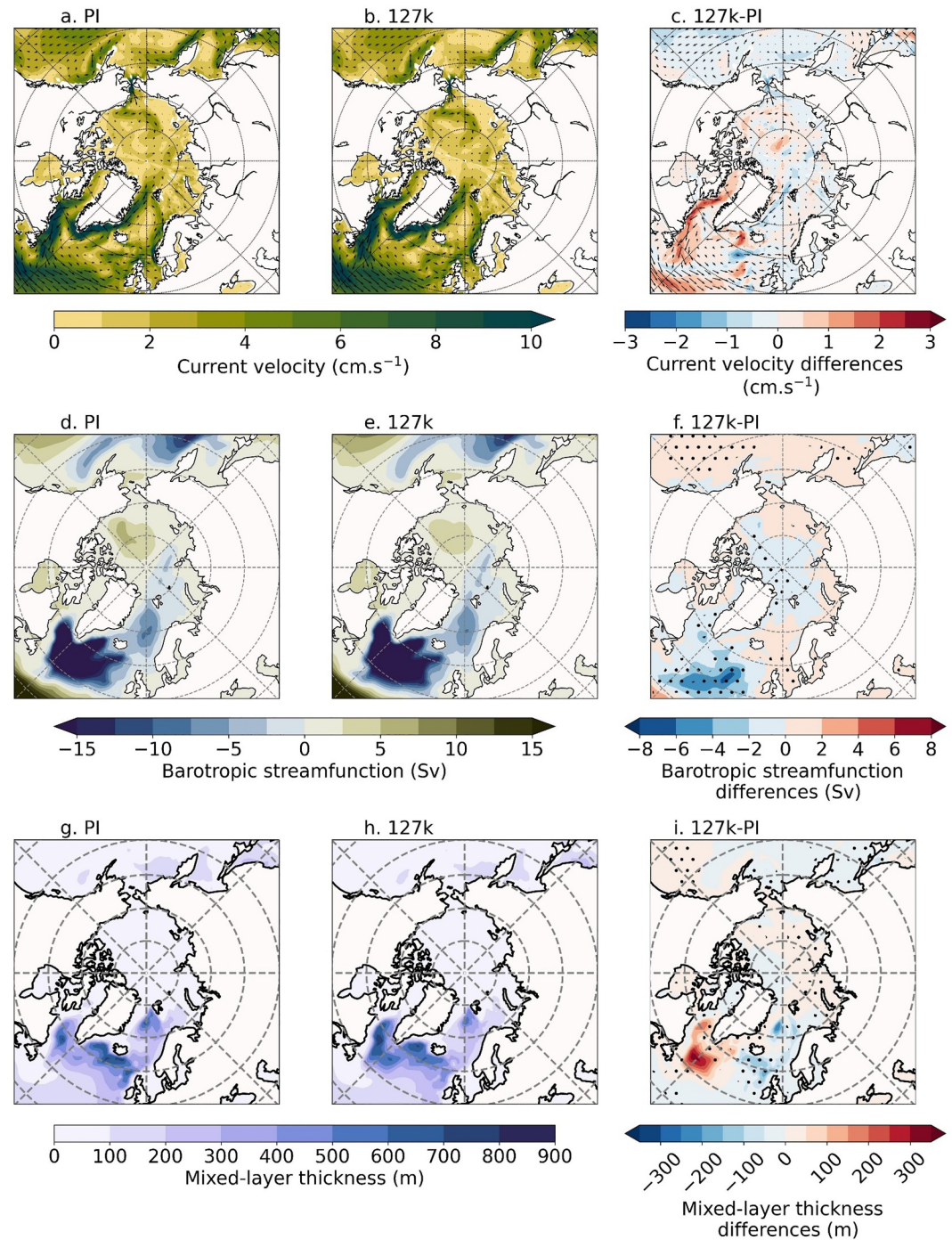


Figure 4. Multi-model mean of annual upper-ocean dynamics for the pre-industrial (PI), Last Interglacial (127k), and their differences: (a–c) ocean surface currents (colors indicate current speed in cm.s^{-1} ; arrows show direction), (d–f) barotropic streamfunction (Sv; NESM3 not included), and (g–i) mixed-layer thickness (m; MIROC not included). In panels (f), and (i), dots mark regions where at least six (five) of the eight (seven) models agree on the sign of change between the 127k and PI simulations, indicating robust differences.

where the 127k simulation is characterized by stronger velocities along the Baffin and Labrador currents relative to PI. This is associated with an enhancement of the cyclonic circulation of the SPG in most models (Figure 4f). Only the IPSL model deviates from this general behavior by simulating a weaker SPG, likely due to its inaccurate

representation of overflow waters and deep western boundary currents, as well as precipitation biases in the North Atlantic (Boucher et al., 2020).

The depth of the winter ocean mixed layer is commonly used to monitor deep convection in climate models. It mainly varies in response to changes in surface buoyancy and surface wind stress. In the 127k and PI experiments, the models generally show three main regions of thick mixed layer, corresponding to areas of NADW formation (Figures 4g and 4h): the Labrador Sea (with an extension southward into the northern North Atlantic), the Greenland Sea, and the Irminger Sea south of Iceland. At 127 ka, there is a general thinning of the mixed layer in the Greenland and eastern Irminger seas (Figure 4i). This is a robust result despite inter-model differences in SSS changes (Section 3.1, Figure 2f). This implies that mixed-layer thinning in these regions is primarily driven by sea surface warming (Figure 2c), which contributes to reducing surface density, strengthening stratification, and subsequently inhibiting mixing. In the northern Labrador and western Irminger seas, most models simulate a thickening of the mixed layer. However, in the southern Labrador Sea, differences in mixed-layer thickness are not consistent across models, similar to what is found for SST and SSS. This region is strongly influenced by the advection of subtropical waters, and inter-model differences may therefore reflect variations in local processes and/or in the properties of the advected water masses.

Finally, it is worth noting that mixed-layer thickening in the Labrador Sea and its thinning in the Greenland and Irminger seas offset one another, resulting in no significant change in the Atlantic Meridional Overturning Circulation (AMOC) strength relative to PI (Jiang et al., 2023; Table S4 in Supporting Information S1).

3.3. Annual Volume-, Heat-, and Freshwater-Transports Through the Main Arctic Gateways

The analysis of oceanic transport across key gateways provides further insight into changes in water masses property and circulation in the Arctic Ocean basin. Although models show a substantial spread in transport magnitudes (Table 1), the results presented in the following are robust since most models agree on the sign of the transport differences unless otherwise noted.

In the PI simulation, annual volume transports into the Arctic through Bering Strait and BSO are positive, while water exits the Arctic through Fram and Davis straits (Table 1a). Simulated volume transports compare well with observations for the 1987–2007 period (Beszczyska-Möller et al., 2011). Transport through Davis Strait is slightly lower in the PI simulation, but remains within the uncertainty range. In the 127k experiment, these major entry and exit routes remain the same, but the volume transport is reduced through Davis Strait (more export), higher through BSO (more import) and Fram Strait (less export) and similar through the Bering Strait relative to PI. These differences in volume transport are consistent with changes in surface current intensity (Figure 4c) and affect heat and freshwater transports.

The Arctic Ocean receives heat from lower latitudes primarily through Fram Strait and BSO, where warm AW enters the Arctic Ocean. At 127 ka, the MMM indicates an increase in net heat transport (Table 1b), mainly driven by enhanced heat transport through Bering Strait and BSO relative to PI. This may suggest stronger inflows of both PW and AW during the early LIG. However, this result is not robust, and some models exhibit different patterns. For example, the IPSL model simulates reduced heat transport through Bering Strait and increased transport through the other three gateways. Two models (MIROC and NorESM2) even show lower net heat transport in the 127k simulation than in the PI experiment (not shown).

Total freshwater transport results from the combined inflow of relatively fresh PW and saline AW into the Arctic Ocean and freshwater export through Fram and Davis straits. In the PI simulation, the sum of these fluxes is negative (Table 1c). At 127 ka, models generally simulate reduced freshwater flux through Bering Strait and reduced saline inflow through BSO relative to PI. At the same time, freshwater export through Davis Strait is stronger than for PI and no significant changes occur through Fram Strait. As a result, total freshwater transport becomes more negative, contributing to a reduction in Arctic freshwater content. Therefore, changes in freshwater transport through gateways do not explain why the Amerasian Basin experiences surface freshening in the 127k simulation (Figure 2f). As the SSS changes highlighted in Section 3.1 cannot be attributed to freshwater exchange with regions outside the Arctic, the redistribution of river runoff, precipitation, and sea-ice meltwater flux within the Arctic Ocean is likely the main driver of surface freshening north of Greenland and the CAA.

Table 1
Mean Annual Ocean Transports Through the Main Arctic Gateways and Inter-Model Standard Deviations

Arctic gateways	Observations	PI	127k	Future
(a) Volume transport (Sv)				
Bering Strait	0.8 ± 0.2 (1990–2007)	0.9 ± 0.4	0.9 ± 0.4	0.9 ± 0.3
Barents Sea Opening (BSO)	2.0 (1997–2007)	2.2 ± 1.3	2.5 ± 1.5	2.7 ± 1.5
Fram Strait	−2.2 ± 2.7 (1997–2007)	−2.2 ± 1.4	−2.1 ± 1.4	−2.8 ± 1.6
Davis Strait	−2.6 ± 1.0 (1987–1990)	−1.1 ± 0.9	−1.4 ± 0.9	−0.8 ± 0.8
Total		0.0 ± 0.1	0.0 ± 0.1	−0.1 ± 0.1
(b) Heat transport (TW)				
Bering Strait	10 to 20 (1998–2007)	2.5 ± 1.5	3.0 ± 1.5	5.3 ± 2.9
Barents Sea Opening (BSO)	50 to 70 (1997–2007)	51.8 ± 27.7	59.8 ± 16.4	70.8 ± 45.4
Fram Strait	36 ± 6 (1997–2009)	17.6 ± 11.4	16.4 ± 9.5	25.4 ± 11.1
Davis Strait	18 ± 17 (1987–1990)	7.4 ± 3.2	7.5 ± 2.9	6.7 ± 2.6
Total		79.3 ± 32.4	86.8 ± 44.5	108.2 ± 54.0
(c) Freshwater transport (10 ³ km ³ · year ^{−1})				
Bering Strait	2.5 ± 0.6 (1999–2005)	2.5 ± 1.1	2.2 ± 1.0	2.5 ± 1.0
Barents Sea Opening (BSO)	1.7 to 1.9 (1997–2007)	−0.7 ± 0.4	−0.4 ± 0.7	−0.4 ± 0.4
Fram Strait	−2.5 to −2.1 (1997–2009)	−2.2 ± 1.4	−2.3 ± 0.9	−3.7 ± 1.5
Davis Strait	−2.9 ± 1.1 (1987–1990)	−2.0 ± 1.5	−3.0 ± 1.7	−2.3 ± 1.8
Total		−2.5 ± 0.6	−3.5 ± 0.6	−3.9 ± 1.1

Note. Volume transports are defined as positive when entering the Arctic. Heat transport is positive when warmer water enters the Arctic (relative to a reference temperature $T_{ref} = 0^{\circ}\text{C}$) and negative when colder water enters the Arctic. Freshwater transport is positive when fresher water enters the Arctic (relative to a reference salinity $S_{ref} = 34.8$ psu) and negative when more saline water enters the Arctic. Observational data are from Beszczyska-Möller et al. (2011), and the observation period is indicated in parentheses for each strait.

4. Comparison of the Arctic Ocean Under Future and Last Interglacial Conditions With Equivalent Annual Sea-Ice Volume

4.1. Arctic Ocean Hydrography

In the idealized future experiment, at the time of similar sea-ice volume as in 127k, the SST are generally higher than in the PI simulation (Figure 5b), with a mean increase of about 0.45°C north of 60°N . This general warming is stronger over the North Pacific sector and along the AW pathway in the Nordic Seas, with the highest increase in the Barents Sea. In the Eurasian Basin, oceanic temperatures are consistently higher at the AWCD (Figure 3a and Figure S3 in Supporting Information S1). Below this depth, temperature differences become negative or close to zero. In the Amerasian Basin, the overall changes are similar, but individual model responses are more variable at the AWCD: four models (ACCESS, HadGEM3, IPSL, and NorESM2) simulate a warming, whereas the other three show a slight cooling (Figure 3b and Figure S4 in Supporting Information S1). Regarding salinity, most changes occur at the surface (Figures 3c and 3d). North of the CAA and along the northern and eastern coasts of Greenland, SSS is consistently lower, whereas changes in the Eurasian Basin are small and not robust (Figure 5e). It is worth noting that differences in ocean temperature and salinity relative to PI are generally more robust in the idealized future experiment (Figures 5b and 5e) than in the 127k simulation (Figures 2c and 2f), both in terms of magnitude of change and model agreement.

Mean SST differences relative to PI are remarkably similar in the idealized future ($+0.74^{\circ}\text{C}$) and 127k ($+0.79^{\circ}\text{C}$) simulations, even though surface air temperatures are on average substantially higher under increased CO_2 forcing than under insolation forcing (Sicard et al., 2023). The spatial pattern of surface warming, however, differs locally between the two simulations. South of Greenland, SST are lower in the idealized future experiment than in the LIG simulation. In the Pacific sector and the Barents Sea, they are higher (Figure 5c). These temperature changes coincide with corresponding salinity anomalies, that is, fresher waters south of Greenland and

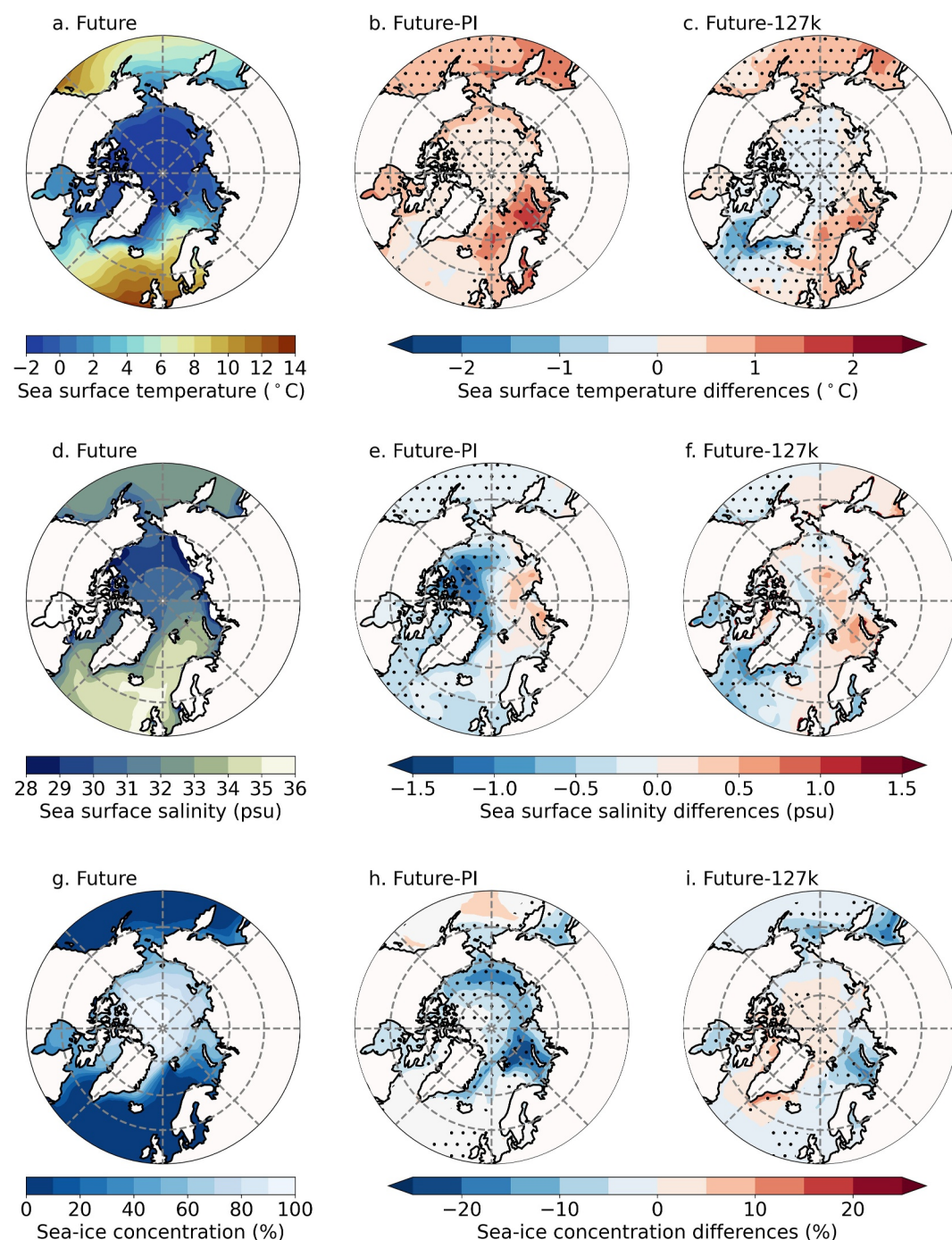


Figure 5. Multi-model mean of annual surface conditions in the idealized future experiment (Future), differences between the future and pre-industrial (PI) simulations, and differences between the future and Last Interglacial (127k) simulations: (a)–(c) sea surface temperature ($^{\circ}\text{C}$), (d)–(f) sea surface salinity (psu), and (g)–(i) sea-ice concentration (%). In panels (b), (c), (e), (f), (h) and (i), dots mark regions where at least six of the eight models agree on the sign of change between the 127k and PI simulations, indicating robust differences.

more saline waters in the Pacific sector and Barents Sea (Figure 5f), and are consistent with the sea-ice changes described by Sicard et al. (2023). In contrast, no robust SSS differences emerge between the two simulations in the central Arctic, even if models indicate a larger increase in $P-E$ and runoff in the idealized future simulation, when these diagnostics are available (Figures S9 and S10 in Supporting Information S1).

In the Eurasian Basin, the largest changes in oceanic temperatures appear at the AWCD. Most of the models simulate warmer conditions than at 127 ka (Figure 3a and Figure S3 in Supporting Information S1). Below the AWCD, the differences are small, but this only reflects compensating model behavior: half of the models indicate a deep-water cooling, and the other half indicate a warming. In the Amerasian Basin, the AW layer is on average warmer than in the 127k simulation, although several models show little change, and one model (HadGEM3) even simulates cooler conditions under increased CO₂ forcing (Figure 3b and Figure S4 in Supporting Information S1). Finally, salinity differences between the two experiments are very small in both basins, except within the upper few meters (Figures 3c and 3d; Figures S5 and S6 in Supporting Information S1).

4.2. Oceanic Circulation in the Arctic and Sub-Arctic Regions

In the idealized future experiment, surface currents generally show only minor differences relative to the PI simulation, except east and south of Greenland (Figure 6b). In particular, the EGC is stronger. Most other changes are small and/or inconsistent across models (not shown), partly due to model differences in simulating changes in surface wind (Figure S6 in Sicard et al., 2023), which is a key driver of surface circulation. Despite this inter-model variability, the weakening and shrinking of the SPG (Figure 6e) and the mixed-layer thinning at the three convection sites (Figure 6h) remain robust signals. Changes in mixed-layer thickness are associated with a reduction in the AMOC strength (Table S4 in Supporting Information S1). The concurrent weakening of the SPG and AMOC could explain the surface freshening and cooling south of Greenland, as it limits the inflow of warm, saline AW to this region. These features represent classic fingerprints of future AMOC weakening observed in scenario-based experiments (Weijer et al., 2020).

The circulation differences in the Arctic and sub-Arctic regions between the idealized future and 127k experiments are larger and more consistent than the differences between the idealized future and PI simulations. Under increased CO₂ forcing, surface currents within the Beaufort Gyre lose intensity (Figure 6c), which aligns with a reduction in winter surface winds over the Amerasian Basin (Sicard et al., 2023). Furthermore, around Greenland, surface currents respond differently: the Baffin and Labrador currents are weaker than at 127 ka, whereas the EGC is stronger (Figure 6c). The SPG also experiences a stronger weakening and contraction in the future simulation relative to the LIG than relative to PI (Figure 6f). Similarly, decrease in mixed-layer thickness is also stronger at the three convection sites (Figure 6i). Differences in the SPG and mixed layer between the idealized future and 127k experiments highlight distinct ocean dynamics in the Arctic-Atlantic sector. These differences alter the transport, mixing, and distribution of water masses, mainly polar waters and AW, affecting the hydrography of both the Arctic and northern North Atlantic.

4.3. Annual Volume-, Heat-, and Freshwater-Transports Through the Main Arctic Gateways

In the idealized future simulation, the increase in export of 0.6 Sv through Fram Strait is on average compensated for by a 0.5 Sv increase in volume influx through BSO and a decrease of 0.3 Sv in export through Davis Strait (Table 1a), while the magnitude of inflow through Bering Strait does not change. This is consistent with differences in surface current intensity between the PI and idealized future experiments (Figure 6b). All models simulate increased heat transport to the Arctic from both the North Pacific and North Atlantic, contributing to Arctic Ocean warming (Table 1b). Freshwater transport through Bering Strait is higher, while saline inflow through BSO is reduced, contributing to increased Arctic freshwater content (Table 1c). This effect is balanced by stronger freshwater export through Fram and Davis straits.

Most differences in volume and freshwater transports between the idealized future and 127k experiments are closely linked to the different responses of surface winds and currents to the forcing (Figure 6b). Although wind-driven changes partly explain the larger MMM heat transport between the two simulations, changes in ocean temperature are also a key contributing factor. In particular, the idealized future experiment shows enhanced advection of warmer PW and AW toward the Arctic Ocean (Figure 2 in Sicard et al., 2023).

5. Discussion

5.1. Drivers of Surface Ocean Circulation Changes at 127 ka

Although models analyzed here differ widely in the magnitude of summer sea-ice decline at 127 ka (Kageyama et al., 2021), they are consistent in their representation of surface ocean circulation changes relative to PI, including

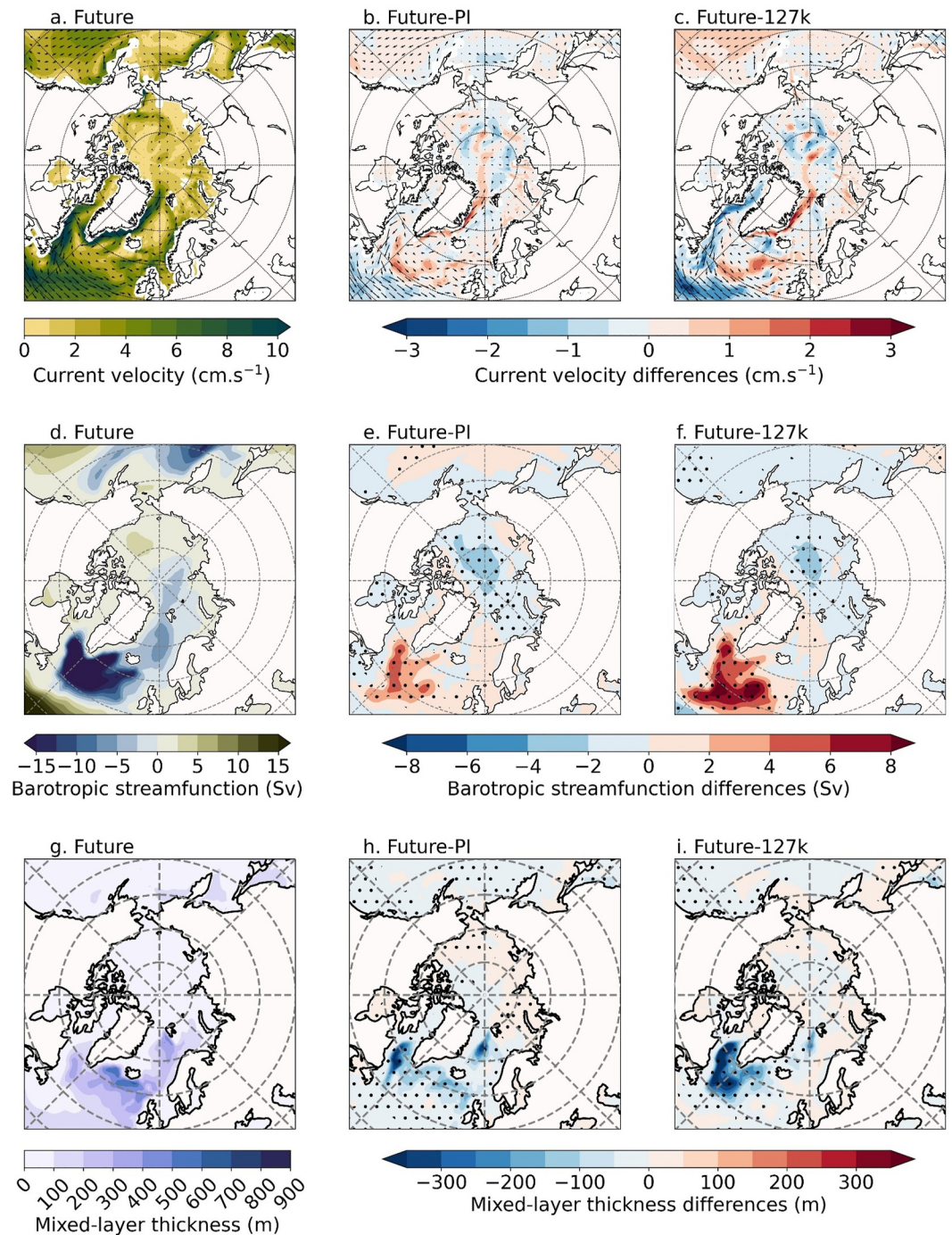


Figure 6. Multi-model mean of annual upper-ocean dynamics in the idealized future experiment (Future), differences between the future and pre-industrial (PI) simulations, and differences between the future and Last Interglacial (127k) simulations: (a–c) ocean surface current velocity (cm.s^{-1}), (d–f) barotropic streamfunction (Sv; NESM3 not included), and (g–i) mixed-layer thickness (m; MIROC not included). In panels (e), (f), (h) and (i), dots mark regions where at least six (five) of the eight (seven) models agree on the sign of change between the 127k and PI simulations, indicating robust differences.

a strengthening of the Baffin and Labrador currents and an enhanced cyclonic circulation of the SPG. These circulation patterns are driven by a negative sea level pressure (SLP) anomaly that spreads over much of the Arctic region, with a maximum over Baffin Bay and the Labrador Sea (Figure 7). The negative SLP anomaly in the Arctic is part of a larger pattern extending southward to western Europe and the Mediterranean Sea (Figure 7h). They

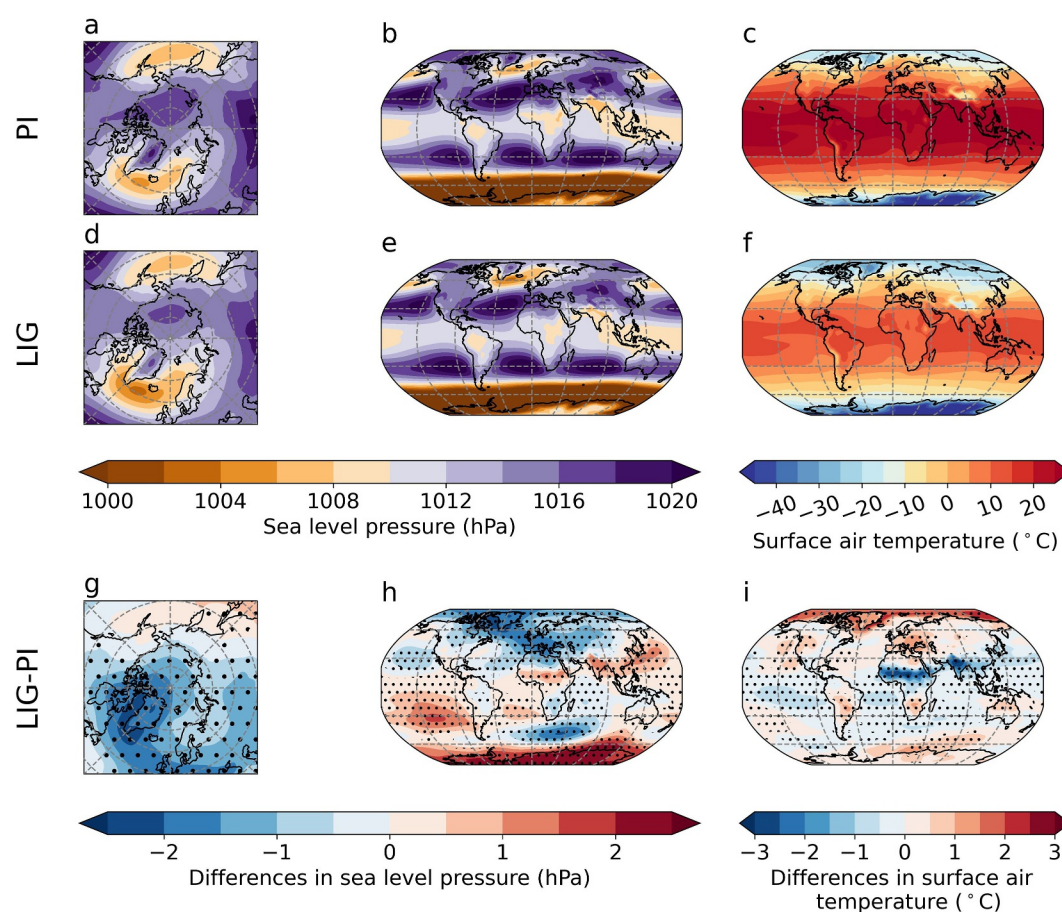


Figure 7. Annual multi-model mean sea-level pressure (hPa) and surface air temperature (°C) for the pre-industrial (PI) and Last Interglacial (127k) simulations. Panels (a), (d), and (g) show sea-level pressure over the Arctic for the PI, 127k, and for the 127k–PI difference, respectively. Panels (b), (e), and (h) show the corresponding global fields. Panels (c), (f), and (i) illustrate the global surface air temperature for the PI, 127k, and for the 127k–PI difference, respectively. In panels (g), (h) and (i), dots indicate regions where at least six out of eight models agree on the sign of change, highlighting robust differences.

correspond to regions where the increase in surface temperature over the Northern Hemisphere is most pronounced (Figure 7i). Therefore, we speculate that the warming pattern at 127 ka may be a key contributor to the simulated changes in ocean circulation.

5.2. Impacts of Surface Current Changes on the Nordic and Labrador Sea Hydrography

Differences in surface wind intensity driven by the SLP anomaly and resulting changes in surface currents strongly impact water transport on either side of Greenland. Volume export from the Arctic to the Atlantic is reduced through Fram Strait and increased through Davis Strait, leading to an anomalous cyclonic circulation around Greenland. Such compensation between the volume transport through these two gateways is also evident in decadal variability of higher-resolution simulations (de Boer et al., 2018) and sensitivity experiments (Karami et al., 2021). Changes in water export through Davis Strait are known to affect the heat content of the subpolar North Atlantic and the mixed-layer depth in the Greenland, Iceland, and Norwegian seas (Karami et al., 2021). In the 127k experiments, these changes result in a greater influx of low-salinity, cold polar waters into the subpolar North Atlantic, while less of these waters are carried toward the Greenland, Iceland, and Norwegian seas via the EGC compared with the PI simulation. This could explain the dipole pattern in mixed-layer thickness observed in Figure 4i, with a decreases in the Greenland, Irminger, and Norwegian seas, but a increase in the subpolar North Atlantic and Labrador Sea relative to PI.

5.3. Impacts of the Subpolar Gyre Strengthening on Atlantic Water Transport

In the 127k simulation, SLP anomaly also drives strong changes in zonal wind stress (not shown) in the northern North Atlantic, which reinforces the SPG. This is consistent with the findings of Irvall et al. (2012, 2016) and Steinsland et al. (2023), who demonstrated that the SPG was more active and/or extended during the early phase of the LIG (128–126.5 ka) based on marine sediment analyzes. Previous studies have highlighted the crucial role of SPG dynamics in influencing the contribution of subpolar relative to subtropical source waters to the AW inflow (e.g., Kenigson & Timmermans, 2021). AW of subtropical origin is carried by the Irminger Current, forming the eastern branch of the SPG, and by the Norwegian Current, which continues northward toward the Nordic Seas. When the SPG is weak, northward transport of AW to the Nordic Seas is enhanced, limiting AW recirculation within the gyre. This allows polar waters transported by the EGC to spread into the gyre. In contrast, a strong SPG drains more AW in the gyre and prevents polar waters from expanding eastward. In the 127k simulation, the strengthening of the SPG is associated with a warming of surface waters south of Greenland and in the Labrador Sea. As suggested in Section 3.1, this warming is not solely driven by sea-ice loss, as the reduction in sea ice is primarily confined to the southeastern coast of Greenland, while the warming extends further southward. Possible explanations include an increased inflow of warm AW into the SPG and/or enhanced deep water formation in the Labrador Sea. Only few models simulate a clear thickening of the mixed layer in this region (Figure 4i). This suggests that enhanced convection plays a role in the warming observed in some models, but other processes must be involved such as advection of warmer waters.

5.4. Simulated Versus Reconstructed Summer Sea Surface Temperatures

Surface warming south of Greenland aligns well with annual SST reconstructions (Figure S2 in Supporting Information S1; Capron et al., 2017; Hoffman et al., 2017; Otto-Bliesner et al., 2021). However, models do not capture the summer cooling in the Labrador and Norwegian seas as previously shown by Otto-Bliesner et al. (2021). This mismatch has been previously attributed to missing processes in climate models, such as the effect of freshwater fluxes from the melting of the Northern Hemisphere ice sheets following the penultimate deglaciation (~138–128 ka; e.g., Stone et al., 2016). Hosing experiments have highlighted that applying freshwater forcing in the northern North Atlantic slows down the AMOC, weakens the SPG and reduces the northward heat transport in the Northern Hemisphere (Govin et al., 2012; Guarino et al., 2023; Otto-Bliesner et al., 2013). This leads to lower SST in the North Atlantic, providing a better match with temperature reconstructions from Capron et al. (2014). However, major Greenland meltwater events are difficult to reconcile with the presence of a strong SPG during the early Last Interglacial, as inferred by other proxy-based reconstructions (e.g., Irvall et al., 2012, 2016; Steinsland et al., 2023). An alternative freshwater source would be sea ice melting (Ezat et al., 2024). In this study, we examined eight models exhibiting different rates of summer sea-ice loss. Nevertheless, none of them simulate a Labrador and Nordic seas summer cooling of the magnitude suggested by temperature reconstructions. Assuming that the proxy reconstructions are right, this implies that PMIP4 simulations may not accurately capture the oceanic circulation patterns and their role in redistributing freshwater. This limitation has been highlighted by Zhang et al. (2023), who showed that changing the land–sea mask consistently with LIG global mean sea-level rise (not done in PMIP4 simulation) modify both atmospheric and oceanic circulations, leading to improved model–data agreement in the Southern Hemisphere. Conversely, some proxies have millennial-scale dating uncertainties and lack the temporal resolution to clearly distinguish deglacial from interglacial signals. They may therefore reflect either late-deglacial conditions, when large meltwater fluxes entered the North Atlantic, or mid-LIG conditions, when polar waters transported by the EGC became dominant in the Labrador Sea (Irvall et al., 2012; Steinsland et al., 2023).

5.5. Assessing Signs of “Arctic Atlantification” During the Last Interglacial

In recent years, the Arctic Ocean has been increasingly influenced by changes in the North Atlantic, a process known as “Arctic Atlantification.” This phenomenon, characterized by a weakening of the Eurasian Basin stratification, a surface salinification, and a warming and a shoaling of the AW layer, accelerates Arctic sea-ice loss (Polyakov et al., 2017, 2020). Recent studies suggest Atlantification also occurred during the LIG or earlier Quaternary interglacials (e.g., Vermassen et al., 2023), potentially driven by different mechanisms. A signature of the Atlantification has been investigated here by analyzing variations in sea water properties at AWCD in the Eurasian Basin. As shown in Section 3, we find no consistent warming of the AW layer or clear increase in heat transport through BSO and Fram Strait, despite higher volume transports in the 127k experiment. These results

are consistent with changes in the SPG dynamics and potential infiltration of polar waters into the northward flow. Alternatively, the AW could have time to cool down enough before reaching the Arctic. Only two models, ACCESS and HadGEM3 have both greater heat transports (not shown) and a warming of the AW layer in the Eurasian Basin. They also simulate the largest sea-ice decline in this region. However, due to limited data availability, our analysis includes only a subset of models that produced the 127k experiment. While these models span a broad range of responses, they may not fully represent the diversity of possible outcomes. In addition, known biases in simulating present-day Arctic hydrography (Athanasé et al., 2025; Heuzé et al., 2023; Khosravi et al., 2022; Muilwijk et al., 2023) may affect LIG simulations too, possibly underestimating Atlantification. Consequently, from a modeling perspective, it remains uncertain whether Atlantification occurred in the early LIG.

5.6. Investigating Future Arctic Ocean Changes in Light of the Last Interglacial

Under CO₂ forcing, all models consistently simulate a rise in SST along the pathway of AW toward the Arctic, as well as larger heat transport through BSO and Fram Strait than in the 127k simulation. This also reflects in the vertical temperature profiles within the Eurasian Basin, showing a clear warming of the AW layer in this region. A similar pattern is observed in the Amerasian Basin, although the warming is less pronounced. Consequently, in contrast to the 127 ka experiments, all models exhibit evidence of Atlantification of the Eurasian Basin in the idealized future simulation.

Changes in the SPG and mixed-layer thickness do not seem to influence so much these results. While the strength of the SPG and AMOC weakens and convection is less active for higher CO₂ levels, both the volume and heat transports into the Arctic are stronger relative to the PI and 127k simulations. This suggests that changes in Atlantic inflows are not solely driven by changes in the oceanic circulation in the northern North Atlantic in these simulations. Moreover, no substantial differences in the strength of currents or gyres in the Nordic Seas are observed that would explain the enhanced heat transport toward the Arctic. Instead, the critical factor appears to be the temperature of the AW as it enters the Arctic.

For the same extent of Arctic sea-ice loss, annual surface conditions are warmer in future scenarios compared to the 127k simulations (Sicard et al., 2023). In the North Atlantic, annual SST at 127 ka are on average slightly lower relative to the PI period, whereas the idealized future simulation exhibits a rise by about 0.6°C. This difference arises from the latitudinal and seasonal variations in LIG solar forcing compared to the uniformly distributed increase in atmospheric CO₂ concentration in future scenarios. Therefore, our results suggest that, under future CO₂-induced warming, the Arctic and sub-Arctic regions may be more strongly influenced by heat transported from lower latitudes than they were during the early LIG.

6. Summary and Conclusion

In this study, we have analyzed changes in oceanic conditions under warmer-than-PI climates in CMIP6/PMIP4 lig127k and 1pctCO₂ simulations. In summary, the Arctic Ocean hydrography and circulation at 127 ka differ from those of the PI period, primarily due to insolation forcing and associated feedback mechanisms, including the decline in sea ice and shifts in atmospheric regimes. In the 127k experiment, a negative anomaly in SLP modifies the surface current intensity around Greenland relative to PI. West of Greenland, the Baffin and Labrador currents transport more freshwater faster through Davis Strait. Models also generally simulate a strengthening of the SPG south of Greenland. This enhances the poleward transport of AW, which have contrasting impacts on the water masses and sea ice of the Eurasian Basin depending on the models with no clear sign of Arctic Atlantification. Surface changes in the Amerasian Basin are more consistent: models all simulate a slight warming and a freshening of the upper layer.

Our results demonstrate that, although sea-ice retreat is the primary driver of early LIG sea surface warming in the Arctic as previously shown, oceanic processes also play a key role and contribute to explain inter-model differences. For example, ACCESS, IPSL, and NorESM2 simulate comparable summer sea-ice reductions relative to PI (around −60%; Kageyama et al., 2021), but ACCESS produces a stronger warming in the Arctic–Atlantic sector. Its SST pattern is similar to that of HadGEM3, despite HadGEM3 exhibiting a much larger decrease in summer sea ice (−96%). This is because of more vigorous deep convection in the Labrador Sea in ACCESS. Moreover, SST in the subpolar North Atlantic and Nordic Seas are also modulated by the state of the SPG, which varies among models. While our analysis mainly focused on the Arctic–Atlantic sector, further investigation of

the Arctic-Pacific sector would be valuable, as models have contrasting behavior there too. For example, CESM2 shows minimal summer SST changes in this region, whereas most models exhibit more significant changes (Figure S2 in Supporting Information S1).

Interestingly, under CO₂ forcing, the dynamics of the Arctic Ocean and surrounding seas differ notably, even when comparing periods with similar annual Arctic sea-ice volumes. Especially, when the 127k simulation displays a stronger SPG with no significant changes in the AMOC strength relative to PI, the idealized future experiment has both a weaker SPG and AMOC consistent with emission-based scenarios (Weijer et al., 2020). Despite the weakened SPG, volume and heat transports through BSO are higher, and the AW layer in the Eurasian Basin is warmer, indicating Arctic Atlantification. These results suggest that (a) changes in poleward heat transport and AW inflows not only depend on wind forcing and the resulting surface ocean circulation in the Arctic-Atlantic sector, but also on water temperature changes in the North Atlantic Ocean, and (b) the spatial distribution of Northern Hemisphere surface warming is crucial to explain differences in ocean dynamics and hydrography under LIG insolation versus future CO₂ forcing. Despite these differences, the 127k and idealized future simulations share some similarities. As previously shown, Arctic sea ice has a similar response to the warming when considering moderate future atmospheric CO₂ rise, although it seems to be more sensitive to radiative forcing than to oceanic forcing in the 127k simulation, requiring substantially less annual oceanic warming to achieve a comparable reduction in sea-ice extent to that simulated in the idealized future experiment (Sicard et al., 2023). Both simulations also show consistent surface freshening in the Amerasian Basin, partly driven by larger precipitation and river inflow compared with the PI experiment. Therefore, while the LIG can serve as a valuable case study to evaluate climate models and better understand future Arctic climate response to anthropogenic forcing at a pan-Arctic scale, caution is warranted when extending this comparison to regional scales due to pronounced spatial heterogeneities between the two periods.

The LIG was characterized by significant climatic variability throughout its length, particularly in the subpolar North Atlantic, with pronounced differences between the early and late phases of the period (Irvani et al., 2012, 2016; Steinsland et al., 2023; Zhuravleva, Bauch, & Van Nieuwenhove, 2017). While some high-resolution records are available for the sub-Arctic regions, large uncertainties remain regarding the precise timing and age of proxy data in the Arctic Ocean. These uncertainties limit our understanding of oceanic conditions in the high latitudes of the Northern Hemisphere during the LIG, particularly the influence of the North Atlantic on the central Arctic hydrography and sea-ice cover. Improving the age constraints and enhancing the temporal resolution of climate records for the Arctic and adjacent regions during the LIG and other Quaternary interglacials are therefore crucial. Such improvements would help resolve existing discrepancies between models and data and provide a clearer picture of the sequence and drivers of climatic events during this period.

It is also important to stress that the models used in this study assume a Greenland topography similar to its PI state, whereas a variety of geological records and model studies suggest that the Greenland ice sheet may have been significantly reduced during parts of the LIG (Bierman et al., 2016; Christ et al., 2021; Plach et al., 2018; Schaefer et al., 2016; Vasskog et al., 2015). A smaller Greenland ice sheet geometry could have substantially altered wind forcing and ocean circulation in the central Arctic. Ice sheet contributions to global mean sea level rise can also trigger additional changes in large-scale circulation and heat transport (Zhang et al., 2019). Moreover, the lig127k simulation was designed to reflect the climate state during the early LIG. Some studies (Bauch et al., 2012; Steinsland et al., 2023, 2025; Van Nieuwenhove et al., 2011; Zhuravleva, Bauch, & Spielhagen, 2017) suggest that the peak AW inflow into the central Arctic appears later during the LIG, which means that we may miss some processes looking at this interval. This might help explain why some models do not simulate an Atlantification of the Arctic as it has been suggested in Vermassen et al. (2023). Simulations incorporating reduced Greenland ice sheet scenarios, modifications to the land–sea mask reflecting higher global mean sea level, and different time slices will be necessary to explore these possibilities further.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The CMIP6 data analyzed in this study are freely available from the Earth System Grid Federation (ESGF; <https://esgf-node.llnl.gov/search/cmip6>). Individual simulations are available at Yeung et al. (2019) and Ziehn et al. (2019a, 2019b) for ACCESS-ESM1-5, Danabasoglu (2019a, 2019b, 2019c) for CESM2, NASA Goddard Institute for Space Studies (NASA/GISS) (2018a, 2018b, 2019) for GISS-E2-1G, Ridley et al. (2018, 2019) and Williams et al. (2021) for HadGEM3-GC3.1-LL, Boucher et al. (2018a, 2018b, 2018c) for IPSL-CM6A-LR, Hajima et al. (2019a, 2019b) and O'ishi et al. (2019) for MIROC-ES2L, Cao and Wang (2019a, 2019b) and Cao (2019) for NESM3, Seland et al. (2019a, 2019b) and Zhang et al. (2019) for NorESM2-LM.

Acknowledgments

The authors acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modeling, coordinated and promoted CMIP6. We thank the various modeling groups for producing and making their model outputs available and the Earth Grid System Federation (ESGF) for archiving and providing access. We also thank Louise Sime and Rachel Diamonds for kindly sharing some HadGEM3 data that were not yet available on ESGF. The data handling was enabled by resources provided by the National Academic Infrastructure for Supercomputing in Sweden (NAISS) and the Swedish National Infrastructure for Computing (SNIC) at Tetralith partially funded by the Swedish Research Council (VR) through Grants 2022-06725 and 2018-05973. AdB and MS acknowledge support from VR Grant 2020-04791. TK, MPK and RGLB were supported by the FORMAS project FutureGS, Grant 2021-01374. HC was supported by VR Grant 31001728, MJ by VR Grant 2021-04512, MO by VR Grant 2020-04379 and FV by Formas Grant 2022-02861. Finally, we thank the three anonymous reviewers for their critical reading which helped improving the manuscript.

References

- Aagaard, K., & Carmack, E. C. (1989). The role of sea ice and other fresh water in the arctic circulation. *Journal of Geophysical Research*, 94(C10), 14485–14498. <https://doi.org/10.1029/JC094iC10p14485>
- AMAP. (2021). AMAP Arctic climate change update 2021: Key trends and impacts.
- Athanase, M., Köhler, R., Heuzé, C., Lévine, X., & Williams, R. (2025). The Arctic Beaufort gyre in CMIP6 models: Present and future. *Journal of Geophysical Research: Oceans*, 130(4), e2024JC021873. <https://doi.org/10.1029/2024JC021873>
- Bauch, H. A. (2013). Interglacial climates and the Atlantic meridional overturning circulation: Is there an arctic controversy? *Quaternary Science Reviews*, 63, 1–22. <https://doi.org/10.1016/j.quascirev.2012.11.023>
- Bauch, H. A., Kandiano, E. S., & Helmke, J. P. (2012). Contrasting ocean changes between the subpolar and polar North Atlantic during the past 135 ka. *Geophysical Research Letters*, 39(11). <https://doi.org/10.1029/2012GL051800>
- Berger, A., & Loutre, M.-F. (1991). Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, 10(4), 297–317. [https://doi.org/10.1016/0277-3791\(91\)90033-Q](https://doi.org/10.1016/0277-3791(91)90033-Q)
- Beszczyska-Möller, A., Woodgate, R. A., Lee, C., Melling, H., & Karcher, M. (2011). A synthesis of exchanges through the main oceanic gateways to the Arctic Ocean. *Oceanography*, 24(3), 82–99. Retrieved from <http://www.jstor.org/stable/24861302>
- Bierman, P. R., Shakun, J. D., Corbett, L. B., Zimmerman, S. R., & Rood, D. H. (2016). A persistent and dynamic East Greenland ice sheet over the past 7.5 million years. *Nature*, 540(7632), 256–260. <https://doi.org/10.1038/nature20147>
- Boucher, O., Denvil, S., Levassasseur, G., Cozic, A., Caubel, A., Foujols, M.-A., et al. (2018a). IPSL IPSL-CM6A-LR model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5049>
- Boucher, O., Denvil, S., Levassasseur, G., Cozic, A., Caubel, A., Foujols, M.-A., et al. (2018b). IPSL IPSL-CM6A-LR model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5251>
- Boucher, O., Denvil, S., Levassasseur, G., Cozic, A., Caubel, A., Foujols, M.-A., et al. (2018c). IPSL IPSL-CM6A-LR model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5228>
- Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., et al. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, 12(7), e2019MS002010. <https://doi.org/10.1029/2019MS002010>
- Cao, J. (2019). NUIST NESMv3 model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.8772>
- Cao, J., & Wang, B. (2019a). NUIST NESMv3 model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.8709>
- Cao, J., & Wang, B. (2019b). NUIST NESMv3 model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.8776>
- Capron, E., Govin, A., Feng, R., Otto-Bliesner, B., & Wolff, E. (2017). Critical evaluation of climate syntheses to benchmark CMIP6/PMIP4 127 ka Last interglacial simulations in the high-latitude regions. *Quaternary Science Reviews*, 168, 137–150. <https://doi.org/10.1016/j.quascirev.2017.04.019>
- Capron, E., Govin, A., Stone, E. J., Masson-Delmotte, V., Mulitza, S., Otto-Bliesner, B., et al. (2014). Temporal and spatial structure of multi-millennial temperature changes at high latitudes during the last interglacial. *Quaternary Science Reviews*, 103, 116–133. <https://doi.org/10.1016/j.quascirev.2014.08.018>
- Christ, A. J., Bierman, P. R., Schaefer, J. M., Dahl-Jensen, D., Steffensen, J. P., Corbett, L. B., et al. (2021). A multimillion-year-old record of Greenland vegetation and glacial history preserved in sediment beneath 1.4 km of ice at camp century. *Proceedings of the National Academy of Sciences*, 118(13), e2021442118. <https://doi.org/10.1073/pnas.2021442118>
- Crow, B. R., & Prange, M. (2025). Long- and short-term variability of arctic sea-ice cover during the last interglacial and marine isotope stage 11c. *Communications Earth & Environment*, 6(1), 274. <https://doi.org/10.1038/s43247-025-02267-4>
- Danabasoglu, G. (2019a). NCAR CESM2 model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.7497>
- Danabasoglu, G. (2019b). NCAR CESM2 model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.7673>
- Danabasoglu, G. (2019c). NCAR CESM2-WACCM model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.10094>
- de Boer, A. M., Gavilan Pascual-Ahuir, E., Stevens, D. P., Chafik, L., Hutchinson, D. K., Zhang, Q., et al. (2018). Interconnectivity between volume transports through Arctic straits. *Journal of Geophysical Research: Oceans*, 123(12), 8714–8729. <https://doi.org/10.1029/2018JC014320>
- de Vernal, A., Gersonde, R., Goosse, H., Seidenkrantz, M.-S., & Wolff, E. W. (2013). Sea ice in the paleoclimate system: The challenge of reconstructing sea ice from proxies—An introduction. *Quaternary Science Reviews*, 79, 1–8. <https://doi.org/10.1016/j.quascirev.2013.08.009>
- Diamond, R., Sime, L. C., Schroeder, D., & Guarino, M.-V. (2021). The contribution of melt ponds to enhanced Arctic sea-ice melt during the last interglacial. *The Cryosphere*, 15(11), 5099–5114. <https://doi.org/10.5194/tc-15-5099-2021>
- Druckenmiller, M. L., Moon, T. A., Thoman, R. L., Ballinger, T. J., Berner, L. T., Bernhard, G. H., et al. (2021). The Arctic. *Bulletin of the American Meteorological Society*, 102(8), S263–S316. <https://doi.org/10.1175/BAMS-D-21-0086.1>

- Dyer, B., Austermann, J., D'Andrea, W. J., Creel, R. C., Sandstrom, M. R., Cashman, M., et al. (2021). Sea-level trends across The Bahamas constrain peak last interglacial ice melt. *Proceedings of the National Academy of Sciences*, 118(33), e2026839118. <https://doi.org/10.1073/pnas.2026839118>
- Eynaud, F., Turon, J., & Duprat, J. (2004). Comparison of the Holocene and Eemian palaeoenvironments in the south Icelandic basin: Dinoflagellate cysts as proxies for the north Atlantic surface circulation. *Review of Palaeobotany and Palynology*, 128(1), 55–79. [https://doi.org/10.1016/S0034-6667\(03\)00112-X](https://doi.org/10.1016/S0034-6667(03)00112-X)
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model inter-comparison project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, 9(5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- Ezat, M. M., Fahl, K., & Rasmussen, T. L. (2024). Arctic freshwater outflow suppressed Nordic Seas overturning and oceanic heat transport during the last interglacial. *Nature Communication*, 15(8998), 8998. <https://doi.org/10.1038/s41467-024-53401-3>
- Galaasen, E. V., Ninnemann, U. S., Irvani, N., Kleiven, H. K. F., Rosenthal, Y., Kissel, C., & Hodel, D. A. (2014). Rapid reductions in North Atlantic deep water during the peak of the last interglacial period. *Science*, 343(6175), 1129–1132. <https://doi.org/10.1126/science.1248667>
- Govin, A., Braconnot, P., Capron, E., Cortijo, E., Duplessy, J.-C., Jansen, E., et al. (2012). Persistent influence of ice sheet melting on high northern latitude climate during the early last interglacial. *Climate of the Past*, 8(2), 483–507. <https://doi.org/10.5194/cp-8-483-2012>
- Guarino, M.-V., Sime, L. C., Schröder, D., Malmierca-Vallet, I., Rosenblum, E., Ringer, M., et al. (2020). Sea-ice-free Arctic during the last interglacial supports fast future loss. *Nature Climate Change*, 10(10), 928–932. <https://doi.org/10.1038/s41558-020-0865-2>
- Guarino, M. V., Sime, L. C., Diamond, R., Ridley, J., & Schroeder, D. (2023). The coupled system response to 250 years of freshwater forcing: Last interglacial CMIP6–PMIP4 hadgem3 simulations. *Climate of the Past*, 19(4), 865–881. <https://doi.org/10.5194/cp-19-865-2023>
- Hajima, T., Abe, M., Arakawa, O., Suzuki, T., Komuro, Y., Ogura, T., et al. (2019a). MIROC MIROC-ES2L model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5370>
- Hajima, T., Abe, M., Arakawa, O., Suzuki, T., Komuro, Y., Ogura, T., et al. (2019b). MIROC MIROC-ES2L model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5710>
- Heuzé, C., Zanowski, H., Karam, S., & Muilwijk, M. (2023). The deep Arctic Ocean and fram strait in CMIP6 models. *Journal of Climate*, 36(8), 2551–2584. <https://doi.org/10.1175/JCLI-D-22-0194.1>
- Hoffman, J. S., Clark, P. U., Parnell, A. C., & He, F. (2017). Regional and global sea-surface temperatures during the last interglaciation. *Science*, 355(6322), 276–279. <https://doi.org/10.1126/science.aai8464>
- Irvani, N., Ninnemann, U. S., Galaasen, E. V., Rosenthal, Y., Kroon, D., Oppo, D. W., et al. (2012). Rapid switches in subpolar North Atlantic hydrography and climate during the last interglacial (MIS 5e). *Paleoceanography*, 27(2). <https://doi.org/10.1029/2011PA002244>
- Irvani, N., Ninnemann, U. S., Kleiven, H. K. F., Galaasen, E. V., Morley, A., & Rosenthal, Y. (2016). Evidence for regional cooling, frontal advances, and East Greenland ice sheet changes during the demise of the last interglacial. *Quaternary Science Reviews*, 150, 184–199. <https://doi.org/10.1016/j.quascirev.2016.08.029>
- Jakobsson, M., Mayer, L. A., Bringenspar, C., Castro, C. F., Mohammad, R., Johnson, P., et al. (2020). The international bathymetric chart of the Arctic Ocean version 4.0. *Nature Scientific Data*, 7(116), 176. <https://doi.org/10.1038/s41597-020-0520-9>
- Jiang, Z., Brierley, C., Thornalley, D., & Sax, S. (2023). No changes in overall AMOC strength in interglacial PMIP4 time slices. *Climate of the Past*, 19(1), 107–121. <https://doi.org/10.5194/cp-19-107-2023>
- Kageyama, M., Braconnot, P., Harrison, S. P., Haywood, A. M., Jungclauss, J. H., Otto-Bliesner, B. L., et al. (2018). The PMIP4 contribution to CMIP6 – Part 1: Overview and over-arching analysis plan. *Geoscientific Model Development*, 11(3), 1033–1057. <https://doi.org/10.5194/gmd-11-1033-2018>
- Kageyama, M., Sime, L. C., Sicard, M., Guarino, M.-V., de Vernal, A., Schroeder, D., et al. (2021). A multi-model CMIP6 study of Arctic sea ice at 127 ka: Sea ice data compilation and model differences. *Climate of the Past*, 17(1), 37–62. <https://doi.org/10.5194/cp-17-37-2021>
- Karami, M. P., Myers, P. G., de Vernal, A., Trembley, L. B., & Hu, X. (2021). The role of Arctic gateways on sea ice and circulation in the Arctic and North Atlantic Oceans: A sensitivity study with an ocean-sea-ice model. *Climate Dynamics*, 57(7–8), 2129–2151. <https://doi.org/10.1007/s00382-021-05798-6>
- Kenigson, J. S., & Timmermans, M.-L. (2021). Nordic seas hydrography in the context of arctic and north Atlantic Ocean dynamics. *Journal of Physical Oceanography*, 51(1), 101–114. <https://doi.org/10.1175/JPO-D-20-0071.1>
- Khosravi, N., Wang, Q., Koldunov, N., Hinrichs, C., Semmler, T., Danilov, S., & Jung, T. (2022). The Arctic Ocean in CMIP6 models: Biases and projected changes in temperature and salinity. *Earth's Future*, 10(2), e2021EF002282. <https://doi.org/10.1029/2021EF002282>
- Meredith, M., Sommerkorn, M., Abram, N., Arblaster, J., Arrigo, K., Azetzu-Scott, K., et al. (2019). Polar regions. In *IPCC special report on the ocean and cryosphere in a changing climate (SROCC)*. N.M. Weyer.
- Muilwijk, M., Nummelin, A., Heuzé, C., Polyakov, I. V., Zanowski, H., & Smedsrud, L. H. (2023). Divergence in climate model projections of future Arctic atlantification. *Journal of Climate*, 36(6), 1727–1748. <https://doi.org/10.1175/JCLI-D-22-0349.1>
- NASA Goddard Institute for Space Studies (NASA/GISS). (2018a). NASA-GISS GISS-E2.1G model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.6950>
- NASA Goddard Institute for Space Studies (NASA/GISS). (2018b). NASA-GISS GISS-E2.1G model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.7380>
- NASA Goddard Institute for Space Studies (NASA/GISS). (2019). NASA-GISS GISS-E2.1G model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.7223>
- Nørgaard-Pedersen, N., Mikkelsen, N., Lassen, S. J., Kristoffersen, Y., & Sheldon, E. (2007). Reduced sea ice concentrations in the Arctic Ocean during the last interglacial period revealed by sediment cores off northern Greenland. *Paleoceanography and Paleoclimatology*, 22(1). <https://doi.org/10.1029/2006PA001283>
- O'ishi, R., Abe-Ouchi, A., Ohgaito, R., Abe, M., Arakawa, O., Ogochi, K., et al. (2019). MIROC MIROC-ES2L model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5645>
- Otto-Bliesner, B. L., Braconnot, P., Harrison, S. P., Lunt, D. J., Abe-Ouchi, A., Albani, S., et al. (2017). The PMIP4 contribution to CMIP6 – Part 2: Two interglacials, scientific objective and experimental design for Holocene and last interglacial simulations. *Geoscientific Model Development*, 10(11), 3979–4003. <https://doi.org/10.5194/gmd-10-3979-2017>
- Otto-Bliesner, B. L., Brady, E. C., Zhao, A., Brierley, C., Axford, Y., Capron, E., et al. (2021). Large-scale features of last interglacial climate: Results from evaluating the lig127k simulations for CMIP6-PMIP4. *Climate of the Past*, 17(1), 63–94. <https://doi.org/10.5194/cp-17-63-2021>
- Otto-Bliesner, B. L., Rosenbloom, N., Stone, E. J., McKay, N. P., Lunt, D. J., Brady, E. C., & Overpeck, J. T. (2013). How warm was the last interglacial? New model–data comparisons. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(2001), 20130097. <https://doi.org/10.1098/rsta.2013.0097>

- Penaud, A., Eynaud, F., Turon, J., Zaragosi, S., Marret, F., & Bourillet, J. (2008). Interglacial variability (mis 5 and mis 7) and dinoflagellate cyst assemblages in the Bay of Biscay (North Atlantic). *Marine Micropaleontology*, 68(1), 136–155. <https://doi.org/10.1016/j.marmicro.2008.01.007>
- Plach, A., Nisancioglu, K. H., Le clec'h, S., Born, A., Langebroek, P. M., Guo, C., et al. (2018). Eemian Greenland SMB strongly sensitive to model choice. *Climate of the Past*, 14(10), 1463–1485. <https://doi.org/10.5194/cp-14-1463-2018>
- Polyakov, I. V., Pnyushkov, A. V., Alkire, M. B., Ashik, I. M., Baumann, T. M., Carmack, E. C., et al. (2017). Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. *Science*, 356(6335), 285–291. <https://doi.org/10.1126/science.aai8204>
- Polyakov, I. V., Rippeth, T. P., Fer, I., Alkire, M. B., Baumann, T. M., Carmack, E. C., et al. (2020). Weakening of cold halocline layer exposes sea ice to oceanic heat in the eastern Arctic Ocean. *Journal of Climate*, 33(18), 8107–8123. <https://doi.org/10.1175/JCLI-D-19-0976.1>
- Rasmussen, T. L., Oppo, D. W., Thomsen, E., & Lehman, S. J. (2003a). Deep sea records from the southeast Labrador Sea: Ocean circulation changes and ice-rafting events during the last 160,000 years. *Paleoceanography*, 18(1). <https://doi.org/10.1029/2001PA000736>
- Rasmussen, T. L., Thomsen, E., Kuijpers, A., & Wastegård, S. (2003b). Late warming and early cooling of the sea surface in the Nordic seas during mis 5e (eemian interglacial). *Quaternary Science Reviews*, 22(8), 809–821. [https://doi.org/10.1016/S0277-3791\(02\)00254-8](https://doi.org/10.1016/S0277-3791(02)00254-8)
- Razmjooei, M. J., Henderiks, J., Coxall, H. K., Baumann, K.-H., Vermassen, F., Jakobsson, M., et al. (2023). Revision of the Quaternary calcareous nannofossil biochronology of Arctic Ocean sediments. *Quaternary Science Reviews*, 321, 108382. <https://doi.org/10.1016/j.quascirev.2023.108382>
- Ridley, J., Menary, M., Kuhlbrodt, T., Andrews, M., & Andrews, T. (2018). MOHC HadGEM3-GC31-LL model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.6294>
- Ridley, J., Menary, M., Kuhlbrodt, T., Andrews, M., & Andrews, T. (2019). MOHC HadGEM3-GC31-LL model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.5788>
- Schaefer, J. M., Finkel, R. C., Balco, G., Alley, R. B., Caffee, M. W., Briner, J. P., et al. (2016). Greenland was nearly ice-free for extended periods during the Pleistocene. *Nature*, 540(7632), 252–255. <https://doi.org/10.1038/nature20146>
- Schulzweida, U. (2022). CDO user guide [Computer software manual]. *Zenodo*. <https://doi.org/10.5281/zenodo.7112925>
- Seland, Ø., Bentsen, M., Olivie, D. J. L., Toniazzo, T., Gjermundsen, A., Graff, L. S., et al. (2019a). NCC NorESM2-LM model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.7802>
- Seland, Ø., Bentsen, M., Olivie, D. J. L., Toniazzo, T., Gjermundsen, A., Graff, L. S., et al. (2019b). NCC NorESM2-LM model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.8217>
- Sicard, M., de Boer, A. M., Coxall, H. K., Koenigk, T., Karami, M. P., Jakobsson, M., & O'Regan, M. (2023). Similarities and differences in Arctic Sea-ice loss during the solar-forced last interglacial warming (127kyr bp) and CO2-Forced future warming. *Geophysical Research Letters*, 50(24), e2023GL104782. <https://doi.org/10.1029/2023GL104782>
- Sicard, M., Kageyama, M., Charbit, S., Braconnot, P., & Madeleine, J.-B. (2022). An energy budget approach to understand the Arctic warming during the last interglacial. *Climate of the Past*, 18(3), 607–629. <https://doi.org/10.5194/cp-18-607-2022>
- Sime, L. C., Diamond, R., Stepanek, C., Brierley, C., Schroeder, D., Kageyama, M., et al. (2025a). A sea ice free arctic: Assessment fast track abrupt-127k experimental protocol and motivation. *EGU sphere*, 1–33. <https://doi.org/10.5194/egusphere-2025-3531>
- Sime, L. C., Sivankutty, R., Malmierca-Vallet, I., Goursaud Oger, S., LeGrande, A. N., McClymont, E. L., et al. (2025b). H11 meltwater and standard 127 ka last interglacial simulations suggest more modest peak temperatures for both Greenland and Antarctica: A multi-model study of water isotopes. *Climate of the Past*, 21(10), 1725–1753. <https://doi.org/10.5194/cp-21-1725-2025>
- Sime, L. C., Sivankutty, R., Vallet-Malmierca, I., de Boer, A. M., & Sicard, M. (2023). Summer surface air temperature proxies point to near-sea-ice-free conditions in the Arctic at 127 ka. *Climate of the Past*, 19(4), 883–900. <https://doi.org/10.5194/cp-19-883-2023>
- Solomon, A., Heuzé, C., Rabe, B., Bacon, S., Bertino, L., Heimbach, P., et al. (2021). Freshwater in the Arctic Ocean 2010–2019. *Ocean Science*, 17(4), 1081–1102. <https://doi.org/10.5194/os-17-1081-2021>
- Steele, M., Morley, R., & Ermold, W. (2001). Phc: A global ocean hydrography with a high-quality arctic ocean. *Journal of Climate*, 14(9), 2079–2087. [https://doi.org/10.1175/1520-0442\(2001\)014<2079:PAGOHV>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<2079:PAGOHV>2.0.CO;2)
- Stein, R., Fahl, K., Gierz, P., Niessen, F., & Lohmann, G. (2017). Arctic Ocean sea ice cover during the penultimate glacial and the last interglacial. *Nature Communications*, 8(373), 373. <https://doi.org/10.1038/s41467-017-00552-1>
- Steinsland, K., Grant, D. M., Fahl, K., Stein, R., Rasmussen, T. L., Risebrobakken, B., et al. (2025). Sea ice variability from the penultimate glacial to the last interglacial in the eastern fram strait. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 663, 112779. <https://doi.org/10.1016/j.palaeo.2025.112779>
- Steinsland, K., Grant, D. M., Ninnemann, U. S., Fahl, K., Stein, R., & De Schepper, S. (2023). Sea ice variability in the North Atlantic subpolar gyre throughout the last interglacial. *Quaternary Science Reviews*, 313, 108198. <https://doi.org/10.1016/j.quascirev.2023.108198>
- Stone, E. J., Capron, E., Lunt, D. J., Payne, A. J., Singarayer, J. S., Valdes, P. J., & Wolff, E. W. (2016). Impact of meltwater on high-latitude early last interglacial climate. *Climate of the Past*, 12(9), 1919–1932. <https://doi.org/10.5194/cp-12-1919-2016>
- Stroeve, J., & Notz, D. (2018). Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, 13(10), 103001. <https://doi.org/10.1088/1748-9326/aade56>
- Timmermans, M.-L., & Marshall, J. (2020). Understanding Arctic Ocean circulation: A review of ocean dynamics in a changing climate. *Journal of Geophysical Research: Oceans*, 125(4), e2018JC014378. <https://doi.org/10.1029/2018JC014378>
- Timmermans, M.-L., & Toole, J. M. (2023). The Arctic Ocean's Beaufort gyre. *Annual Review of Marine Science*, 15(1), 223–248. <https://doi.org/10.1146/annurev-marine-032122-012034>
- Van Nieuwenhove, N., Bauch, H. A., Eynaud, F., Kandiano, E., Cortijo, E., & Turon, J.-L. (2011). Evidence for delayed poleward expansion of North Atlantic surface waters during the last interglacial (MIS 5e). *Quaternary Science Reviews*, 30(7), 934–946. <https://doi.org/10.1016/j.quascirev.2011.01.013>
- Vasskog, K., Langebroek, P. M., Andrews, J. T., Ø. Nilsen, J. E., & Nesje, A. (2015). The Greenland ice sheet during the last glacial cycle: Current ice loss and contribution to sea-level rise from a palaeoclimatic perspective. *Earth-Science Reviews*, 150, 45–67. <https://doi.org/10.1016/j.earscirev.2015.07.006>
- Vermassen, F., O'Regan, M., de Boer, A. M., Schenk, F., Razmjooei, M., West, G., et al. (2023). A seasonally ice-free Arctic Ocean during the last interglacial. *Nature Geosciences*, 16(8), 723–729. <https://doi.org/10.1038/s41561-023-01227-x>
- Wang, X., Liu, Y., Key, J. R., & Dworak, R. (2022). A new perspective on four decades of changes in Arctic sea ice from satellite observations. *Remote Sensing*, 14(8), 1846. <https://doi.org/10.3390/rs14081846>
- Weijer, W., Cheng, W., Garuba, O. A., Hu, A., & Nadiga, B. T. (2020). CMIP6 models predict significant 21st century decline of the Atlantic meridional overturning circulation. *Geophysical Research Letters*, 47(12), e2019GL086075. <https://doi.org/10.1029/2019GL086075>
- Williams, C., Lunt, D., Singarayer, J., & Guarino, M. V. (2021). NERC HadGEM3-GC31-LL model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.12128>

- Yeung, N., Menviel, L., Meissner, K., Ziehn, T., Chamberlain, M., Mackallah, C., et al. (2019). CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.13703>
- Zhang, Z., Bentsen, M., Olivieri, D. J. L., Seland, Ø., Toniazio, T., Gjermundsen, A., et al. (2019). NCC NorESM2-LM model output prepared for CMIP6 PMIP lig127k [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.8078>
- Zhang, Z., Jansen, E., Sobolowski, S. P., Otterå, O. H., Ramstein, G., Guo, C., et al. (2023). Atmospheric and oceanic circulation altered by global mean sea-level rise. *Nature Geoscience*, 16(4), 321–327. <https://doi.org/10.1038/s41561-023-01153-y>
- Zhuravleva, A., Bauch, H. A., & Spielhagen, R. F. (2017). Atlantic water heat transfer through the arctic gateway (fram strait) during the last interglacial. *Global and Planetary Change*, 157, 232–243. <https://doi.org/10.1016/j.gloplacha.2017.09.005>
- Zhuravleva, A., Bauch, H. A., & Van Nieuwenhove, N. (2017). Last Interglacial (MIS5e) hydrographic shifts linked to meltwater discharges from the East Greenland margin. *Quaternary Science Reviews*, 164, 95–109. <https://doi.org/10.1016/j.quascirev.2017.03.026>
- Ziehn, T., Chamberlain, M., Lenton, A., Law, R., Bodman, R., Dix, M., et al. (2019a). CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 CMIP 1pctCO2 [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.4231>
- Ziehn, T., Chamberlain, M., Lenton, A., Law, R., Bodman, R., Dix, M., et al. (2019b). CSIRO ACCESS-ESM1.5 model output prepared for CMIP6 CMIP piControl [Dataset]. *Earth System Grid Federation*. <https://doi.org/10.22033/ESGF/CMIP6.4312>