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Arctic sea-ice export as a mechanism for cold climate events during the last deglaciation

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ABSTRACT: Recently it was proposed that a sudden drainage of accumulated Arctic sea ice could have caused cold climate events during the last deglaciation. To explore this mechanism, we performed numerical experiments with an atmosphere–ocean–sea ice model. In these experiments, the impact of a large flush of Arctic sea ice was compared to a reference glacial state of the climate. In our results, the sea ice flush produces a major surface freshening of the North Atlantic Ocean and a 17% weakening of the strength of the Atlantic Meridional Overturning Circulation. Together with an increase in surface albedo, this weakening in ocean circulation leads to a cooling over the North Atlantic, extending to the downwind continents. Compared to our reference glacial state, the cooling reaches 5°C and lasts about 80 years. This climate anomaly is similar in magnitude and duration to relatively short cooling events during the last deglaciation, such as the Older Dryas, the Inter-Allerød cold period and the Preboreal Oscillation. We thus conclude that the sea-ice flush mechanism is consistent with the occurrence of such cooling events in the North Atlantic region. However, longer cooling events such as the Younger Dryas would require additional mechanisms.
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KEYWORDS: cold events; palaeoclimate model experiment; sea-ice drainage

Introduction

During the last deglaciation (21–8 ka), several marked centennial-scale cooling events occurred that have been recorded in various proxy records in the North Atlantic region. These events include the Older Dryas (ca. 14 ka), the Younger Dryas (ca. 12.9 ka) and the Preboreal Oscillation (ca. 11.3 ka) (Lowe et al., 2008). The classical explanation for the occurrence of these events is that they were caused by catastrophic drainage of meltwater lakes associated with the Laurentide icesheet still existing at that time (e.g. Broecker et al., 1989; Clark et al., 2001; Teller et al., 2002; Murton et al., 2010). Such lake drainage would cause abrupt freshening of the North Atlantic Ocean, reducing the surface water density perturbing the deepwater formation and leading to a weakening of the Atlantic Meridional Overturning Circulation (AMOC) and the associated northward heat transport (e.g. Broecker et al., 1989). However, an alternative explanation proposed by Bradley and England (2008) is that the freshwater perturbation originated from the sudden export of old sea ice that had accumulated in the Arctic Basin for thousands of years. Such a flush of old sea ice would have occurred through Fram Strait, this being the only available outlet from the Arctic basin during the last glacial. It is suggested that the breakup of this sea ice could have been triggered by the steadily increasing sea levels after 19 ka, allowing Atlantic waters to circulate across the Barents Shelf and enter the Arctic basin again (Bradley and England, 2008). In addition, the Bering Strait opened again, providing access to Pacific waters.

Besides the idea of a flush of old sea ice, there is also the possibility that other sources of ice were involved in ice drainage during deglaciation. There is the potential impact of ice in the central Arctic associated with continental ice sheets in the form of large icebergs (Moore, 2005; Green et al., 2010) or ice shelves (Polyak et al., 2001). Erosional features from the sea floor provide evidence for much thicker ice (at least 1 km thick) covering the central Arctic Ocean during glaciations (Polyak et al., 2001; Jakobsson et al., 2010; 2015; Gasson et al., 2018). These erosional features were caused by either iceberg scouring or an extensive ice shelf (Green et al., 2010; Jakobsson et al., 2015). Breakup of such an ice shelf can be expected to have an important impact on the climate system. However, the evidence for this very thick ice has been dated to the penultimate glaciation and there is no indication for such thick ice cover in the Arctic during the last glaciation (Gasson et al., 2018). An extensive thick ice cover of the Arctic would be consistent with very low sediment deposition rates during the glacial maximum (Darby et al., 2006). In this paper we focus on the impact of accumulated Arctic sea ice as proposed by Bradley and England (2008).

Recently, Condrón et al. (2020) explored the explanation for accumulated sea ice by performing several climate model experiments that included massive export of Arctic sea ice through Fram Strait. They showed that such sea-ice flushes could have acted as drivers of centennial-scale cold events during the last deglaciation, as their results indicate that sea ice could potentially have caused disruptions of the AMOC that were sufficiently large to cause significant cooling around the North Atlantic basin. However, the model applied by Condrón et al. (2020) did not include a dynamic atmosphere, implying that important feedbacks involving the atmosphere were not considered and that the impact on terrestrial climate conditions could not be studied.

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Therefore, in this paper we further investigate the impact of massive export of Arctic sea ice on the climate in transient experiments performed with a coupled atmosphere–ocean model. We started our model with standard glacial boundary conditions for the Last Glacial Maximum (LGM) taken from the PMIP4 project (Kageyama et al., 2017). Starting from this LGM state, we prevented Arctic sea-ice export over 2000 years by forcing the sea-ice velocity to be zero at Fram Strait, leading to accumulation of sea ice in the Arctic Ocean. Subsequently, this obstacle at Fram Strait was suddenly removed, allowing us to study the impact of massive sea-ice export on the climate system. We focus on the following research questions:

1. What was the impact of a massive sea-ice flush on the global climate during the last glacial?
2. To what extent can this ice export mechanism explain abrupt cold events that occurred during the last deglaciation?

Methods

The iLOVECLIM climate model

We performed our experiments with the iLOVECLIM global climate model of intermediate complexity (Goosse et al., 2010; Roche et al., 2014). We applied a version with dynamic representations of the oceans, sea ice, atmosphere and terrestrial vegetation. The atmospheric component is ECBilt (Opsteegh et al., 1998), a quasi-geostrophic model with three layers in the vertical and T21 horizontal resolution ($5.6^\circ \times 5.6^\circ$ latitude–longitude). The component representing the oceans and sea ice is CLIO (Goosse and Fichefet, 1999), an oceanic general circulation model coupled to a dynamic–thermodynamic sea-ice model. CLIO has 20 unevenly spaced layers in the vertical and a $3^\circ \times 3^\circ$ latitude–longitude horizontal resolution. Finally, VECODE is the component describing the interaction between the terrestrial vegetation and atmospheric dynamics (Brovkin et al., 1997). VECODE includes two plant functional types, grass and trees, and bare ground as a dummy type. Earlier versions of iLOVECLIM have been successfully applied to study the climate of the LGM (e.g. Roche et al., 2007), the Younger Dryas event (Renssen et al., 2015, 2018), the 8.2-ka BP event (Renssen et al., 2001; Wiersma and Renssen, 2006; Li et al., 2019) and the Holocene (Renssen et al., 2012; Zhang et al., 2018).

Experimental design

We configured our model with glacial boundary conditions, consistent with the set-up applied by Condron et al. (2020). As our starting point, we took the results of a 6000-year-long LGM experiment with fixed PMIP4 boundary conditions (for details, see Kageyama et al., 2017). First, we continued this LGM experiment for another 1000 years to obtain a reference state (our control experiment LGM_ctrl, see Table 1). Second, we

started again from the same initial conditions, but this time with the sea-ice export from Fram Strait being blocked (LGM_block experiment). The latter experiment was continued for 2000 years. Finally, after these 2000 years we removed this disruption by allowing sea ice to be exported again through Fram Strait (LGM_release experiment). This experiment was run for 500 years. Thus, in these three experiments, the only change made was in sea-ice transport through Fram Strait, implying that all boundary conditions were fixed at LGM conditions identical to the LGM experiment that was used for initial conditions. We note that using fixed LGM conditions implies that we have not accounted for the impact of a rising sea level.

Results

As expected, preventing the export of sea ice through Fram Strait in experiment LGM_block results in a drastic increase in sea-ice volume (Fig. 1a). Relative to LGM_ctrl, the ice volume almost doubles in 150 years from 64.6×10^3 to 121.5×10^3 km³, followed by a stabilization until sea-ice export is enabled again at model year 2000. The blocking of sea-ice export in LGM_block had no effect on the AMOC strength (Fig. 1b) or on the temperature at 60°N (Fig. 1c).

The level with high sea-ice volume in LGM_block corresponds to an ice thickness of around 25 m in the central Arctic Ocean, compared to about 10 m thickness in LGM_ctrl (compare Figs. 2a and 2b). After release of the blockage, the sea-ice thickness rapidly decreased back to the 10 m thickness level in the Arctic Ocean (Figs. 2c and 3). In contrast, ice thickness increased considerably in the path of ice export just south of the blockage. For instance, at 79.5°N the ice thickness increased from 4.0 to 7.5 m within 2 years after the release, followed by a decrease over 70 years to a mean level of 4.5 m (Fig. 3). Further south the rise in sea-ice thickness was less sudden and was delayed, with a peak 18 years after the release, for instance at 69.5°N (Fig. 3). The increase in ice thickness is simulated over most of the Nordic Seas, and further south down to Denmark Strait and the Labrador Sea (Fig. 2d).

As expected, the melting of this sea-ice flush caused sea surface salinity (SSS) to decrease considerably, especially in the Eastern North Atlantic between 45°N and 60°N where SSS was reduced by more than 1 psu (practical salinity units; Fig. 4a), resulting in a decrease in surface water density. As this part of the North Atlantic is one of the main areas with deep convection under LGM conditions in the model (Fig. 5a), this decrease in density led to reduced convective activity as evidenced by a reduction of the mixed layer depth by up to 500 m (Fig. 5b). Associated with this decrease in convective activity is a weakening of the AMOC as seen by a 3 Sv decrease (i.e. 17%) in southward deepwater export at 20°S (Fig. 1b). The combination of an influx of cold meltwater with

Table 1. Overview of the model experiments performed in this study.

Experimental design				
Experiment name	Purpose	Initial conditions	Sea ice through Fram Strait	Duration (years)
LGM_ctrl	Control run. Continuation of 6000-year run with PMIP4 LGM forcing	PMIP4 LGM	Yes	1000
LGM_block	Impact of Arctic ice accumulation – no ice transport though Fram Strait	PMIP4 LGM	No	2000
LGM_release	Impact of ice release through Fram Strait	LGM_block after year 2000	Yes	500

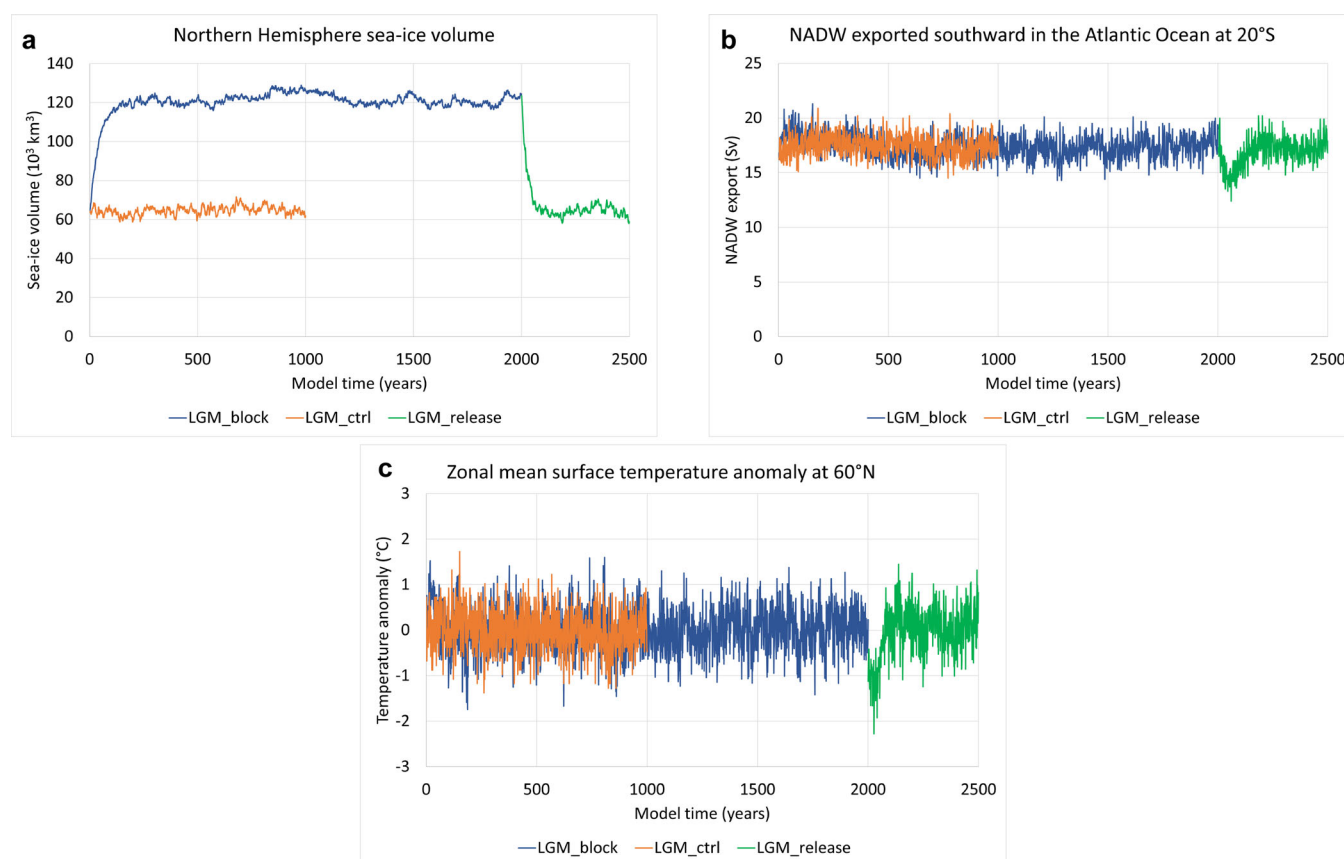


Figure 1. Time series of (a) Northern Hemisphere sea ice volume, (b) North Atlantic Deep Water (NADW) exported at 20°S and (c) zonal average surface temperature at 60°N. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3665)]

the weakening of the AMOC resulted in surface cooling of the North Atlantic Ocean by more than 3°C (Figs. 4b, 6a and 7b). In the areas with increased sea-ice cover the lower atmosphere experienced strong cooling of more than 5°C, such as over the Nordic Seas, Denmark Strait and Labrador Sea (Fig. 7). These overall cold conditions over the North Atlantic Ocean also resulted in cooling over downwind land surfaces, with 1–2°C cooling over Europe and Greenland (Figs. 6a–c and 7a, b), and about 0.5°C cooling over North Africa and large parts of mid-latitude Asia (Fig. 7b). Globally, there is a significant cooling of 0.3°C.

The climate anomaly caused by the sea-ice flush lasted for about 80 years, as seen in temperature and SSS. This indicates that the system relatively quickly bounces back to the control state obtained before any perturbation in sea ice (i.e. LGM_ctrl).

Discussion

In our LGM_block experiment there is no sea-ice export possible because Fram Strait and the other gateways are blocked. This blockage leads to a growth in ice volume until a new balance is reached, with the ice thickness increasing in 150 years from about 10 to 25 m in the central Arctic. The thickness of 10 m is representative for our LGM_ctrl experiment with sea ice export through Fram Strait preventing the ice from becoming thicker. The stabilization of sea-ice thickness after 150 years in LGM_block is related to energy exchange in the ocean–ice–atmosphere system. At high latitudes, the ocean is typically warmer than the atmosphere, implying that the ocean loses heat to the air above. The heat flux at the ice base depends on the temperature gradient between the surface ocean water (sea surface temperature) and the ice surface, and on the thickness of the ice and the latent heat exchange during

freezing of sea water or melting of ice. The surface ocean freezes if heat loss from the ocean is large enough for the seawater temperature to reach the threshold freezing temperature, typically -1.8°C for sea water. During this freezing of sea water, some latent heat is released at the ocean–ice interface. Even if there is permanent sea-ice cover, the ocean continues to lose heat to the atmosphere through an ocean-to-atmosphere heat flux through the sea ice, causing the sea ice to grow in thickness from below. However, the sea ice has an insulating effect, implying that a thickening of the sea-ice cover results in a dampening of ocean-to-atmosphere heat exchange, thus reducing the rate of ocean heat loss. This continues until heat loss becomes insignificant and the surface ocean water below the sea ice is no longer cooled, implying that the sea ice no longer becomes thicker.

The huge discharge of sea ice in the LGM_release experiment represents a large volume of fresh water. The discharge in our experiment is equivalent to a release of 59 400 km³ of fresh water. This volume is substantially larger than the 18 500 km³ reported in Condrón et al. (2020), but falls between the estimates of meltwater drainage of 9500 km³ at the Younger Dryas onset and 163 000 km³ for the 8.2-ka event, based on geological data (Teller et al., 2002).

A comparison of our results with those of Condrón et al. (2020) reveals several similarities. First, the thickness of sea ice (25 m) in the Arctic Ocean is comparable, as Condrón et al. (2020) simulates a mean thickness of 26 m before export through Fram Strait. Second, ice export through Fram Strait peaks at 0.14 Sv in Condrón et al. (2020), which is comparable to our peak value of 0.16 Sv over the first 2 years of the flush. Third, the duration of the perturbation is also of the same order, as we find 80 years in our experiment that falls within the range (50–140 years) suggested by Condrón et al. (2020). Despite these similarities, they simulate a larger impact of the

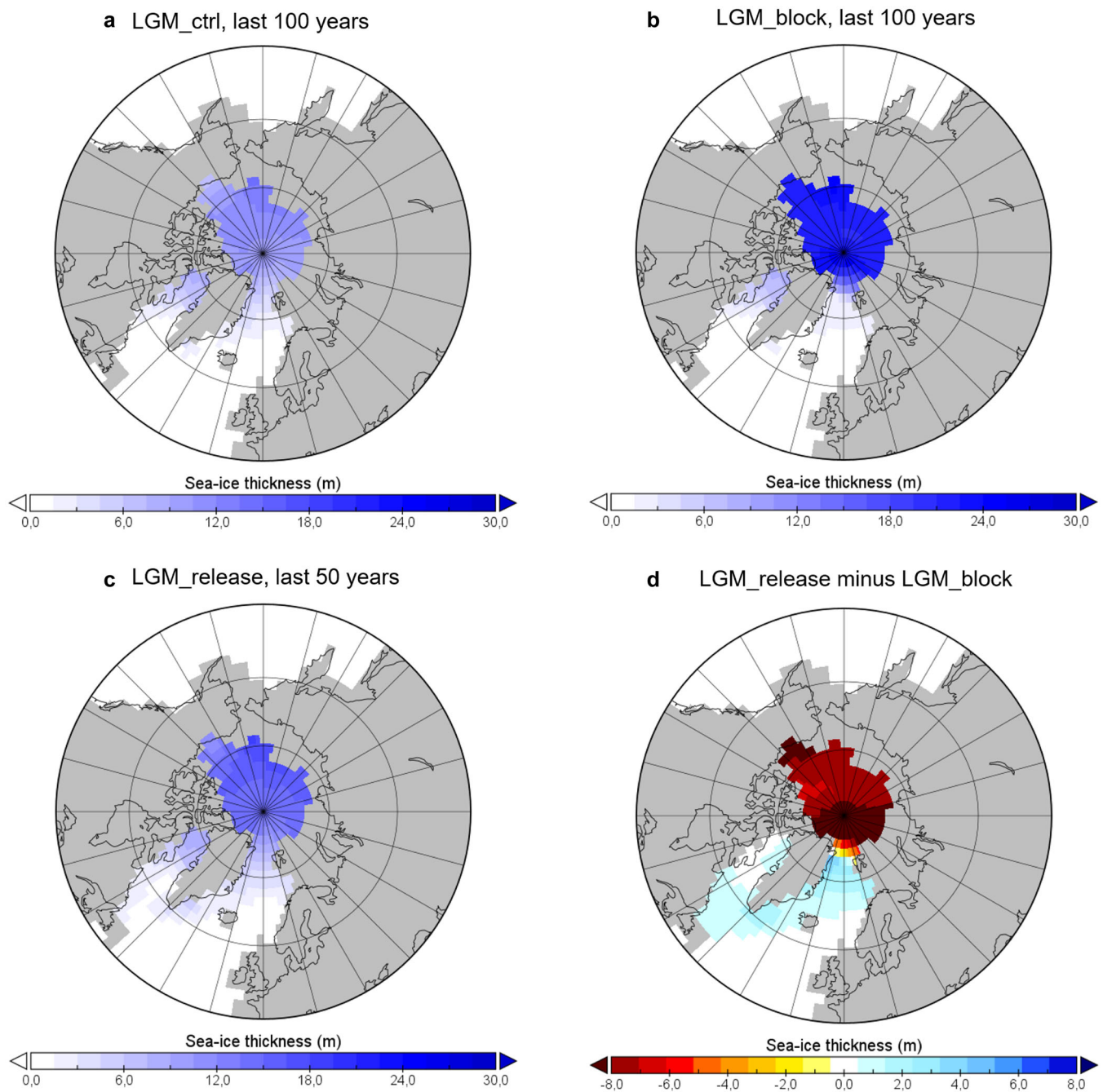


Figure 2. Sea ice thickness in different stages. (a) Control experiment LGM_ctrl, last 100 years; (b) LGM_block, last 100 years; (c) LGM_release, first 50 years; (d) anomaly LGM_release minus LGM_block. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

melting of sea ice on salinity in the Nordic Seas, with a decrease in SSS of 0.7 psu compared to 0.3 psu in our model. However, in our experiment, most of the ice melts in the eastern North Atlantic where we find a larger reduction of 0.9 psu in SSS. The eastern North Atlantic is one of the main areas of deep convection in our LGM state, so possibly this difference in melting also explains why the 17% weakening in AMOC strength is larger in our experiment than the 5% reduction in Condron et al. (2020).

Compared to the ocean model experiments performed by Condron et al. (2020), our set-up includes an additional dynamic atmospheric component and feedbacks involving the atmosphere. Condron et al. (2020) speculated that such feedbacks could lead to additional ice growth and prolonged cooling relative to their results. An example of such an amplification of cooling could be through more extensive snow cover, leading to additional cooling at high latitudes

through the snow–albedo feedback. In our LGM_release experiment, surface albedo is indeed higher than in the other two experiments when averaged over the area north of 40°N, but the difference is minor (+0.8% relative to LGM_ctrl and +0.6% relative to LGM_block). Although albedo is substantially higher (more than +10% relative to LGM_ctrl) over the extended Atlantic sea-ice cover, this is partly compensated for by a reduced albedo further east over the Eurasian continent (up to 5% lower). This reduction in albedo over Eurasia is caused by a decrease in snow fall in LGM_release. We can thus conclude that over the North Atlantic the enhanced albedo contributes to surface cooling, but at the scale of the entire Arctic snow–albedo feedback does not lead to a stronger cooling event. Overall, our results are consistent with Condron et al. (2020), also with respect to the duration and severity of the climate anomaly associated with sea-ice export. After the perturbation, the climate in our LGM_release experiment

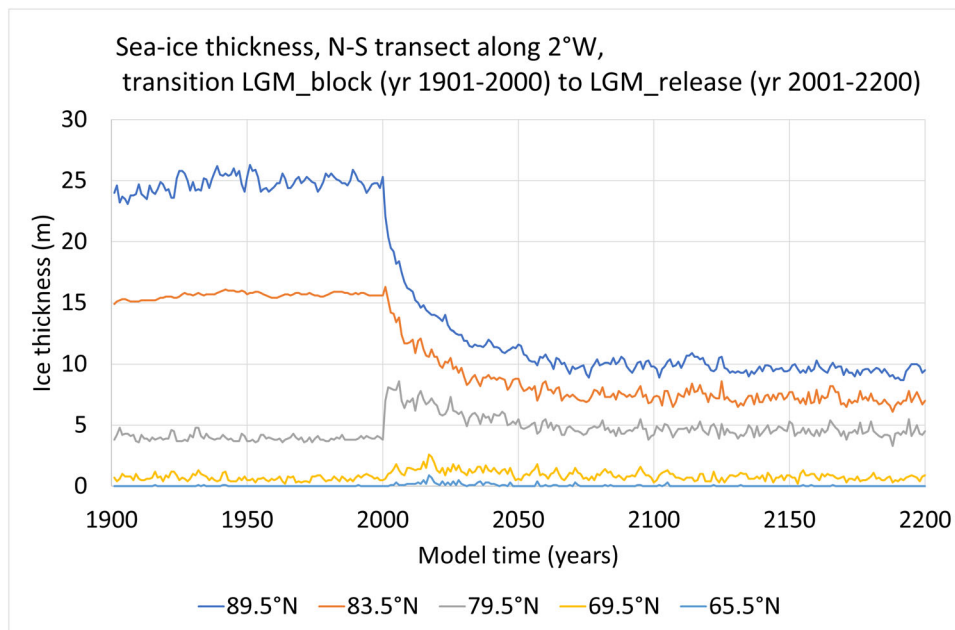


Figure 3. Sea ice thickness changes during the transition from LGM_block to LGM_release. North–south transect along 2°W. Ice export is blocked in Fram Strait at 81.5°N. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

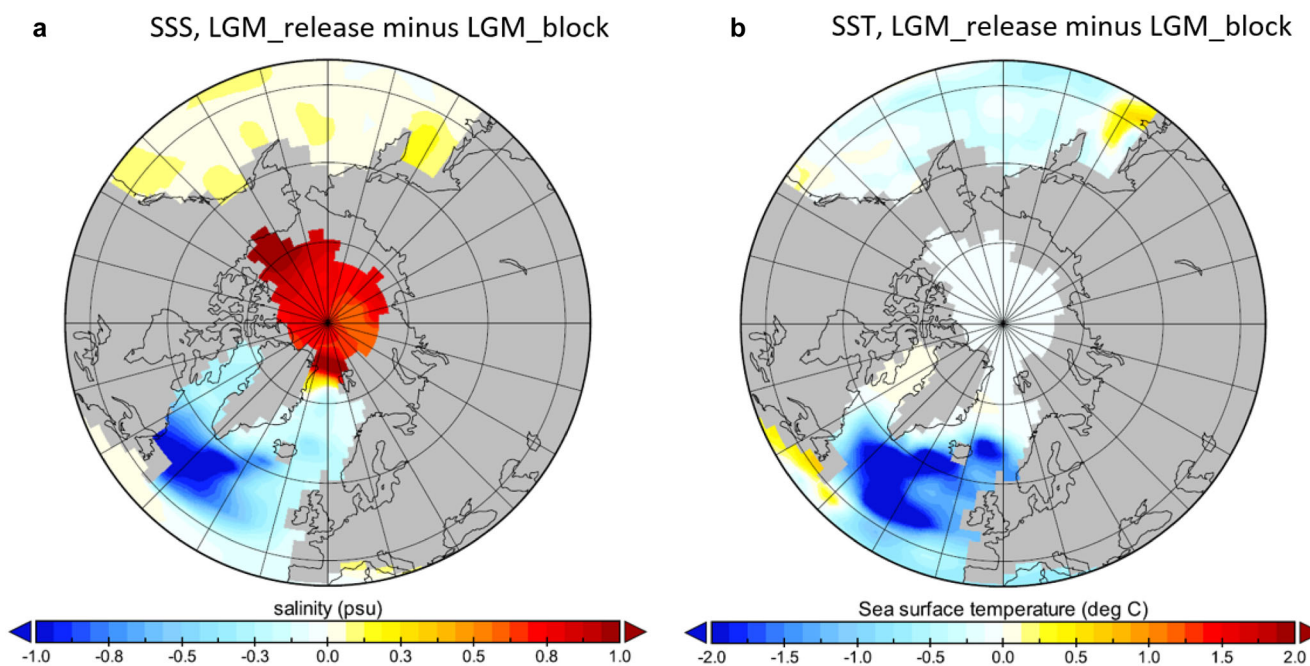


Figure 4. Annual mean anomalies LGM_release (first 50 years) minus LGM_block (last 100 years). (a) Sea surface salinity and (b) sea surface temperature. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

bounces back to the pre-perturbed state within 80 years. Thus, according to our model results, the atmospheric feedbacks included in our experiments do not prolong the impact of sea-ice export on the climate as anticipated by Condron et al. (2020).

The relatively short duration of the climate anomaly of 80 years implies that our model results suggest that the export of old sea ice cannot fully explain relatively long climate cooling events such as the Younger Dryas event that lasted approximately 1200 years (Alley, 2000). However, it is possible that the sea-ice flush has acted as a trigger for the onset of the Younger Dryas, followed by other cooling mechanisms such as altered atmospheric circulation and radiative cooling due to an enhanced atmospheric dust load and/or reduced atmospheric

methane and nitrous oxide levels (Renssen et al., 2015). In addition, there is also a possibility that the massive discharge of sea ice occurred simultaneously with meltwater drainage from proglacial lakes, either to the Arctic Ocean through the Mackenzie River (e.g. Tarasov and Peltier, 2005; Murton et al., 2010) or to the North Atlantic Ocean through the St. Lawrence River (e.g. Carlson et al., 2007), potentially leading to a more substantial weakening of the AMOC than with sea ice alone.

The timescale of the simulated cold anomaly is closer to that of other cold events occurring during the last deglaciation that lasted less than 200 years, such as the Older Dryas (or Greenland Interstadial 1d, ca. 14.0 ka), the inter-Allerød cold period (or Greenland Interstadial 1b, ca. 13.2 ka) or the

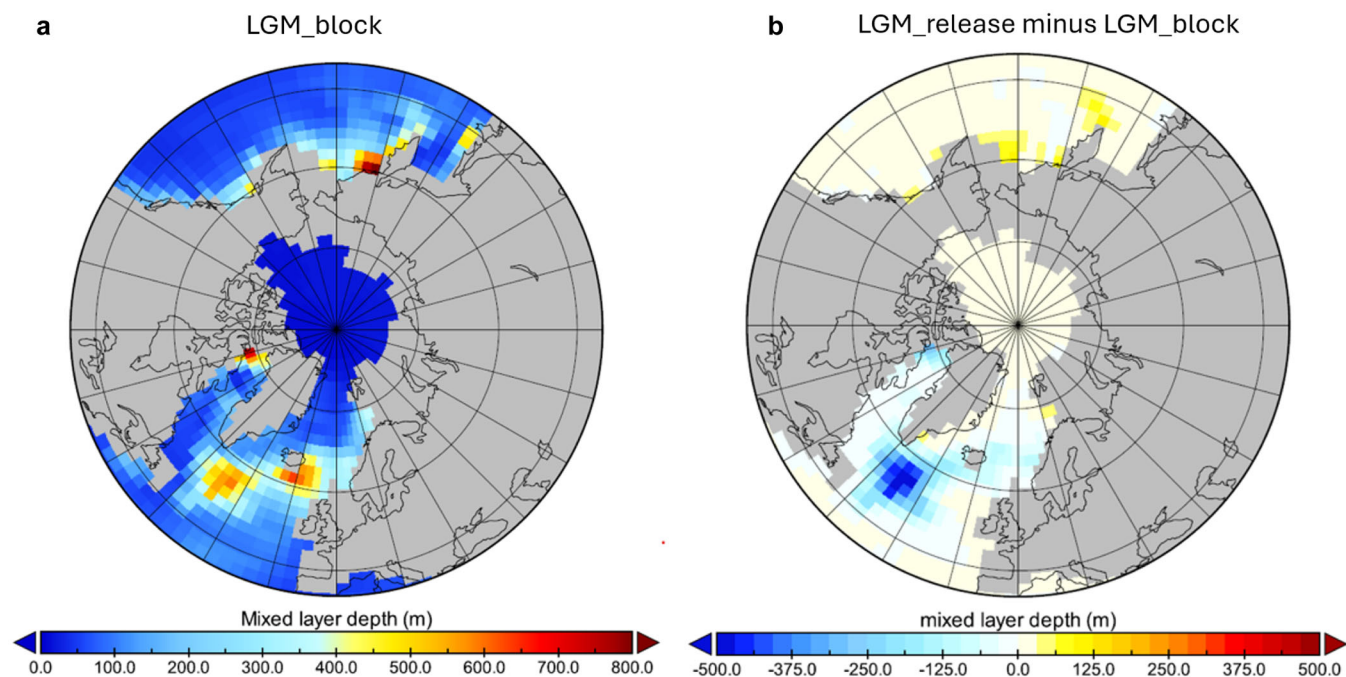


Figure 5. (a) Annual mean mixed layer depth LGM_block (last 100 years), and (b) anomaly annual mean mixed layer depth, LGM_release (first 50 years) minus LGM_block (last 100 years). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

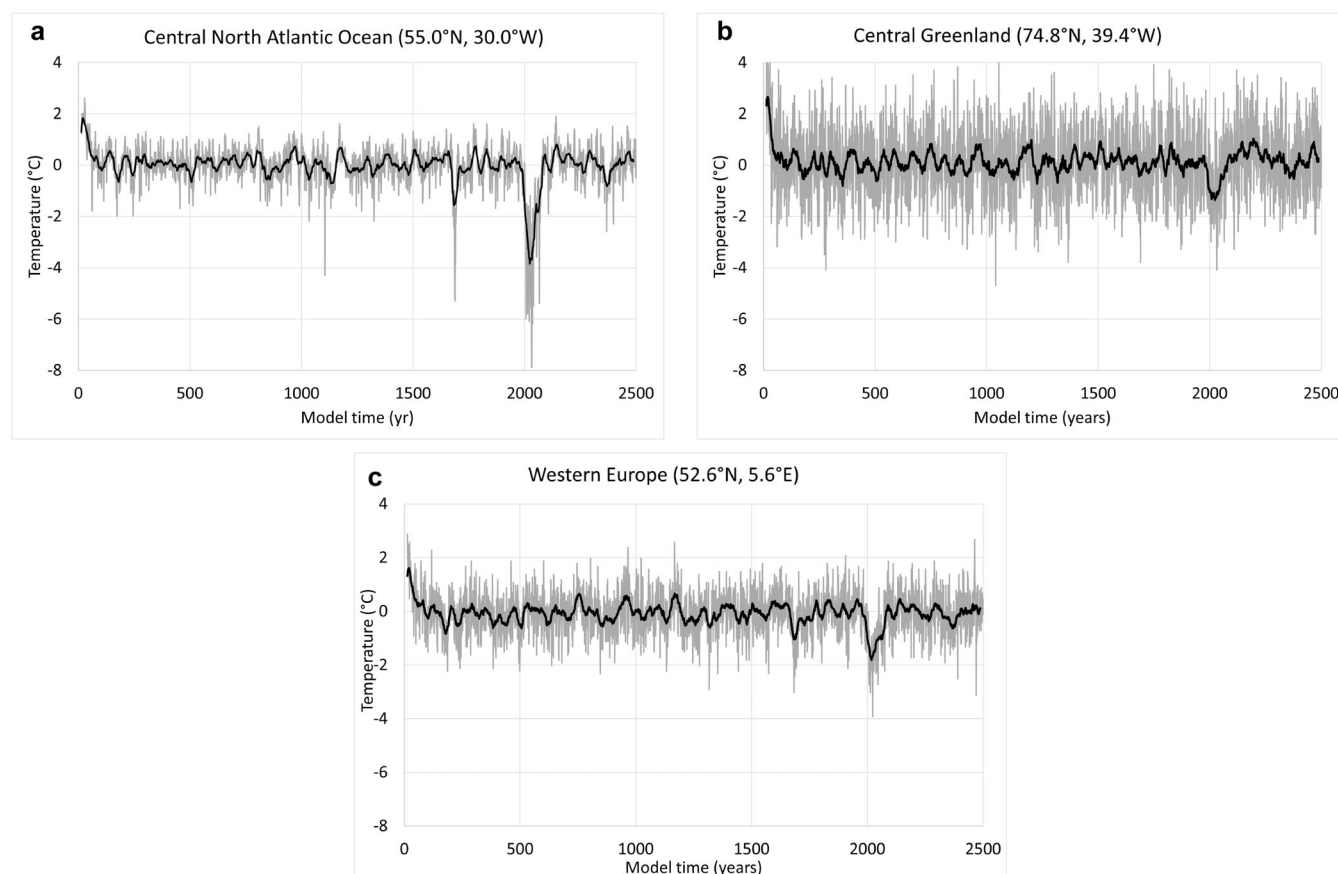


Figure 6. Simulated time series of surface temperature for LGM_block (first 2000 years) and LGM_release (last 500 years), shown as an anomaly relative to the last 100 years of LGM_block. (a) Central North Atlantic Ocean (55.0°N, 30.0°W), (b) Central Greenland (74.8°N, 39.4°W) and (c) Western Europe (52.6°N, 5.6°E). Both the raw annual data (grey) and a 25-year running mean (black) are shown.

Preboreal Oscillation (ca. 11.3 ka) (Lowe et al., 2008). These climate events have been recognized in proxies in the North Atlantic region and downwind continents, thus having a spatial distribution that is consistent with our simulation results

for the cold anomaly (Fig. 7b). In addition, the temperature anomalies reconstructed for these events (e.g. -2 to -5°C in central Greenland, Cuffey and Clow, 1997; Alley, 2000) are also similar to what our model suggests, indicating that sudden

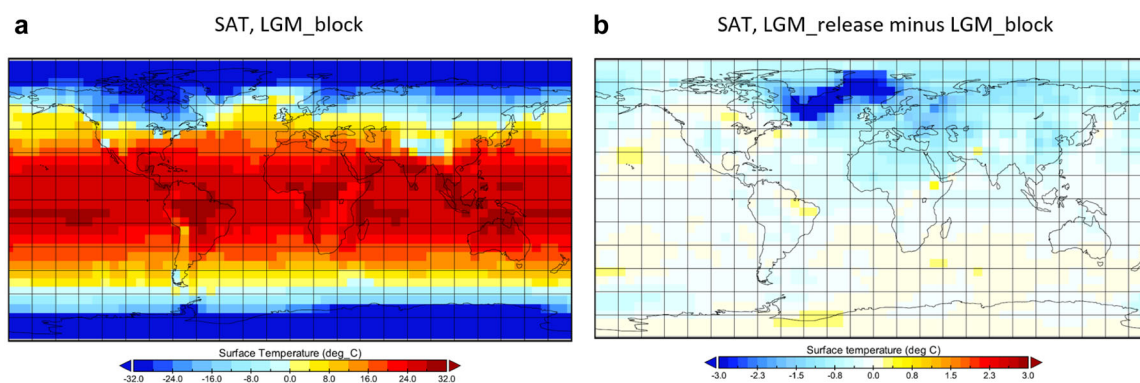


Figure 7. (a) Annual mean surface temperature in LGM_block, and (b) annual mean surface temperature anomaly LGM_release (first 50 years) minus LGM_block (last 100 years). [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/jqs.3665)]

export of accumulated sea ice could have been responsible for one or more of these cold events.

It is important to note that our model experiments have several limitations. First, consistent with Condrón et al. (2020), we applied fixed LGM boundary conditions that were different from the conditions during most of the last deglaciation when the discussed cooling events occurred. For instance, around 14–13 ka the ice sheets were smaller, and sea level had already risen by 20–40 m relative to its LGM minimum (e.g. Clark et al., 2009; Brendryen et al., 2020). During the deglaciation, the rising sea levels caused opening of the Bering Strait and flooding of Arctic shelves, resulting in a larger area for sea ice formation. Previous modelling studies have shown that Arctic shelf flooding produces a more extensive sea-ice cover and a slight weakening of the AMOC (e.g. Blaschek and Renssen, 2013). In addition, orbital forcing was different, leading to higher summer insolation at mid- to high latitudes of the Northern Hemisphere relative to the LGM (i.e. at 13 ka more than 40 W m^{-2} difference in July at 65°N , Berger and Loutre, 1991). It is unclear how our experimental set-up with fixed LGM boundary conditions has influenced the results. Second, our results depend on the sensitivity of the applied model to perturbations, specifically the sensitivity of the AMOC to freshwater forcing. It is well known that this sensitivity varies among models (e.g. Rahmstorf et al., 2005). In a between-model comparison based on the 8.2-ka event, the freshwater sensitivity of our model was comparable to that of the CCSM model and GISS-model-ER (Morrill et al., 2013). However, the sensitivity of ocean circulation to freshwater perturbations is poorly constrained, especially for periods in the past. Given these limitations, our experiments should be considered as a first estimate of the climate response to sea-ice export, and it is recommended that this mechanism is studied further in experiments with boundary conditions for the Lateglacial, to be performed with a range of different models.

In addition to experiments with Lateglacial boundary conditions, it is important to further explore the potential impact of the breakup of a kilometre-thick Arctic ice shelf (e.g. Gasson et al., 2018) on the climate system. Erosional features from the ocean floor provide evidence for such very thick ice during the penultimate glaciation (e.g. Jakobsson et al., 2015). However, modelling the effect of an ice shelf would require a climate model that includes a dynamical representation of ice shelves in the Arctic.

Conclusion

We performed numerical experiments with a global climate model to explore the effect of a sudden flush of sea ice that

accumulated in the Arctic basin during the last glacial period. We find that such a flush causes a major freshening of the North Atlantic Ocean and a substantial weakening of the AMOC. The reduction in heat transport associated with this AMOC weakening, combined with a higher surface albedo due to sea-ice expansion, resulted in a surface cooling over the North Atlantic and the downwind continents of $0.5\text{--}5^\circ \text{C}$ that lasts about 80 years. This climate anomaly is consistent with proxy-based evidence for relatively short (decadal- to centennial-scale) cooling events such as the Older Dryas, the Inter-Allerød cold period and the Preboreal Oscillation. We thus conclude that a sudden flush of old sea ice into the North Atlantic can potentially explain such cooling events in the North Atlantic region, as previously suggested by Bradley and England (2008). However, this process cannot explain longer cooling events such as the Younger Dryas without invoking additional mechanisms. Thus, according to our model results, the atmospheric feedbacks included in our experiments do not prolong the impact of sea-ice export on the climate as anticipated by Condrón et al. (2020).

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Abbreviations. AMOC, Atlantic Meridional Overturning Circulation; CCSM, Community System Climate Model; CLIO, Coupled Large-scale Ice Ocean model; GISS, Goddard Institute for Space Studies; LGM, Last Glacial Maximum; PMIP4, Paleoclimate Modelling Inter-comparison Project phase 4; psu, practical salinity units; SSS, sea surface salinity; Sv, Sverdrup ($1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$); VECODE, Vegetation Continuous Description Model.

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