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REVIEW ARTICLE

The role of Arctic Ocean freshwater during the past 200 ky

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Abstract As part of the hydrologic cycle, the freshwater system plays a pivotal role for the Arctic Ocean. It maintains the strong stratification in the upper waters and fosters the formation of sea ice on the circum-Arctic shelves from where the ice is being exported toward Fram Strait and into the Nordic Seas. Recent projections of climate change under the greenhouse effect predict severe changes for the hydrologic cycle in the Arctic. This manuscript reviews the current knowledge of past changes in freshwater fluxes to and from the Arctic Ocean and their possible impact on ocean circulation and climate outside the Arctic during the past 200,000 years. It becomes evident that abrupt and large-volume discharges into the Arctic Ocean during times of major climate transitions were capable of disturbing the global ocean circulation and triggering further climate change, e.g., at the onset of the Younger Dryas cold event. During sea-level rise in the Holocene, a connection between the increasing areas available for sea ice formation, the position of the ice margin in the ice export area (the Fram Strait) and the deepwater convection in the Greenland Sea is suggested. Further work is needed to investigate the effects of other catastrophic freshwater discharges from previously ice-dammed lakes in northern Eurasia during the Weichselian and Saalian glaciations. Events like the 8.2 ka and the Younger Dryas, which were associated with flooding and routing of glacial meltwaters and had a significant effect on climate, could serve as a template to better validate the impact of similar occurrences in the past. To date, the actual influence of the earlier events on ocean circulation and climate remains elusive.

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Introduction

Rapid increases in freshwater input to the North Atlantic Ocean are recognized as a potential threat to the global climate system because they may cause a drastic reduction in the Atlantic meridional overturning circulation (AMOC) which is responsible for the heat transport to higher latitudes [71]. A wealth of paleoclimatic studies has shown that this has happened a number of times in the geological past. Probably the most prominent examples were the so-called Heinrich events [19, 37], millennial-scale cooling events in the last glacial recorded around the North Atlantic, triggered by iceberg and freshwater discharges mostly from the Laurentian ice sheet in eastern Canada. Similar disturbances of the climate system could also be proven for pre-Weichselian times (e.g., [3, 59]), but the sources of the icebergs may have varied through time. During the last deglaciation and in the early Holocene, two rapid cooling events occurred in the North Atlantic realm. The Younger Dryas and 8.2 ka (8.200 ky before present; all ages are given as calendar years) events were ascribed to the release of large amounts of freshwater from ice-dammed lakes Agassiz and Ojibway in North America to the North Atlantic (e.g., [4, 21]). In the last decade, however, alternative hypotheses have been presented concerning the trigger of the Younger

Dryas event. The most widely accepted one involves a routing of freshwater from Lake Agassiz and the Keewatin ice dome through the valley of Mackenzie River and into the Arctic Ocean [57, 82]. Considering the fact that there have been multiple large-scale glaciations on the circum-Arctic continents in the past, the role of Arctic freshwater events in rapid climate change has received rather little attention yet. In this manuscript, we address this issue on longer geological timescales and review available marine geological records to investigate the causes and possible consequences of freshwater events in the Arctic Ocean for the oceanic and climate system.

Freshwater in the modern Arctic Ocean

The total volume of freshwater in the Arctic Ocean (Fig. 1) is estimated to be ~84,000 km^3 of which ~10 % are annually exported from the Arctic Ocean and replenished from river runoff, precipitation and meltwater from glaciers [76]. Inflow of low-saline Pacific Water through the Bering Strait accounts for ~40 % of the freshwater input to the Arctic Ocean [96]. About a third of the export occurs in the form of sea ice, mainly through the Fram Strait [75, 90]. Most of the freshwater is stored in the upper 200 m of the water column. The stark contrast between low salinities in the near-surface waters and the much saltier waters of primarily Atlantic origin below amounts to >4 PSU and is shaping the Arctic halocline (Fig. 1). The cold low-salinity surface layer (T < −1.5 °C) effectively seals the underlying warmer waters from the atmosphere and allows for the maintenance of the Arctic sea ice cover which, in turn, seals the low-salinity layer from the atmosphere. Lowest salinities in the surface waters are found off the huge river systems on the vast Arctic shelves. These rivers have catchment areas that reach deep into the hinterland and discharge enormous amounts of freshwater to the Arctic Ocean (Fig. 1). The shelves are particularly important because here ice-free areas (polynyas) are established, largely parallel to the coastline, where sea ice is formed by offshore winds under sub-zero temperatures. The polynyas serve as the "ice factories" for the Arctic Ocean. Since their effective operation is also depending on the existence of a low-salinity surface layer, the freshwater discharge

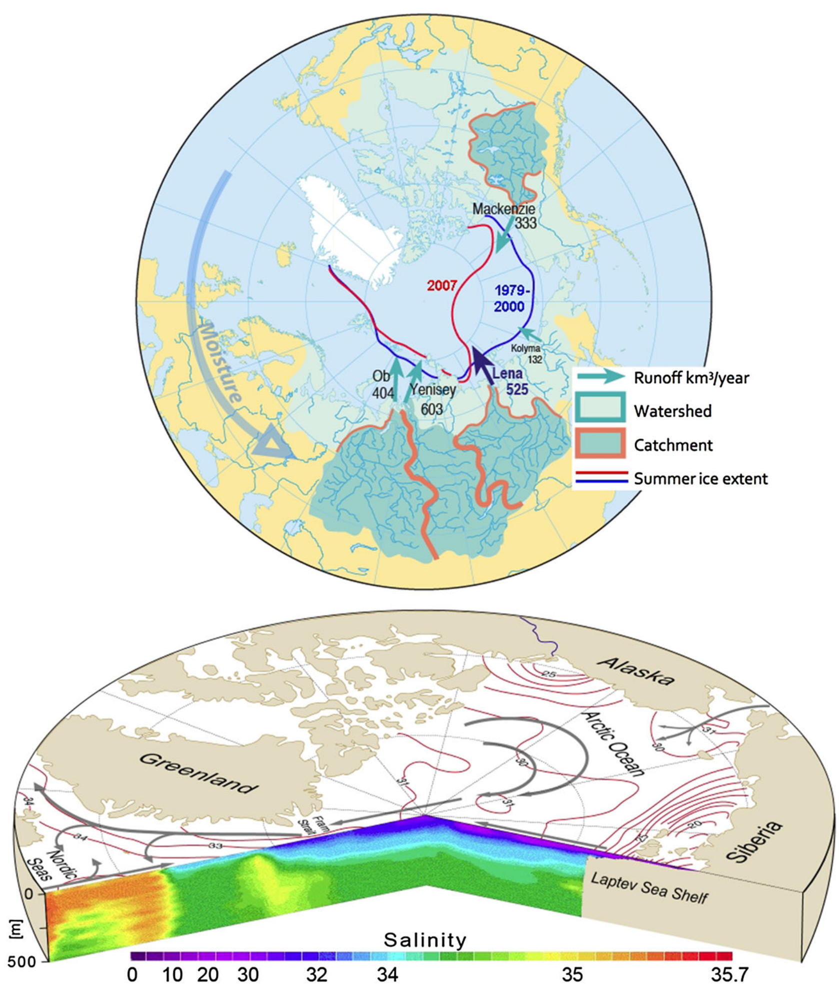

Fig. 1 Map of the circum-Arctic continents with the catchment areas and average annual discharge (km^3) of major Siberian and North American rivers. The average summer sea ice extents 1979–2000 (*blue*) and 2007 (*red*) are marked. Modified from http://www.amap.no. *Below* map and vertical structure (500 m) of salinity in the Arctic Ocean. *Gray arrows* mark the average surface water circulation. Data from EWG [31]

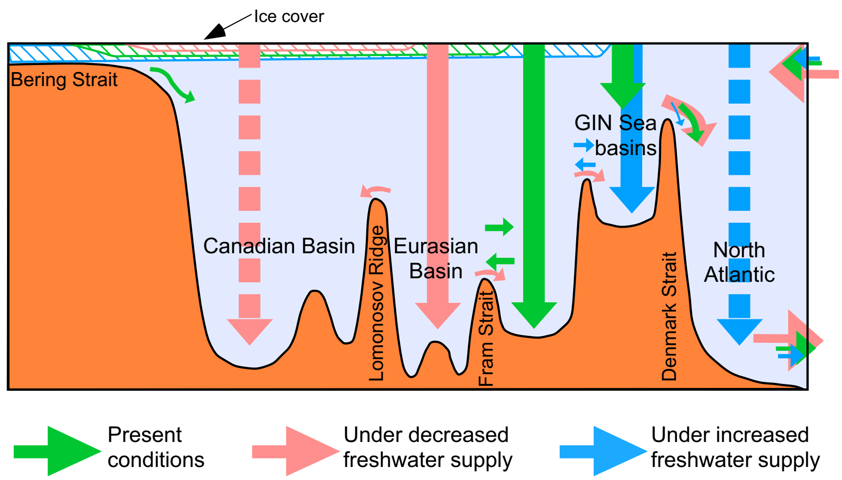

Fig. 2 Hypothesized dependence of vertical convection (*vertical arrows*), thermohaline circulation (*horizontal arrows*) and overflows (*curved arrows*) under present conditions (*green*), increased freshwater supply (*blue*) and decreased supply (*red*). *Arrows size* depicts strengths/rates of currents and convection. *Barred arrows* represent extreme locations of convection. Modified after Aagaard and Carmack [1]

plays a critical role for the entire Arctic environmental system. It has been hypothesized that any change in the extension of the ice cover will also modify the areas and rates of convective water mass renewal in the Arctic Ocean and the northernmost North Atlantic [1]; Fig. 2). Geological proof is lacking, though, mainly because realistic reconstructions for periods with potentially less sea ice (e.g., past interglacials warmer than present) are difficult to obtain due to a lack of high-resolution records from the deep-sea Arctic.

The last centennial in the Arctic has seen a rapid retreat of glacier ice on the continents [28] as well as ongoing freshwater accumulations in the Arctic Ocean from increasing river runoff [65, 66] and changes in the oceanic freshwater pathways [55]. The release of a freshwater accumulation from the interior Arctic Ocean led to the "Great Salinity Anomaly" observed in the northern North Atlantic in the 1970s [16, 26]. A recent study indicated a drastic reduction (~10 %) in AMOC strength as a consequence of this freshwater export from the Arctic [72]. A number of numerical modeling studies (e.g., [29, 41, 42, 94]) have investigated the response to present and future freshwater fluxes from the Greenland ice sheet under ongoing global warming. They unanimously concluded on a future weakening of the AMOC which will lead to a reduced northward heat transport that may, at least around the northern North Atlantic, compensate to a certain degree for the overall warming as a result of the greenhouse effect.

Detection of freshwater events in Arctic history

To define periods or short-term events in the geological history, when large amounts of freshwater were discharged to the Arctic Ocean requires evidence in the geological record which may point directly or indirectly to extremely low salinities in the surface waters. Several analytical approaches can lead to such evidence. High concentrations of freshwater diatoms and aquatic palynomorphs versus marine species in sediments from Siberian shelves have been shown to reflect the proximity of a terrestrial freshwater source [68, 69]. Hydrogen isotopes (δD) of short-chain biogenic compounds (*n*-alkane n-C_{17}) were used to infer information on salinity changes in the Arctic Ocean at ~55 Ma, during the so-called Paleocene/Eocene Thermal Maximum [64]. Findings of large amounts of the free-floating fern *Azolla* together with abundant freshwater organic and siliceous microfossils in Arctic sediments from ~50 Ma indicate an episodic freshening of Arctic surface waters [20].

The almost linear correlation between salinity and the oxygen isotope composition of seawater is slightly disturbed in Arctic near-surface waters by the formation and melting of sea ice [6]. Nevertheless, the isotopic composition of living planktic foraminifers quite well reflects that of the ambient seawater [5, 63, 92]. Accordingly, the pattern of decreasing near-surface salinities from the northern Barents Sea margin to the Arctic Ocean interior is documented in oxygen isotope values ($\delta^{18}O$) of planktic foraminifers from sediment surface samples [78]. A recent study by Xiao et al. [97] confirmed this result and the earlier hypothesis that higher $\delta^{18}O$ values in these foraminifers reflect a deeper habitat of these organisms at the shelf break.

Although the modern Arctic Ocean stores huge amounts of freshwater, conditions during freshwater events in the Late Quaternary were probably significantly different. Evidence comes from the carbon isotope values ($\delta^{13}C$) of living planktic foraminifers from the freshwater-rich near-surface layer and specimens from interior Arctic sediment surface samples which are all unusually high (up to 1.5 ‰; [63, 78, 92, 97]). This correlates with the high $\delta^{13}C$ values of dissolved inorganic carbon (DIC) in the uppermost water column of the Arctic Ocean which are in contrast to the low

$\delta^{13}C_{DIC}$ values of Arctic river water (cf. Bauch et al. this issue). Nutrient availability and $\delta^{13}C_{DIC}$ values are anti-correlated in the Canada Basin, while in the Eurasian Basin, both show little variability (Bauch et al. this issue). Most likely, in the latter area there is little alteration of the carbon isotope budget by bioproduction under the sea ice, along the drift path of the freshwater from the Siberian shelves toward the Fram Strait [78, 97]. The high values found in living and Late Quaternary planktic foraminifers can thus be explained by an input of low-^{13}C atmospheric CO_2 that is balanced by the fixation of ^{12}C through bioproduction.

Events triggered by rapid outbursts of freshwater from a well-defined source, however, produce a different signal in the paired planktic isotope records from the Arctic and sub-Arctic than found in modern surface sediment samples. While low $\delta^{18}O$ values of the foraminifers, as can be expected, reflect the light isotopic composition of the additional freshwater, planktic $\delta^{13}C$ values are typically low (e.g., [14, 45, 74, 77, 80]). This is interpreted to result from an increased stratification which blocked convection and trapped the nutrients so that the planktic foraminifers favored a (less ventilated) habitat underneath the freshwater layer. The strong stratification allowed metabolic CO_2 from residual bacterial respiration (with low $\delta^{13}C$ values) to accumulate in the water and decrease the $\delta^{13}C$ of the dissolved inorganic carbon (DIC) of the water column. Accordingly, freshwater events can be identified in planktic isotope records by a combination of both low oxygen and carbon isotope values (e.g., [74, 77, 80]). In cases of extreme or very proximal freshwater discharges, salinities in the upper water layers may have dropped below the tolerance limit of planktic foraminifers (i.e., $S < 28$, estimated by correlation with the limits of related species; cf. [17]), with the consequence that no specimens are deposited in the respective sediments below (e.g., [79]).

Late Quaternary freshwater variability and events in the Arctic

Holocene and Eemian interglacials

The ice production on the vast Arctic shelves, especially those of the Kara, Laptev and East Siberian seas, is by nature extremely sensitive to salinity changes in the surface waters because of the seasonal and long-term variability in riverine freshwater output. From records of marine and freshwater diatoms and palynomorphs, large fluctuations of near-surface salinity around the Lena River delta could be reconstructed for the last 9000 years [12]. The strong and rapid changes from very low saline to brackish conditions (Fig. 3) are very likely not a result of variable river discharge, but mainly reflect the history of sea-level rise in the area. Flooding of the Laptev Sea shelf (modern water depth 0–50 m) started only around 11 ka, and the modern 30 m isobath was reached at ~9 ka [10]. Because the polynya area runs largely parallel to the coastline, the volume of

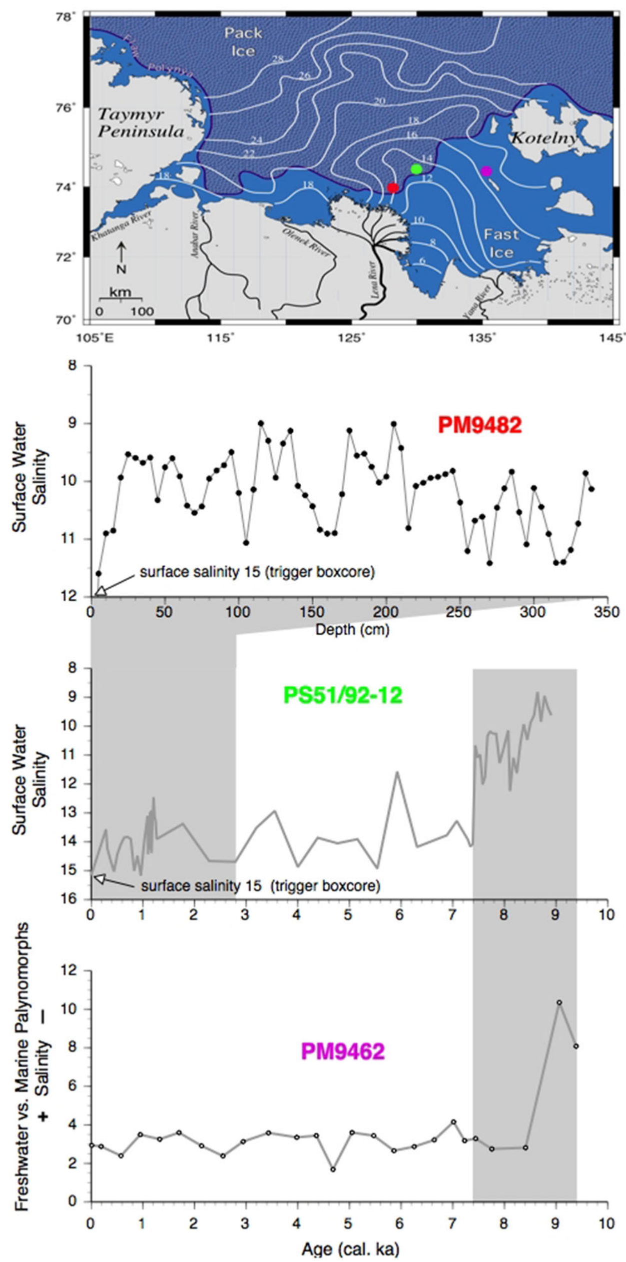

Fig. 3 Map of average summer salinity in the Laptev Sea (data from EWG [31]) and the average position of the polynya between pack ice in the north (*dark blue*) and landfast ice in the south (*blue*). *Below* Reconstructed and relative surface salinities in sediment cores from the eastern Laptev Sea shelf using diatom data (cores PM9482, PS51/92-12) and aquatic palynomorphs (core PM9462). The base of core PM9482 dates back to approximately 2.8 ka (modified from [12])

present-day sea ice production was approached only after sea level reached its highstand at ~5–6 ka. Although the variability of total river discharge to the Arctic Ocean in the first half of the Holocene is unknown, only minor changes were indicated between 7 ka and ~1800 AD by numerical modeling [93]. However, the records from the Laptev Sea shelf (Fig. 3) suggest a more regional short-term variability on decadal to millennial timescales that is found also in the model results. Indeed, the core with the highest temporal resolution (PM9482) reveals fluctuations of >2 PSU in the last 3000 years. Although there is some uncertainty involved with the age determinations that prevents a fine-scale correlation with other high-resolution records, the reconstructed salinity variations on decadal to multicentennial scales must have had consequences for the sea ice formation in the polynyas. Well-dated, high-resolution records of sea ice variability (e.g., from IP_{25} measurements) are urgently needed to define the potential relationship between post-glacial shelf flooding, river runoff and sea ice formation on the Arctic shelves in the geological past. Further on, one may speculate that abrupt paleoenvironmental changes in sea ice export area like the Nordic Seas were also related to (or even triggered by) the spatial increase in flooded areas available on the Siberian shelves for sea ice formation at a given time. For example, the variable strength of Atlantic Water advection to the Arctic Ocean between 9 and 5 ka, together with eastward shifts of the sea ice margin in the Fram Strait [56, 95], may correlate with morphology-controlled stepwise transgression events in major parts of the Laptev and the other Siberian seas where water depths of less than 30 m occupy ~10^6 km^2 of the shelf (i.e., ~10 % of the total Arctic Ocean area). In particular, the prominent change after 5 ka toward a state of relatively weak Atlantic Water advection, largely resembling the modern (pre-industrial) conditions, occurred time-coeval with the establishing of the modern coastline in the Laptev Sea [10, 95] and likely also in the neighboring East Siberian Sea. Since ice coverage as well as temperature and salinity contrasts are important factors for the rate of deepwater renewal in the Greenland Sea, the gradual increase in ventilation in the deep Nordic Seas between 9 and 5 ka [9, 84] may to a certain yet unknown degree be connected also to the increasing ice production on Arctic shelves. During flooding of the Siberian shelves, a threshold of ice formation may have been reached from 7 ka onward when sufficient freshwater in the form of sea ice was available to be transported into the northern Nordic Seas and to improve conditions there (i.e., enhanced temperature and salinity contrasts), eventually leading to a more deep-reaching vertical convection. Obviously, further work is needed here to explore these hypothetical connections in more detail and to define the role of sea ice production and export in Holocene climate change.

Arctic Ocean environmental conditions during the last interglacial (Eemian) are far less well understood than in the Holocene. There is evidence for a cooler Atlantic Water inflow to and a stronger freshwater export from the Arctic Ocean in the early Eemian (e.g., [8, 13, 89]). The latter likely resulted from melting of the huge Saalian ice sheets on northern Eurasia which were much larger than later during Weichselian times (cf. Svendsen et al. [81]). Details of the interdependency of Arctic freshwater export, sea ice formation and the convective activity in the northern North Atlantic during the entire Eemian, however, remain elusive—mostly due to the lack of well-dated higher-resolution Eemian records from the Arctic Ocean.

Last deglaciation

The last deglaciation was a period of strong freshwater fluxes from the glaciated circum-Arctic continents to the Arctic Ocean. In marine sediment cores from shelf, margin and deep-sea sites, planktic and benthic isotope records document short-term events of freshwater discharge. Such evidence was found on the northern Barents, Kara and Laptev seas and Alaska margins and in the western Fram Strait (e.g., [2, 9, 44, 45, 50, 51, 62, 79]) as well as on intra-basin morphological highs like the Mendeleyev, Lomonosov and Gakkel ridges (e.g., [36, 61, 67, 70, 80]). Because these deep-sea records often have a low temporal resolution, it seems difficult to directly correlate the individual peaks of low $\delta^{18}O$ and $\delta^{13}C$ values between cores and with the records from the circum-Arctic margins (Fig. 4). Layers of coarse, iceberg-rafted debris (IRD) deposited during the freshwater events allow for tracing the source regions of icebergs. These suggest that major freshwater fluxes from the decay of the ice sheet on the Barents and Kara seas arrived in the central Arctic Ocean early in the deglaciation (ca. 18–15 ka), and seem to have preceded in time the major discharges from Arctic North America by 1–2 ky [61]. Since the decay of the ice sheets surrounding the Nordic Seas was largely contemporaneous with events in the Arctic (cf. [9, 18, 74, 85, 88]), it appears difficult to distinguish between the individual effects of freshwater fluxes from the Greenland, Barents Sea and Scandinavian ice sheets and those originating from the Arctic Ocean. Therefore, the impact of deglacial excess Arctic freshwater discharge on the oceanographic system in the northern North Atlantic and the meridional overturning circulation remains elusive, at least for the time before the onset of the Younger Dryas (YD) cold event.

In the last decade, evidence has been accumulating that the trigger for the most abrupt and severe climatic event during the last deglaciation originated in the Arctic. Besides latest hypotheses which also involved considerations of extraterrestrial impacts and volcanic eruptions, etc.

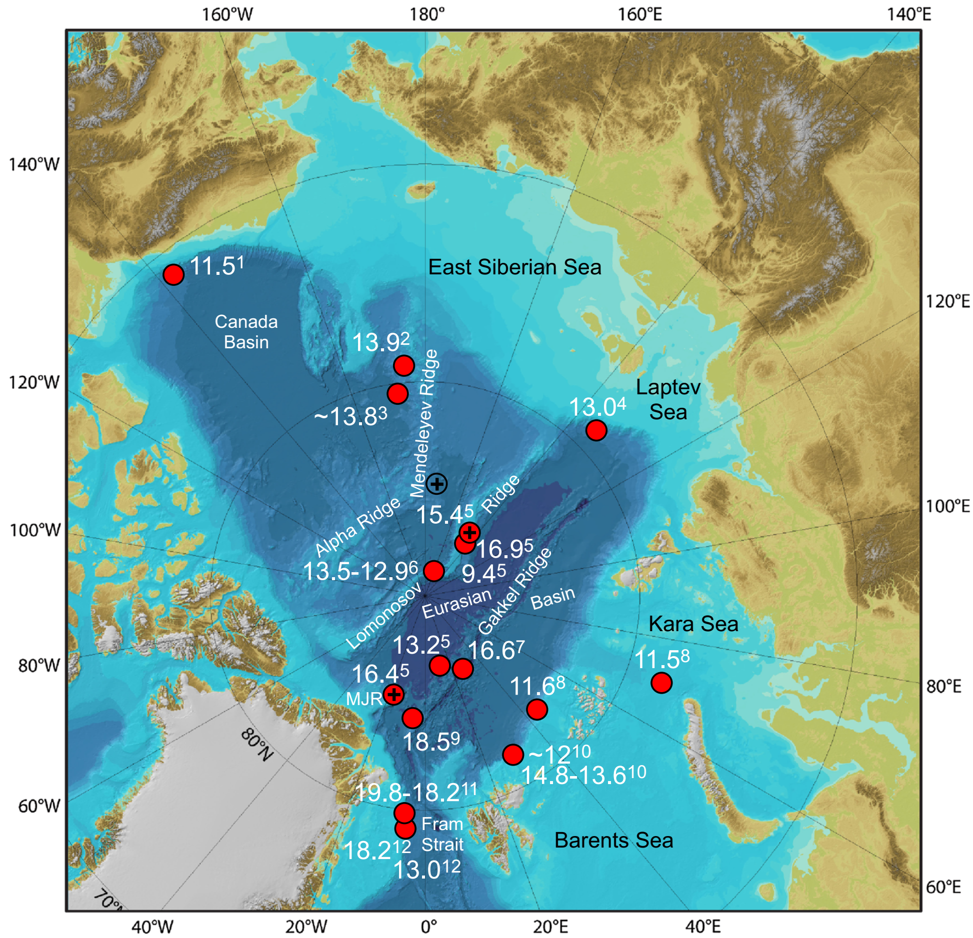

Fig. 4 Ages of freshwater events during the last deglaciation as recorded in sediment cores from the Arctic Ocean. *MJR* Morris Jesup Rise. Ages are given in ky B.P. Radiocarbon ages were calibrated using the Calib 7.1 program and the Marine13 data set at http://radiocarbon.pa.qub.ac.uk/calib/. *Circles* with "+" mark locations of cores used for the Arctic core stack in Fig. 6. Original data published by *1* Andrews and Dunhill [2], *2* Polyak et al. [67], *3* Poore et al. [70], *4* Spielhagen et al. [79], *5* Nørgaard-Pedersen et al. [61], *6* Hanslik et al. [36], *7* Stein et al. [80], *8* Lubinski et al. [51], *9* Markussen et al. [53], *10* Knies and Stein [44], *11* Nørgaard-Pedersen et al. [62], *12* Bauch et al. [9, 10]

(e.g., [33, 54, 58]), earlier explanations for the YD event (12.8–11.6 ka) focused on a deviation of freshwater discharge from the glacial Lake Agassiz south of the Laurentian ice sheet in North America (e.g., [21–23]). It was suggested that an abrupt change from a southward drainage (to the Mississippi) to a westward discharge through the St. Lawrence River valley at ~12.9 ka established a freshwater lid on the northern North Atlantic that reduced or shut down vertical convection and significantly weakened the AMOC. Several authors, however, have claimed a lack of field evidence for large-volume freshwater fluxes in the proposed through-flow regions west of the St. Lawrence River (e.g., [49, 86]). Combining results from modeling and field studies, an alternative theory involves a northward routing of freshwater discharge through the Mackenzie valley, entering the Arctic Ocean at 135°W in the Beaufort Sea [57, 82, 83]. Recent results from high-resolution numerical ocean modeling are in strong support of this hypothesis. Condron and Winsor [24] show that only minor amounts of the freshwater from a Lake Agassiz outburst toward the St. Lawrence valley could ever reach the areas of present ocean overturning in the Greenland and Labrador seas, while a discharge toward the Arctic Ocean and export through Fram Strait should result in a significant freshening in these areas. Marine evidence for a large-scale freshwater event in the Arctic Ocean and in waters off East Greenland is still scarce, probably because of effects such as low sedimentation rates and enhanced bioturbational mixing. A few records, however, have captured some signs. Planktic isotope data series from the Laptev Sea continental margin, the western Fram Strait and the Greenland Sea show a peak of low values centered at 13 ka [9, 79, 84] and are consistent with a reconstruction of enhanced sea ice formation off the Laptev Sea [32]. Radiogenic and IRD data from the central Lomonosov Ridge suggest a significantly increased export of sea ice from Arctic North America, close to the area where the freshwater may have entered the Arctic Ocean [60]. These data corroborate the results from terrestrial fieldwork and modeling that argue for a paradigm shift regarding the likely origin of the freshwater as the possible trigger for the YD cold event. Apparently, this major cooling, which interrupted the warming trend after the last glacial and which was recorded in a wealth of marine and terrestrial paleoclimatic data series all across the northern hemisphere, was caused by an excess freshening of Arctic Ocean surface waters and the export of these waters (also in the form of sea ice) to the major areas of oceanic deep convection.

The cause of a younger and significantly weaker cooling event than the YD may, at least in part, also be attributed to the Arctic Ocean. A core from the northern Alaskan continental margin (142°W) showed a distinct freshwater spike at ~11.5 ka in the isotopic records [2]. That one correlates well in time with another massive outburst of meltwater from glacial Lake Agassiz which went down the Mackenzie River valley and into the Arctic Ocean [34, 86]. This low-salinity event may have contributed to the freshening of surface waters in the Nordic Seas which, together with the discharge from the Baltic Ice Lake, triggered the so-called Preboreal Oscillation [35], a brief (max. 200 year) but distinct cooling event recognized in many records from areas around the Nordic Seas.

Weichselian and Saalian glaciations

During the multiple glaciations in the Late Quaternary, ice sheets on the circum-Arctic continents stored tremendous amounts of freshwater [30], equaling a global sea-level drop of >120 m. Large parts of the shallow shelves were, if not covered by glacier ice, exposed to the atmosphere due to a lowered sea level. River valleys, incised into these exposed shelves, document an ongoing discharge of freshwater during the glacials (e.g., [39, 40, 43]). Since morphologic witnesses of older glaciations were overrun by ice during the last glacial maximum, little is known about ice margins and drainage patterns in northern North America before ~20 ka. In northern Eurasia, the situation appears different. As a consequence of the huge ice sheets on parts of the Eurasian Arctic shelves, large rivers like Ob and Jenisei were dammed by the southern ice margins and deviated to the south [52]. In consequence, large proglacial lakes developed in front of the southern Eurasian ice sheet edge. Freshwater storage in these lakes may have reached 34,000 km^3 at 80–90 ka [52], much larger than, e.g., in deglacial Lake Agassiz (max. 23,000 km^3; [48]). Terrestrial fieldwork revealed a complex history of buildup and decay of the Eurasian ice masses during the last ~200 ky (Svendsen et al. [81]; Larsen et al. [47]). Whenever these ice sheets decayed, pathways opened which allowed for the freshwater to enter the Arctic Ocean (Fig. 5). Importantly, by then also the meltwater stored in the previously ice-dammed lakes was able to flow northward. In a study of deep-sea sediment cores from the Alpha Ridge, the Lomonosov Ridge and the Morris Jesup Rise, it could be shown that planktic isotope records display sharp freshwater spikes exactly in those deposits that correlate in time with the ice sheet decay events on the northern Eurasian shelves [77], despite the fact that individual stratigraphic models were established for the marine and terrestrial records. Peak discharge events must have occurred at the

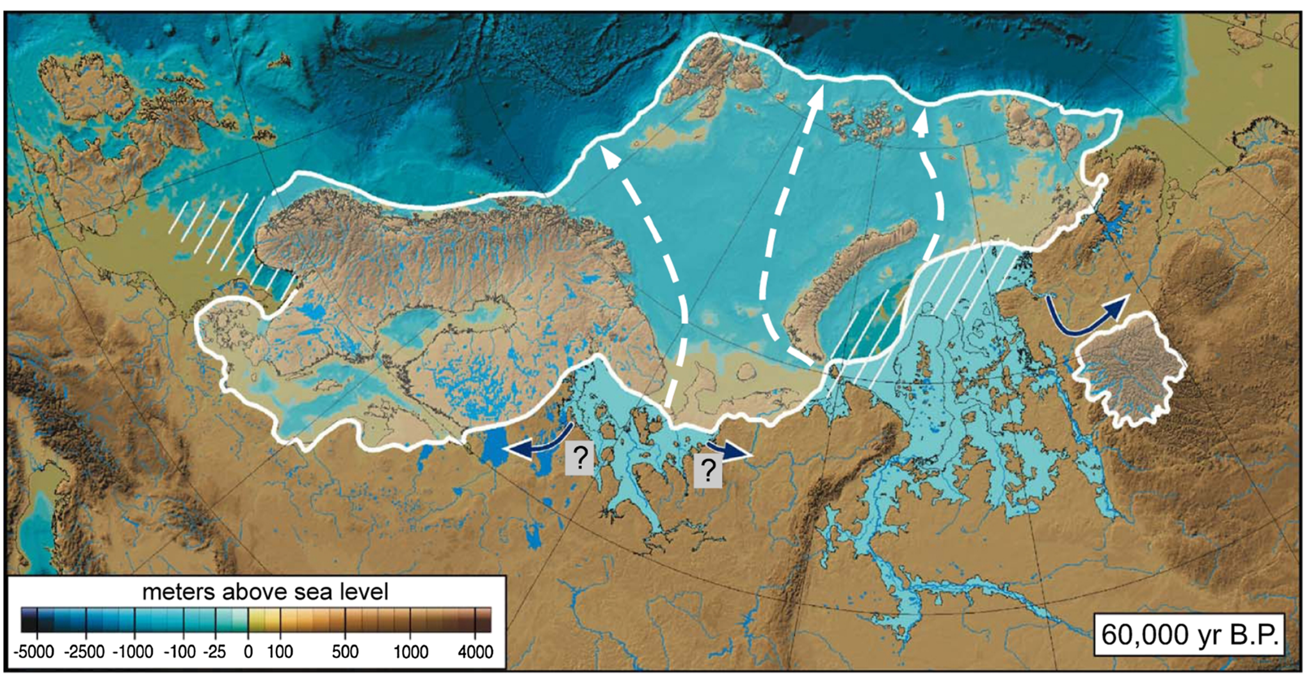

Fig. 5 Reconstruction of ice-dammed lakes and rerouting of rivers during the Middle Weichselian at ca. 60 ka. Ice margins are taken from Svendsen et al. [81]. In the hatched areas, the exact position of the ice margin is unknown. *Olive green areas* mark dry shelves at a sea-level drop of 60 m. *Blue arrows* mark possible overflows to river systems in the south and east. Hatched *white arrows* mark possible discharge directions during decay of the ice sheet. Modified from Mangerud et al. [52]

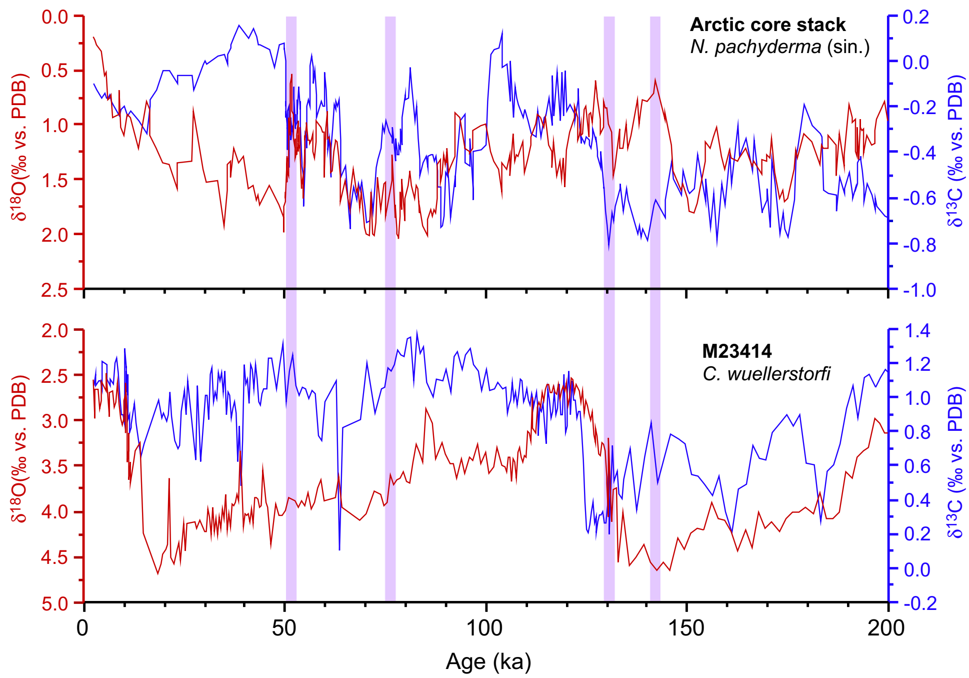

Fig. 6 Stack of planktic oxygen and carbon isotope data from three long sediment cores in the central Arctic Ocean (for locations, see Fig. 4) plotted versus benthic isotope data from a core obtained on the Rockall Plateau off Ireland. *Purple bars* mark major freshwater events in the Arctic Ocean characterized by low oxygen and carbon isotope data. *Data sources* Spielhagen et al. [77] and Didié and Bauch [27]

end of the major Saalian and middle Weichselian glaciations (at ~130 and 52 ka), next to a number of minor events in the last 200 ky (Fig. 6). All of these reflect the dynamics between ice sheet buildup and decay, the history of lake formations and their drainage to the Arctic Ocean. Considering the likely role of Arctic Ocean freshwater as the trigger of the YD event, one may expect that similar discharges at other times could also have exerted a significant influence on the AMOC. However, a comparison of the Arctic freshwater discharge record and a benthic isotope record from the northern North Atlantic, which is thought to reflect the variable strength of the AMOC, does not reveal a relation clear enough to suggest a direct influence of Arctic events on deepwater convection farther in the south (Fig. 6). This is even the case if possible uncertainties of ±5 ky are applied to any of the age models. Possibly the glacial AMOC operated in a mode that was less sensitive to a northern input of freshwater than during the last deglaciation. Another possible reason could be a more southerly location of the areas where deepwater convection took place. While earlier works suggested such a shift during the last glacial (e.g., [46]), more recent results are in favor of a relatively stable position of the convection cells in the Nordic and Labrador seas (e.g., [25, 73]). Recently, also a much longer residence time of the deeper waters and/or a stronger net export of freshwater in the form of sea ice to areas south of the convection cells was suggested (e.g., [87]). Stable isotope records of sediment cores from the Nordic Seas show evidence of many low-salinity events of which some occurred contemporaneous with the major events recognized in the Arctic at ~130 and ~52 ka (e.g., [11, 15, 38, 91]). Because a number of these events may as well have come from the glaciated margins of the Nordic Seas, it would require precise mapping of the area via time-slice analysis of existing cores to better determine the provenance of the freshwater.

Conclusions and outstanding research questions

- Freshwater discharge to the Arctic Ocean is an essential player in the modern ocean and climate system due to its critical role in the maintenance of near-surface salinity contrasts and the sea ice cover. The analysis of past changes in the Arctic freshwater system and their consequences is a valuable tool to better understand and predict the impact of ongoing climate changes on the Arctic environmental system and its future.
- In the Holocene, sea-level rise played an important role in the freshwater system. Flooding of the vast Eurasian shelves strongly increased the areas available for seasonal sea ice formation. Enhanced ice production after the Holocene Thermal Maximum likely resulted in more freshwater export to the Nordic Seas through Fram Strait. This may have increased the oceanic contrasts between the regions leading to intensified deepwater convection in the Greenland Sea.
- The last deglaciation witnessed a diachronous decay of the circum-Arctic ice sheets and the discharge of

meltwater from various sources to the Arctic Ocean. Evidence from terrestrial field data, marine cores and numerical modeling is accumulating and supports the hypothesis that the Younger Dryas cold event was triggered by an outflow of freshwater from glacial Lake Agassiz and melting of the Keewatin ice dome toward the Arctic Ocean and further through the Fram Strait to the areas of deep ocean convection.

- During the Weichselian and Saalian glaciations, enormous amounts of freshwater were stored in ice-dammed lakes south of the northern Eurasian ice sheets. Catastrophic drainage events were recorded inside the Arctic Ocean, but apparently the vertical convection in the northern North Atlantic was less responsive to this excess freshwater than during the later phase of the last deglaciation.
- A number of open issues need the attention of the Arctic research community to improve our understanding of the interplay between Arctic freshwater, sea ice and the meridional overturning circulation in the past. While evidence is accumulating that points to an Arctic trigger for the Younger Dryas cold event, there is only indirect or ambiguous evidence from Arctic Ocean records of a strong freshwater flow to the basin. Well-dated marine records of higher-resolution, preferably from areas next to the potential outlets in the Mackenzie delta, are needed to better tie modeling and terrestrial fieldwork results to a freshwater event in the Arctic Ocean.
- Considering the size of the ice-dammed lakes which repeatedly developed south of the northern Eurasian ice sheets during Weichselian and Saalian glaciations, the possible influence of the discharge of the trapped water toward the Arctic and potentially to the areas of deepwater renewal needs more refined studies. These should involve coupled ocean modeling and detailed paleoceanographic studies to trace the fate of the freshwater in the northern North Atlantic.
- The Eemian, although of high interest as a potential analog for the Arctic under enhanced global warming, remains one of the least understood time periods in the Late Quaternary Arctic history. While there is evidence from the Nordic Seas for a strong Arctic freshwater discharge during the early Eemian, virtually no information exists in the published literature on the oceanic conditions in the potential source areas of this freshwater on the northern Eurasian shelves during the early Eemian. The interplay of sea-level rise and sea ice formation on these shelves is also of interest because it may have been critical for ice conditions in the Eemian Arctic—another open issue which needs further attention.

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