RESEARCH ARTICLES

PALEOCEANOGRAPHY

A warm and poorly ventilated deep Arctic Mediterranean during the last glacial period

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Changes in the formation of dense water in the Arctic Ocean and Nordic Seas [the "Arctic Mediterranean" (AM)] probably contributed to the altered climate of the last glacial period. We examined past changes in AM circulation by reconstructing radiocarbon ventilation ages of the deep Nordic Seas over the past 30,000 years. Our results show that the glacial deep AM was extremely poorly ventilated (ventilation ages of up to 10,000 years). Subsequent episodic overflow of aged water into the mid-depth North Atlantic occurred during deglaciation. Proxy data also suggest that the deep glacial AM was ~2° to 3°C warmer than modern temperatures; deglacial mixing of the deep AM with the upper ocean thus potentially contributed to the melting of sea ice, icebergs, and terminal ice-sheet margins.

The Atlantic Meridional Overturning Circulation (AMOC) plays an important role in Earth's climate, because it redistributes ocean heat and helps control the storage of carbon in the deep ocean. The primary Northern Hemisphere sources of dense water supplied to the AMOC are produced in the Arctic Mediterranean (AM) (*1*). Warm surface waters from the Atlantic flow northward and circulate around the AM via several different pathways, gradually cooling (thereby releasing heat to the atmosphere) and becoming denser. Much of this water-mass transformation is thought to occur in the Nordic Seas via intermediate and deep open-ocean convection, with a smaller contribution from the Arctic Ocean involving the addition of dense waters from brine-enhanced shelf water production (*1*, *2*). The dense water produced by these processes overflows the Greenland-Scotland Ridge, ultimately forming lower North Atlantic Deep Water (NADW) as part of the deep southward return flow of the AMOC.

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Because of the northward heat transfer associated with the flow of warm surface water to convection sites, changes in deep-water formation in the North Atlantic and Nordic Seas are thought to be associated with the altered climate of the Last Glacial Maximum (LGM) and the abrupt climate events of the last deglaciation [~19 to 7 thousand years ago (ka)], such as the Northern Hemisphere cold intervals Heinrich Stadial 1 (HS1) and the Younger Dryas (YD) (*3*–*5*), which affected global climate (*6*, *7*). In this study, we investigated circulation changes over the past 30 ka in the deep Norwegian Sea (and by inference, the broader AM) by reconstructing radiocarbon (^{14}C) ventilation ages and deep-ocean temperatures. Our results revealed an absence of deep convection within the AM throughout much of the last glacial period and the subsequent deglaciation; they instead suggest the presence of a relatively warm and extremely poorly ventilated water mass in the glacial deep AM that subsequently overflowed southward into the North Atlantic during the deglaciation.

North Atlantic radiocarbon reconstructions

Several studies have used seawater radiocarbon ratios ($\Delta^{14}C$) as a proxy for investigating past changes in the circulation of the North Atlantic (*8*–*12*). In the modern high-latitude North Atlantic, deep convection in the Nordic and Labrador Seas quickly transfers surface waters that have equilibrated with the atmosphere to the deep ocean, resulting in a minimal surface-to-deep gradient in ^{14}C age (~100 years) (*13*) and well-ventilated deep water in the North Atlantic.

Deglacial $\Delta^{14}C$ reconstructions from the subtropical North Atlantic are consistent with the established view that there was shoaling of the AMOC [involving a switch from NADW formation to Glacial North Atlantic Intermediate Water (GNAIW) formation] and a northward incursion into the deep North Atlantic of ^{14}C-depleted southern-sourced water (SSW) (*8*, *11*) during the last glacial period, HS1, and the YD. However,

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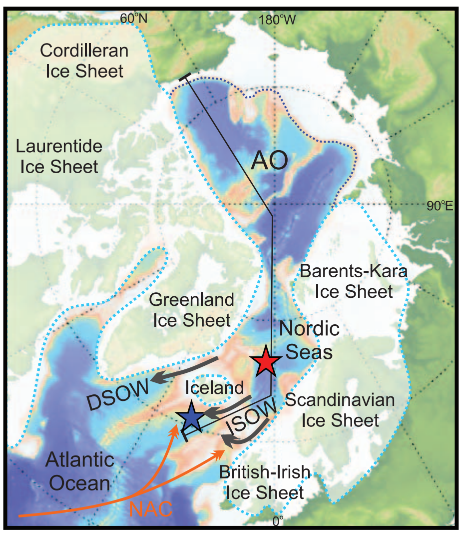

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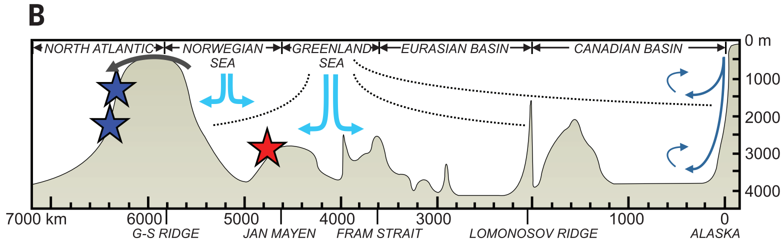

Fig. 1. Sediment core locations. (**A**) Map showing core sites: red star, PS1243, at 2.7 km depth; blue star, RAPiD cores (1P, 4P, and 5P) collected on the South Iceland Rise (*12*). Gray arrows indicate modern Nordic Seas overflow (Denmark Strait Overflow Water, DSOW; Iceland-Scotland Overflow Water, ISOW). Orange arrows show surface inflow of the North Atlantic Current (NAC). The approximate extent of ice sheets during the LGM is indicated by the light blue dashed line (*26*). The dark blue dashed line indicates the extent of the Arctic Ocean (AO) at the shelf edge during the LGM, when sea level was lower. (**B**) Schematic cross section through the AM, as indicated by the black line in (A) (*1*). Deep and intermediate convection occurs in the Greenland and Norwegian Seas (thick blue arrows), whereas the deep Canadian basin may be ventilated by the sinking of small volumes of brine-enhanced shelf water (thin blue arrows) (*1*, *30*). Dashed lines are schematic isopycnals. Deep-water exchange between the AM and the North Atlantic (gray arrow) is restricted by the Greenland-Scotland Ridge, with a depth of ~400 to 800 m.

these data also reveal that large fluctuations in $\Delta^{14}C$ (shifts of up to ~1000 ^{14}C years within ~100 calendar years) occurred in the mid-depth North Atlantic during HS1 and the YD, suggesting a complex history of circulation (*8*). Recently, these fluctuations in mid-depth $\Delta^{14}C$, alongside temperature proxy data, have been cited as evidence that the AMOC switched from a glacial to an interglacial mode of circulation through the release of heat from warm deep water (*14*).

$\Delta^{14}C$ reconstructions from the mid-depth (1.2 to 2.3 km) subpolar Northeast Atlantic, south of Iceland (at the South Iceland Rise), have revealed the presence of an extremely poorly ventilated water mass during cold intervals of the last deglaciation, with ^{14}C ventilation ages in excess of 5000 years (*12*). In addition, rapid and large fluctuations in ventilation ages occurred during HS1 and the YD. These fluctuations are similar to the variability that has been reconstructed in the subtropical Northwest Atlantic, although the shifts south of Iceland are up to four times larger in amplitude. The source of the poorly ventilated water south of Iceland was initially interpreted as Antarctic Intermediate Water (AAIW) (*12*), but more recent studies have shown that AAIW in the deglacial Atlantic was not as poorly ventilated as the water south of Iceland (*9*, *15*, *16*). Available evidence also suggests that deep SSW was not sufficiently depleted in ^{14}C to explain the South Iceland Rise data (*8*–*10*), nor can it explain the observed distinct relationship between $\delta^{13}C$ and $\Delta^{14}C$ (*12*). An alternative proposed source is the AM, although thus far there have been no ^{14}C ventilation data from the deep AM to test this hypothesis. Reconstructions of ^{14}C ventilation ages from the shallow (~700 m) Iceland Sea during the last glacial period reveal benthic-atmosphere ventilation ages of ~500 years, indicating well-ventilated intermediate-depth water in the Nordic Seas that may have contributed to GNAIW formation (*3*, *17*).

This study was therefore motivated by two aims. First, we sought to increase the understanding of AM circulation and to investigate whether there was continued deep convection in the Nordic Seas (or the AM as a whole) during the last glacial period. It is important to better constrain past circulation changes in the AM because (i) the amount of exchange between the surface and deep AM alters the properties of the dense water it exports (*1*, *2*); (ii) regional and global climate are directly influenced by the northward heat transport associated with the inflow of warm surface waters feeding the high-latitude dense water formation sites (*2*); and (iii) ocean circulation changes have the potential to affect other components of the climate system, such as sea-ice extent and adjacent ice sheets. We also wished to investigate the cause of the mid-depth radiocarbon anomalies in the South Iceland Rise data. The present lack of a viable explanation for these data suggests a knowledge gap in our understanding of deglacial ocean circulation. Moreover, a more complete interpretation of deglacial variability in mid-depth North Atlantic ^{14}C ventilation ages—which, for example, have been examined in recent studies of data from the New England seamounts (*14*, *18*)—first requires us to constrain the various end-member water masses and the mechanisms by which they formed.

Ventilation changes in the AM

We obtained new benthic and planktic radiocarbon measurements from a marine sediment core collected in the Norwegian Sea (core PS1243, 2.7 km depth) (Fig. 1), which we selected because of its well-defined stratigraphy (*19*). The age model was slightly modified from its original planktic ^{14}C–based chronology by tuning planktic $\delta^{18}O$ to nearby cores that had been placed on a Greenland ice core–based age model (Fig. 2 and supplementary materials). Core sites from within the central Arctic Ocean were not chosen because of the low abundance of benthic foraminifera; in addition, the extremely low glacial sedimentation rate (*20*) would have increased the uncertainty in the stratigraphic age of samples and hence in the reconstruction of $\Delta^{14}C$.

In contrast to the well-ventilated deep waters and the small benthic-planktic (B-P) ^{14}C offset (~100 years) of the Holocene and the present day, Table 1 and Fig. 2 show that much of the late glacial and deglacial Norwegian Sea was characterized by extremely poorly ventilated deep waters, with benthic ventilation ages of ~7000 to 10,000 years (and B-P ^{14}C offsets of a similar magnitude). Moreover, these extremely old ventilation ages were only associated with a modest decrease in benthic $\delta^{13}C$ values. The coupling of relatively high $\delta^{13}C$ values (~0.8 to 1.4‰) with extremely old ^{14}C ventilation ages suggests that the aging of deep waters was not accompanied by substantial remineralization of organic matter at depth, probably reflecting low surface productivity (Fig. 3 and supplementary materials). These data further suggest that the deep Norwegian Sea was the likely source of poorly ventilated water south of Iceland during the deglaciation (*12*), and the slightly lower $\delta^{13}C$ values reconstructed for deglacial cold intervals south of Iceland can be explained by mixing between the Nordic overflow and low-$\delta^{13}C$ SSW (Fig. 3). The observation of a poorly ventilated yet high-$\delta^{13}C$ end member highlights the complexity of interpreting benthic $\delta^{13}C$ in the subpolar Northeast Atlantic, because it cannot be interpreted as a simple two–end-member mixing scenario (i.e., SSW versus GNAIW or NADW). Our results demonstrate that during the deglaciation, a Nordic Seas overflow of extremely poorly ventilated water with $\delta^{13}C$ values of ~0.8 to 1.4‰ took place; in addition, the chemically distinct contribution to GNAIW during the LGM identified in previous research (*21*) must have been sourced from the intermediate (not deep) Nordic Seas. The high $\delta^{13}C$ values of the *Cibicidoides wuellerstorfi* at this site and the benthic foraminifera samples used

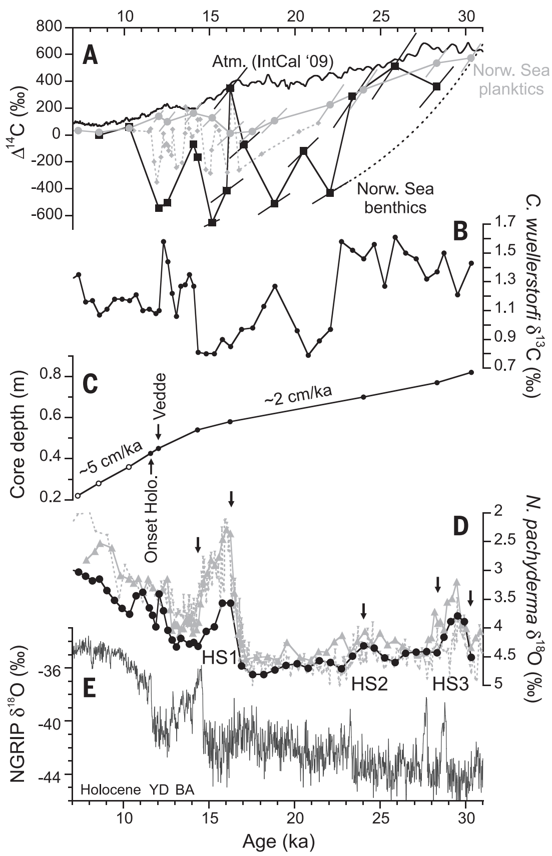

Fig. 2. Deep Norwegian Sea radiocarbon reconstructions. (**A**) $\Delta^{14}C$ from core PS1243, collected in the deep Norwegian Sea (black squares, benthic species; gray circles, planktic species), and from the South Iceland Rise (1.2 to 2.3 km depth; benthics, small gray diamonds) (*12*), shown with the IntCal09 radiocarbon age calibration curve (*40*). "Projection age" extrapolation for the sample at 23 ka is shown by the black dashed line. (**B**) *C. wuellerstorfi* $\delta^{13}C$ measurements from core PS1243 (*19*). (**C**) Age model for core PS1243. White circles are tie points based on planktic ^{14}C using the modern reservoir age of 400 years. Black circles are stratigraphic tie points based on the correlation of *Neogloboquadrina pachyderma* (s) $\delta^{18}O$ data [shown in (D) by black arrows], the occurrence of the Vedde Ash, and an abrupt decrease in the percentage of *N. pachyderma* (s) (not shown) at the onset of the Holocene. (**D**) Correlation of *N. pachyderma* (s) $\delta^{18}O$ measurements between core PS1243 (black) (*19*) and Norwegian Sea cores ENAM93-21 (solid gray) and MD952010 (dashed gray). The cores have been placed on the Greenland Ice Core Chronology 2005 age scale of the North Greenland Ice Core Project (NGRIP) (**E**) on the basis of their magnetic susceptibility (*5*, *41*).

for $\Delta^{14}C$ (table S1) rule out low-$\delta^{13}C$ sources of ^{14}C-depleted carbon, such as methane hydrates, mantle carbon, or remineralized sedimentary organic carbon.

Our records indicate enhanced ventilation at the onset of the Holocene and the Bølling-Allerød (BA) periods, although additional measurements are required for confirmation (see the supplementary materials); they also point to an event at ~16 ka that is in agreement with measurements from south of Iceland. Support for the existence of a brief (multicentennial-scale or less) deep-water formation event at ~16 ka, with a benthic-atmosphere offset of ~300 years recorded both in the deep Norwegian Sea (at 2.7 km depth) and south of Iceland (at 2.3 km depth) (*12*), can also be found in high-resolution records of planktic foraminifer faunal assemblages in the subpolar Northeast Atlantic (fig. S3 and supplementary materials). These records reveal a strong surface warming farther to the south, possibly caused by an increased northward flow of surface waters feeding the deep convection site, the precise location of which is uncertain.

Table 1. Benthic ^{14}C data from core PS1243. Intervals for benthic dates were selected based on local abundance peaks where available (supplementary materials). For some samples, a robust B-P age is not provided, because there was no planktic ^{14}C date at the exact corresponding core depth. Foraminifera species used in this analysis include *C. wuellerstorfi* (*Cw*), *P. depressa* (*Pygro*), and Miliolida species.

Time interval	Depth (m)	Calendar age (ka)	Species	^{14}C age (years)	Error (years)	B-P offset (years)	Error (years)	Benthic-atmosphere offset (years)
Holocene	0.28	8.52	*Cw*	8290	35	170	100	570
	0.28	8.52	*Pygro*	8090	75	−30	110	370
	0.36	10.29	*Cw*	9530	40	−70	100	340
YD (Vedde)	0.45	12.03	*Cw*	18,000	100	7370	140	7760
YD	0.47	12.52	*Pygro*	17,800	150	6400	160	7310
BA	0.53	14.05	*Pygro/Cw*	14,250	65	1810	91	2030
	0.54	14.30	Miliolida	15,350	100	N/A		2930
HS1	0.56	15.15	*Pygro*	23,200	250	9450	290	10,400
	0.575	16.00	*Cw*	19,850	130	N/A		6710
	0.58	16.20	*Pygro*	13,350	60	−2300	140	172
	0.595	17.00	*Pygro/Cw*	17,100	95	N/A		3110
Late glacial	0.62	18.80	Miliolida	24,000	290	6550	350	8370
	0.645	20.50	Miliolida	20,900	160	N/A		3530
	0.67	22.05	Miliolida	26,000	270	6210	340	7640
Early MIS 2	0.69	23.35	*Pygro*	20,700	660	N/A		1220
	0.73	25.84	*Pygro*	21,800	220	N/A		270
	0.77	28.30	Miliolida	25,000	240	950	350	1520

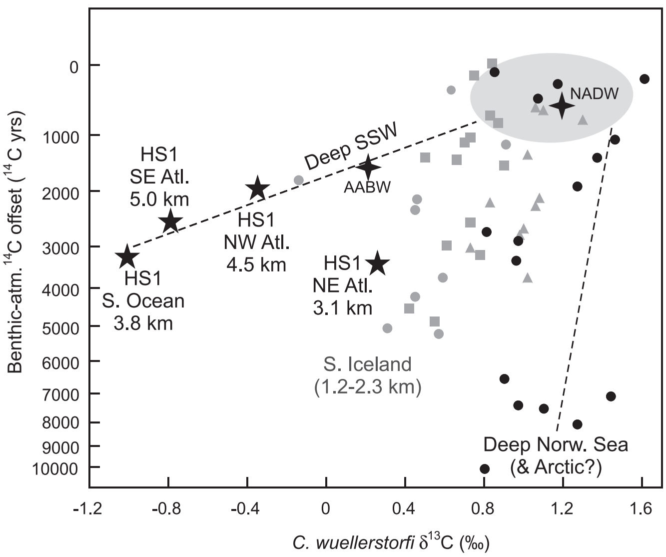

Fig. 3. Cross-plot of *C. wuellerstorfi* $\delta^{13}C$ and benthic-atmosphere ^{14}C ventilation ages (logarithmic scale), modified from (*12*). Black circles are new data from the deep Norwegian Sea; gray shapes are data from RAPiD cores previously collected on the South Iceland Rise (circles, core 5P; squares, core 4P; triangles, core 1P). Five-pointed stars are published estimates for HS1, and four-pointed stars are estimates for modern water masses.

Isolation of the deep central Arctic Ocean

The magnitude and rapidity of the shift from well-ventilated to poorly ventilated water at ~23 ka cannot be explained by in situ aging of deep water at the Norwegian Sea core site; therefore, we infer the incursion of a pre-aged water mass. The most likely candidate for this is shoaling of isolated water in the deep central Arctic Ocean (supplementary materials), which is connected to the Nordic Seas via the Fram Strait and which has a volume of ~1.2×10^7 km^3—approximately four times greater than the deep (>1 km) Nordic Seas. Because the Arctic Ocean (and the AM as a whole) is a semi-enclosed basin that was further restricted during the last glacial period by the closure of the Bering Strait, it was susceptible to isolation and the development of poorly ventilated deep water.

Previous studies have suggested that there was thick ice cover across much of the Arctic Ocean during the LGM, leading to minimal or no sedimentation in the central Arctic of either terrigenous or biogenic material (*20*, *23*). With no appreciable surrounding continental-shelf area, there was probably also only a minor contribution to the deep ocean from brine-enhanced shelf water (*24*). These conditions would favor the development of poorly ventilated bottom water with relatively high $\delta^{13}C$. Benthic $\delta^{13}C$ data from the deep central Arctic before the last glacial period [Marine Isotope Stage (MIS) 3] suggest values of up to 1.7 to 1.8‰ (*25*), which, with a small amount of organic carbon remineralization throughout the glacial period (MIS 2), would have resulted in the observed glacial and deglacial values in the deep Nordic Seas of 0.8 to 1.4‰. Reduced surface productivity across much of the glacial AM and organic carbon export to the North Atlantic by vigorous intermediate-depth circulation presumably helped to prevent the development of anoxia in the deep AM (supplementary materials).

Projecting the benthic $\Delta^{14}C$ onto the atmospheric $\Delta^{14}C$ curve (*11*) (Fig. 2) for the data point at ~23 ka (i.e., the first occurrence of old water in data from core PS1243), using a surface reservoir age of 400 years, suggests that the deep Arctic Ocean may have become isolated at ~30 ka (i.e., close to the onset of MIS 2). At this time, sea-level records indicate the final rapid growth of continental ice sheets to their full glacial extent (*26*) and hence the loss of shelf seas, reducing vertical mixing (*27*) and brine-enhanced shelf water production (*24*). However, this method does not consider any mixing or entrainment with younger waters. Therefore, if such entrainment occurred, it is possible that parts of the AM were older than our recorded ages and that the deep central AM was isolated earlier than ~30 ka. Given its complex bathymetry, it is plausible that there were numerous distinct water masses residing within the deep AM during the

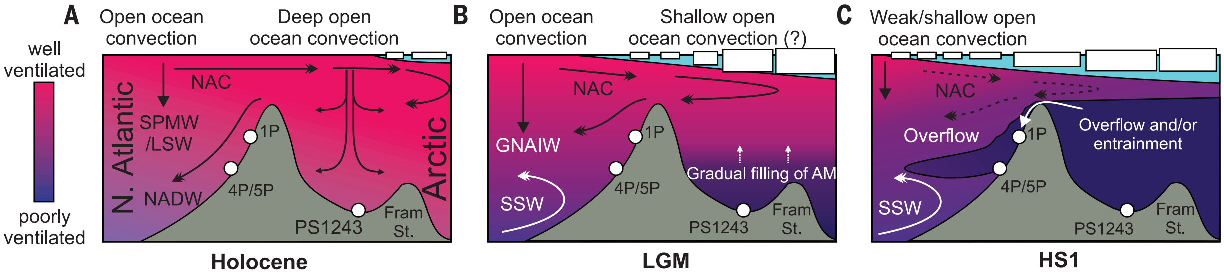

Fig. 4. Cartoon of hypothesized changes in the circulation and ventilation of the Arctic Ocean, Nordic Seas, and Northeast Atlantic. North is to the right. Color shading indicates ^{14}C ventilation. The pale blue layer indicates the varying extent of surface fresh water and sea ice or icebergs (white rectangles). Core locations are indicated by white circles. (**A**) Surface waters flow around the Nordic Seas and Arctic Ocean, losing buoyancy en route (SPMW, Subpolar Mode Water; LSW, Labrador Sea Water); ventilation of the intermediate and deep AM occurs mainly by convection in the Nordic Seas. (**B**) Reduction of deep convection and accumulation of poorly ventilated dense water in the deep AM, resulting in a sharp radiocarbon front (supplementary materials). (**C**) Entrainment and/or overflow of aged AM water into the North Atlantic during HS1.

last glacial period, with various ventilation ages and nutrient chemistry.

Circulation changes and rates

Deep open-ocean convection in the modern Nordic Seas is variable and subject to perturbation (*28*); therefore, it seems probable that during the late glacial and deglacial periods, enhanced surface freshening caused the weakening and shoaling of open-ocean convection in the Nordic Seas. This would mean that the deep AM was only ventilated by limited deep-water formation, probably in coastal polynyas. The timing of the switch to poorly ventilated waters at ~23 ka in the deep Norwegian Sea may have been the result of a marked weakening or shoaling of deep convection in response to surface freshening from melting icebergs (*19*). Alternatively, it may simply have been caused by the slow accumulation of bottom water in the AM that was denser than the products of open-ocean convection in the Nordic Seas. Thus, the rapid switch to older benthic ventilation ages in core PS1243 at ~23 ka probably records the upward migration of a sharp vertical gradient in radiocarbon ventilation age, separating the aged AM bottom waters from the overlying, better-ventilated products of open-ocean convection (supplementary materials). This is somewhat analogous to the model invoked for the glacial Atlantic Ocean, with dense SSW, formed partly by brine rejection processes around Antarctica, being overlain by well-ventilated GNAIW, the product of open-ocean convection south of Iceland (*29*). The mechanism by which the aged water mass was subsequently transported into the North Atlantic is uncertain, but it must have involved either (i) the continued slow accumulation of aged water in the AM and its eventual overflow (Fig. 4) or (ii) a more rapid process of entrainment and displacement by overturning in the Nordic Seas during the deglaciation, possibly related to sea-ice formation and brine rejection as orbitally induced insolation changes promoted seasonal melting and refreezing of sea ice. Investigating these mechanisms will require a depth transect of cores to reconstruct water-column $\Delta^{14}C$ profiles at time intervals throughout the glacial and early deglacial periods.

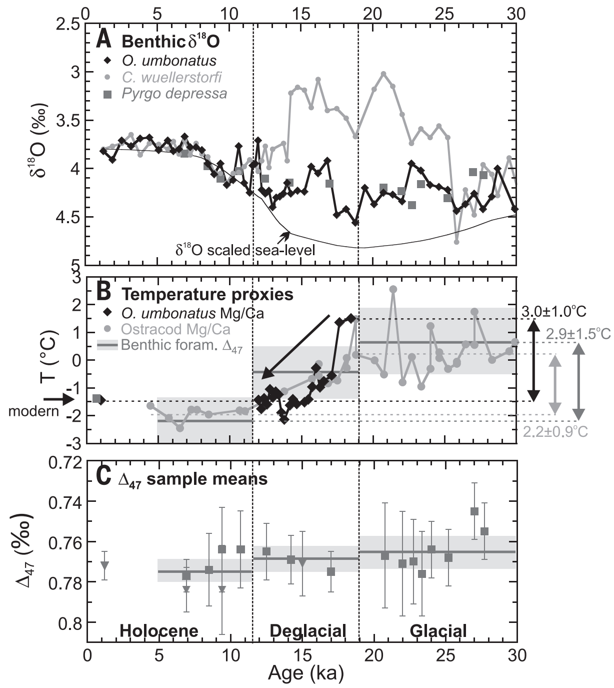

Fig. 5. Deep Norwegian Sea temperature reconstructions. (**A**) Benthic $\delta^{18}O$ data from core PS1243 (*19*). Measurements from *Pyrgo depressa* (gray squares; vital effect, −0.9‰), *C. wuellerstorfi* (gray circles), and *Oridosarlis umbonatus* (black diamonds; vital effect, −0.28‰) are shown with global sea level scaled to a 1‰ whole-ocean $\delta^{18}O$ change. The low $\delta^{18}O$ values of *C. wuellerstorfi* are discussed in the supplementary materials. (**B**) Glacial-to-Holocene temperature change in the deep Norwegian Sea. Shown are new clumped isotope data (Δ_{47}, horizontal gray line; gray square, core top) from core PS1243, published ostracod Mg/Ca data (gray circles) from core PS1243 (*35*), and new benthic foraminifera Mg/Ca data (black diamonds) from core MD992276 (same site as PS1243) (supplementary materials). Dashed lines indicate the Holocene (lower) and glacial (upper) averages used for each proxy to calculate the glacial-to-Holocene temperature change (double-headed arrows, with ±1 SE); the Δ_{47} data set is also shown with ±1σ errors for each time interval (shading). The black arrow in the center highlights the deglacial release of heat from the deep Norwegian Sea. (**C**) Sample-mean Δ_{47} measurements from *P. depressa* (squares) and *C. wuellerstorfi* (triangles) in core PS1243, with averages (lines) and ±2 SE shading for the Holocene, deglacial, and glacial intervals. Core-top foraminifera Mg/Ca and Δ_{47} data points are from (*42*) and (*43*), respectively.

If the deep ventilation age of 10,000 years is interpreted as a water-mass residence time of ~10,000 years in the deep AM, then we can infer that the replenishment rate of deep water must have been limited to ~0.05 sverdrup [1 sverdrup (Sv) = 10^6 m^3 s^{-1}], presumably by processes such as brine-enhanced dense water production in coastal polynyas. This rate can be compared with estimates of ~0.1 Sv for the modern contribution of brine-enhanced shelf-slope and entrained water to the deep Canadian Basin (*30*). Employing estimates of vertical diffusivity from the modern Arctic in a simple advective-diffusive model of the deep Arctic demonstrates that ventilation ages similar to those that we reconstructed in the glacial deep AM (~10,000 years) are achievable, as long as bottom-water formation rates remain low (supplementary materials).

Recent work has suggested that there has been a persistent export of ^{231}Pa from the deep central Arctic Ocean over the past 35 ka (*31*). The Fram Strait and Nordic Seas are a likely sink for this ^{231}Pa because of their higher particle fluxes (*32*), enabling scavenging of dissolved ^{231}Pa from the water column. To reconcile this with our results, we must infer that there was sufficient recirculation of the poorly ventilated deep water within the AM to enable the export of dissolved ^{231}Pa to the Fram Strait and Nordic Seas. However, because uncertainties also remain regarding the influence of reduced particle rain and boundary scavenging on the Arctic ^{231}Pa budget during glacial periods, these factors may also be called upon to explain the ^{231}Pa deficit in the glacial Arctic Ocean (*31*).

Implications

Using simple mass-balance calculations that include the possible volume of the poorly ventilated reservoir (i.e., the volume of the deep AM), limitations on its renewal rate (~0.05 Sv), and the observations from south of Iceland indicating overflow for a total of ~5000 years [i.e., the combined duration of HS1, the YD, and the Intra-Allerød Cold Period, when highly ^{14}C-depleted water was present in the overflow region (*12*)], we conclude that the overflow of poorly ventilated waters from the AM into the Northeast Atlantic must have been relatively weak and would not have exceeded, on average, ~0.1 Sv. Future modeling work, aided by additional proxy reconstructions, should investigate whether the mid-depth Δ^{14}C variability reconstructed for the subtropical Northwest Atlantic (*8*) can be attributed to a weak yet highly ^{14}C-depleted Nordic Seas overflow (*18*) and how this signal propagated throughout the North Atlantic under reduced AMOC conditions. Possibly the AM was the source for the low-Δ^{14}C event at 15.6 ka that was recorded in corals at the New England seamounts (*14*, *18*). However, the reconstructed temperatures of the deglacial AM are colder than those reconstructed at the New England seamounts for the 15.6 ka event (~0° to 1°C versus 3° to 4°C); therefore, substantial mixing with a warmer water mass must also have occurred.

The evidence for poorly ventilated conditions in the deep Nordic Seas also enables us to conclude that there was no significant contribution from the deep Nordic Seas (and by inference, from the deep Arctic Ocean) to the formation of GNAIW. This contrasts with suggestions by earlier workers (*33*) that relied solely on benthic δ^{13}C. Given faunal evidence for a persistent Atlantic inflow to the Nordic Seas (*34*) and possibly to the Arctic as a subsurface layer (*35*), shallow to intermediate overturning in the Nordic Seas probably persisted throughout the LGM, contributing to GNAIW, as suggested by previous studies (*3*, *17*, *19*, *21*, *36*). Also, while the deep AM remained isolated from the overlying, better-ventilated upper ocean, any surface inputs or perturbations to the AM, such as meltwater events, would not have mixed throughout the entire basin; rather, they would have largely been confined to the upper ocean.

Warm temperatures in the glacial deep AM

Because of deep convection, the modern deep Nordic Seas have a temperature of approximately –1° to –1.5°C. Published temperature proxy data, obtained using ostracod Mg/Ca ratios from core PS1243, indicate that temperatures of the deep Norwegian Sea during the last glacial period were ~2° to 3°C warmer than they have been during the Holocene (*35*). In agreement with these estimates, newly obtained clumped isotope (Δ_{47}) and Mg/Ca temperature proxy data from benthic foraminifera in core PS1243 and neighboring core MD992276 indicate that the LGM was warmer than the Holocene by 2.9 ± 1.5°C (Δ_{47}) or 3.0 ± 1.0°C (Mg/Ca) (Fig. 5 and supplementary materials). An intermediate-to-deep AM during MIS 3 that was 2° to 4°C warmer than modern temperatures, caused by a deep inflow of Atlantic water, has been inferred (*24*, *35*). During MIS 2, when we infer an isolated deep AM, it is likely that geothermal heating contributed to warming in the deep AM. The contribution of geothermal heating to the modern Arctic Ocean is 40 to 60 mW m^{-2} (*37*); assuming that all the geothermal heat remained in a bottom-water layer 2000 m thick, the bottom water could have warmed by ~2°C over 10,000 years.

Because of the thermobaric effect, the development of warm and presumably relatively salty deep water, when overlain by colder and fresher water, provides a source of potential energy that can help drive ocean mixing and overturning (*38*). Overturning of the deep Nordic Seas (or the Arctic) would allow the release of heat previously stored in the deep ocean, which could promote the melting of sea ice and destabilize marine-terminating ice sheets, such as the Barents Sea ice shelf, thereby contributing to the deglaciation of the region. Ostracod Mg/Ca data (*35*) and our new benthic foraminifera Mg/Ca data from the Norwegian Sea suggest that much of the heat stored in the deep Nordic Seas was released over the interval from ~18 to 15 ka (i.e., during the early deglacial period, centered around HS1) (Fig. 5). If deep AM waters were brought to the surface ocean, their carbon isotope composition must not have reequilibrated with the atmosphere, given that old ventilation ages are evident during the YD, when the deep AM appears to have lost much of its glacial heat. Probably this was due to surface stratification, sea-ice cover, and insufficient time at the surface for equilibration [analogous to modern upwelling of Circumpolar Deep Water and Antarctic Bottom Water (AABW) formation]. Whereas previous studies have suggested that a subsurface incursion of warm Atlantic water during HS1 triggered the collapse of ice shelves (*39*), we speculate that the release of deep-ocean heat stored in the previously isolated deep AM may have also contributed to the melting of ice shelves and terminal ice-sheet margins (as well as sea ice and icebergs) in the circum-AM region during the end of the glacial period. The buildup and release of heat from an isolated glacial deep AM plausibly also played a role in earlier glacial-to-deglacial transitions.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/349/6249/706/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S10
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References (*44*–*70*)

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A warm and poorly ventilated deep Arctic Mediterranean during the last glacial period

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Slow circulation in the cold Arctic

The Arctic Ocean and Nordic Seas together supply dense, sinking water to the Atlantic Meridional Overturning Circulation (AMOC). The redistribution of heat by the AMOC, in turn, exerts a major influence on climate in the Northern Hemisphere. Thornalley *et al.* report that during the last glacial period, those regions were nearly stagnant and supplied almost none of the water that they presently contribute to the AMOC. This low rate of flow into the Atlantic was probably due to an absence of vigorous deep-water formation in the Arctic Mediterranean as a consequence of the extensive ice cover there at that time.

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