Arctic Ocean stratification set by sea level and freshwater inputs since the last ice age

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Salinity-driven density stratification of the upper Arctic Ocean isolates sea-ice cover and cold, nutrient-poor surface waters from underlying warmer, nutrient-rich waters. Recently, stratification has strengthened in the western Arctic but has weakened in the eastern Arctic; it is unknown if these trends will continue. Here we present foraminifera-bound nitrogen isotopes from Arctic Ocean sediments since 35,000 years ago to reconstruct past changes in nutrient sources and the degree of nutrient consumption in surface waters, the latter reflecting stratification. During the last ice age and early deglaciation, the Arctic was dominated by Atlantic-sourced nitrate and incomplete nitrate consumption, indicating weaker stratification. Starting at 11,000 years ago in the western Arctic, there is a clear isotopic signal of Pacific-sourced nitrate and complete nitrate consumption associated with the flooding of the Bering Strait. These changes reveal that the strong stratification of the western Arctic relies on low-salinity inflow through the Bering Strait. In the central Arctic, nitrate consumption was complete during the early Holocene, then declined after 5,000 years ago as summer insolation decreased. This sequence suggests that precipitation and riverine freshwater fluxes control the stratification of the central Arctic Ocean. Based on these findings, ongoing warming will cause strong stratification to expand into the central Arctic, slowing the nutrient supply to surface waters and thus limiting future phytoplankton productivity.

The Arctic climate system is changing rapidly1, as exemplified by dramatic declines in sea-ice extent, concentration and thickness over the past four decades2–8. Resultant increases in the area and seasonal duration of open water are associated with increased Arctic Ocean biological productivity3. Climate model simulations suggest that the Arctic Ocean could be seasonally ice-free within decades4, with expected impacts on the biological productivity5 of the Arctic Ocean and climate1. Density stratification from salinity is fundamental to Arctic Ocean circulation, sea-ice cover and productivity4. Cold and fresh surface waters of the polar mixed layer (PML) are separated from warmer and saltier subsurface waters of Atlantic and Pacific origin by the ‘halocline’5, which isolates the PML from subsurface heat and nutrients. Excess precipitation relative to evaporation, river discharge and the advection of low-salinity ocean waters across the Bering Strait are each thought to contribute to the Arctic Ocean’s salinity stratification5,6. Over recent decades, this stratification has weakened in the eastern Arctic (Eurasian Basin) and strengthened in the western Arctic (Amerasian Basin)6,7. Whether or not these trends will continue into the future—and how sea-ice coverage and productivity will be impacted—is uncertain6,7,13,16.

To gain insight into past Arctic Ocean stratification, we reconstructed the sources and degree of biological consumption of nitrogen (N), the limiting nutrient for summertime Arctic productivity8, at three locations in the open (that is, off-shelf) western Arctic Ocean, AHW is covered by fresher Pacific-sourced halocline water (AHW) originates from inflow through the Fram Strait and the Barents Sea and dominates the eastern and central Arctic Ocean up to the Mendeleev Ridge in the Amerasian Basin8–10. In the far western Arctic Ocean, AHW is covered by fresher Pacific-sourced halocline water (PHW), which forms in the Chukchi Sea from inflow across the approximately 50-m-deep Bering Strait11. The northern boundary of PHW is at the Mendeleev Ridge today11 (Fig. 1a) but appears to shift with the Arctic Oscillation, having reached the Lomonosov Ridge in the 1980s11.

Salinity-driven density stratification determines two critical aspects of Arctic Ocean biological nitrate consumption. First, the stratification constrains the upward flux of nitrate to the PML, which occurs mostly in the winter10. Second, the stratification sets the depth of the summertime PML12 relative to the depth of the euphotic zone, which impacts the light conditions for phytoplankton. These features are illustrated by comparing the summertime PML characteristics between the Amerasian and Eurasian basins (Fig. 1b). In the Amerasian Basin, a thin (≤10 m)12, low-salinity PML with near-zero nitrate concentration overlies the PHW,
Fig. 1 | Arctic Ocean study locations, hydrography and nitrate distributions. a, Schematic circulation of AHW (in blue) and PHW (in pale red)34. The coloured circles and diamonds indicate sediment cores and water-column nitrate δ\(^{15}\)N profiles, respectively. The white asterisk denotes the location of the NGRIP ice core19; the white diamond, square and triangle and the black cross denote the locations of Holocene sea-ice reconstructions (Extended Data Fig. 2). b, Cross-section along the grey dashed line in a of nitrate concentration (coloured) and salinity S (black contours, interval 0.5 psu) from AOS94 data19. Vertical dashed lines indicate the locations of nitrate isotope data from ARCO1 stations 10, 14, 19, 26, 30 and 32 (in c). c, Arctic Ocean nitrate δ\(^{15}\)N from ARCO1 (for colour code see a). Vertical blue and red shading indicates the average δ\(^{15}\)N values for AHW and PHW nitrate, respectively. The error bar is the average measurement 1 s.d. (Methods). Panels a and b are plotted using ODV51.

reflecting the weakness of wintertime nitrate resupply across the strong salinity gradient19,21,23. By contrast, the salinity gradient in the Eurasian Basin is less extreme. Accordingly, the Eurasian Basin nitrate occurs at a concentration of ~10 µM, and PML nitrate concentrations overlying the AHW are higher (3–10 µM), reflecting the higher nitrate flux across the weaker halocline17,23.

AHW and PHW differ in their nitrate characteristics. In AHW, nitrate occurs at a concentration of ~10 µM and with a δ\(^{15}\)N of 5‰ (Fig. 1c), equivalent to high-latitude North Atlantic subsurface source waters20–23. By contrast, PHW exhibits a higher nitrate concentration of ~15 µM and a δ\(^{15}\)N of 8‰ (Fig. 1c). The PHW nitrate δ\(^{15}\)N reflects that of North Pacific nitrate (~6.5‰)25, with further isotopic enrichment by organic matter regeneration and benthic nitrogen loss on the Bering, Chukchi and East Siberian sea shelves26–28.

The origin of the nitrate (Atlantic versus Pacific) and the degree of nitrate consumption in the PML both affect the δ\(^{15}\)N\(_{\text{NAP}}\). Based on previous work, the δ\(^{15}\)N\(_{\text{NAP}}\) value of 7 ± 0.3‰ for complete consumption of AHW nitrate and 10 ± 0.3‰ for complete consumption of PHW nitrate (errors are 1 s.d.; Methods). In the central Arctic, the coretop δ\(^{15}\)N\(_{\text{NAP}}\) value of 6.1‰ at site B28 on the Lomonosov Ridge is lower than the value expected for complete consumption of AHW nitrate (blue line, Fig. 2), consistent with incomplete nitrate consumption in the central Arctic today17,23 (Fig. 1b). In the western Arctic, the coretop δ\(^{15}\)N\(_{\text{NAP}}\) value of 8.3‰ at the southerly site B8 and 8.0‰ at the northerly site B17 are intermediate between the values expected for complete consumption of AHW and PHW nitrate (Fig. 2). Given complete western Arctic nitrate consumption today17,23 (Fig. 1b), we infer that these δ\(^{15}\)N\(_{\text{NAP}}\) values indicate complete consumption of a mixture of PHW and AHW nitrate sources at the core sites. Mixing of AHW and PHW is probable at these sites on the Mendeleev Ridge, as they are overlain by the PHW–AHW boundary today19 (Fig. 2a). Moreover, multidecadal shifts in PHW–AHW boundary position18,22 will change the influence of the PHW and AHW at these locations, and the coretop δ\(^{15}\)N\(_{\text{NAP}}\) integrates over ~1,000 years.

Past Arctic Ocean nitrate sources

The expanded ice sheets of the last glacial period drove a lower global mean sea level34, exposing the Arctic shelves and the Bering Strait17,23 (Fig. 3b). Under this configuration, Pacific waters could not flow into the Arctic, and the lower western Arctic δ\(^{15}\)N\(_{\text{NAP}}\) in part reflected the replacement of PHW nitrate with AHW nitrate.

The postglacial flooding of the Bering Strait has been dated to 13–11 ka, with complete inundation occurring after 11.5 ka (refs. 33,34) (Fig. 3b). Accordingly, the rapid increase in the western Arctic δ\(^{15}\)N\(_{\text{NAP}}\) values at ~11 ka probably records the resumption of Pacific water inflow due to Bering Strait flooding. Furthermore, the highest Holocene western Arctic δ\(^{15}\)N\(_{\text{NAP}}\) values occurred within
around 1,000 years following flooding of the Bering Strait. This suggests that benthic nitrogen loss on the Bering, Chukchi and East Siberian sea shelves, which contributes to the high δ¹⁵N of modern PHW nitrate, resumed rapidly upon Bering Strait flooding and did not require full inundation of the Arctic shelves, which was not completed until around 5 ka (ref. 35).

The modern central Arctic is not notably influenced by PHW nitrate (Fig. 1c) and could not have been during the last ice age when the Bering Strait was exposed. Moreover, we assume that the δ¹⁵N of AHW nitrate has not changed over the study period, as supported by records from the North Atlantic (Methods; Extended Data Fig. 4). Thus, the δ¹⁵N of the central Arctic site B28 was probably not substantially affected by source nitrate changes.

Completeness of nitrate consumption
In the case of nitrate supply from AHW, a δ¹⁵N of less than 7‰ indicates incomplete nitrate consumption (Fig. 2). During the last ice age, when AHW nitrate was the only nitrate source to the Arctic Ocean, the δ¹⁵N of 5–6‰ at all sites (Fig. 3a) indicates incomplete consumption throughout the Arctic Ocean. During the deglaciation, complete nitrate consumption first commenced at sites B17 and B28 at around 13 ka, as indicated by δ¹⁵N values of approximately 7‰. This timing corresponds to a deglacial meltwater pulse from the Mackenzie River into the Arctic Ocean (Extended Data Fig. 2). The event was not captured at site B8. At site B8, complete nitrate consumption commenced by around 11 ka, coincident with flooding of the Bering Strait (Fig. 3).

Over the Holocene, the δ¹⁵N values at sites B8 and B17 suggest that complete nitrate consumption persisted in the western Arctic; we propose that the ~1‰ variations in δ¹⁵N indicate changes in the relative proportions of PHW and AHW at these locations instead of consumption changes (Methods; Extended Data Fig. 5). In the central Arctic, δ¹⁵N at site B28 follows boreal summer insolation across the Holocene (Fig. 3c). These data indicate that central Arctic nitrate consumption was complete in the early and middle Holocene during peak summer insolation but became incomplete after 5 ka as the summer insolation decreased.

The reconstructed decline in the degree of nitrate consumption could represent reduced nitrate demand in the PML due to less favourable conditions for phytoplankton growth, or to greater nitrate supply to the PML due to weaker stratification. Today, incomplete nitrate consumption in the Eurasian Basin is attributed to light limitation of primary production by sea ice, although grazing pressure or iron limitation may also contribute locally. However, none of these demand-based mechanisms appear to explain the past changes in nitrate consumption indicated by δ¹⁵N values. While the sea-ice extent was reduced in the Arctic marginal seas in the early and middle Holocene (Extended Data Fig. 2), central Arctic site B28 was probably perennially ice covered throughout the Holocene, suggesting that higher early and middle Holocene nitrate consumption occurred without corresponding alleviation of light limitation. Moreover, the abrupt change from incomplete to complete nitrate consumption in the western Arctic at around 11 ka occurs without an apparent change in sea-ice coverage, arguing against alleviation of light limitation as the cause of the increased nitrate consumption at that time. Thus, the changes in the degree of nitrate consumption are best attributed to changes in nitrate supply, as controlled by the density stratification of the Arctic upper water column.

Density stratification and freshwater input
The changes in nitrate supply indicated by δ¹⁵N values require weaker stratification throughout the Arctic Ocean during the ice age and early deglaciation, perversely stronger stratification in the early and middle Holocene, and a bifurcation in the late Holocene, with continued strong stratification in the western Arctic but weaker stratification in the central Arctic (Fig. 4). This stratification history can be explained by changes in freshwater input to the Arctic Ocean. In both simple conceptual and coupled ice–ocean models, the strength of Arctic stratification scales with freshwater input, with greater freshwater input shoaling the PML and strengthening the halocline.

During the last glacial period and early deglaciation (Fig. 4c), freshwater input to the Arctic was reduced due to the closure of the Bering Strait, which today accounts for around 30% of total freshwater inflows to the Arctic Ocean, alongside lower precipitation in the Arctic region under a colder regional climate and ice-damming of major Arctic rivers. The δ¹⁵N data show that incomplete nitrate consumption characterized the upper Arctic Ocean, consistent with weaker stratification in model simulations with reduced freshwater input. Thus, the halocline was probably weaker and the PML was probably deeper during the last glacial period than today, leading to a greater nitrate supply and light limitation of phytoplankton growth, analogous to (but more extreme than) the
Eurasian Basin today. This inference is supported by subsurface temperature reconstructions, which suggest a deeper halocline at the time. After 15 ka, our records indicate a sequence of deglacial events that enhanced freshwater inputs to, and stratification of, the Arctic Ocean. Oxygen isotopes in the NGRIP ice core (Fig. 3d) show that regional deglacial warming was punctuated by millennial-scale warming in the Bølling–Allerød period (14.7–12.9 ka) and cooling in the Younger Dryas period (12.9–11.7 ka). Although riverine input to the Arctic Ocean increased during the Bølling–Allerød period, nitrate consumption remained incomplete throughout the Arctic at this time (Fig. 3a), suggesting that freshwater input was not yet sufficient to substantially intensify stratification. However, at 13 ka, meltwater discharge from the Mackenzie River appears to have strengthened Arctic Ocean stratification, explaining the more complete nitrate consumption at sites B17 and B28 (Fig. 3a and Extended Data Fig. 2). The lack of change at the most southerly site B8 may have been due to north and eastward routing of the meltwater (Fig. 1a). At 11 ka, δ15N of ≥7‰ indicates complete nitrate consumption in both the western and central Arctic Ocean and hence strong stratification. The postglacial flooding of the Bering Strait at around 11 ka would have abruptly increased freshwater input to the western Arctic Ocean, leading to more intense stratification that, in turn, drove complete nitrate consumption. Together, the increase in nitrate consumption and coincident introduction of PHW nitrate to the western Arctic account for the large δ15N increase at sites B8 and B17 (Fig. 4b,c).

In the central Arctic Ocean, the δ15N at site B28 also rose to ~7‰ around 11 ka. While this timing is coeval with the western Arctic δ15N increase and the postglacial flooding of the Bering Strait, the δ15N at site B28 has many other changes that are unrelated to the flooding of the Bering Strait. Moreover, PHW does not reach the central Arctic Ocean today, and the lack of δ15N measurements above 7‰ at site B28 suggests that PHW was absent from the central Arctic Ocean throughout our record (Fig. 4). Accordingly, we attribute the central Arctic δ15N rise at 11 ka to stratification by other local freshwater sources, such as greater riverine input from ice sheet discharge and the breakup of ice-dammed Arctic rivers.

It is possible that the Bering Strait flooding played a role in triggering these additional freshwater sources to the central Arctic Ocean, explaining the coincidence of the δ15N rise at all sites.

Fig. 3 | Arctic Ocean δ15N changes over the past 35,000 years and records related to their causes. a, Downcore δ15N values; colours are as in Fig. 2. The horizontal grey bar is the expected δ15N from complete consumption of AHW nitrate. Error bars are ±1 s.d. from sample replicates (average ±0.3‰, 1 s.d.). b, Global ice volume equivalent sea level (ESL) (light red) and relative sea level (RSL) reconstructed at the Bering Strait (dark red). The horizontal dashed line indicates the modern depth of the Bering Strait. c, 75° N peak summer (21st June) insolation. d, Ice δ18O, a climate proxy, at the NGRIP ice core (Fig. 1a). The vertical blue and red bars denote, respectively, the Younger Dryas (YD) event and the proposed timing of postglacial Bering Strait flooding (BSF).
During the Holocene, the $\delta^{15}N_{N_p}$ data indicate diverging nitrate consumption trajectories in the western and central Arctic Ocean. In the western Arctic, complete nitrate consumption and thus strong stratification persisted throughout the Holocene (Fig. 4a,b). We propose that this reflects robust stratification in the western Arctic maintained by the continuous input of low-salinity water across the Bering Strait.

In the central Arctic, complete nitrate consumption continued from 10 to 5 ka, indicating strong central Arctic Ocean stratification through the early and middle Holocene (Fig. 4b). This period, referred to as the Holocene Thermal Maximum (HTM), is characterized by a warmer-than-preindustrial summer climate in the Arctic region and sea-ice retreat on the Arctic shelves due to high summer insolation and temperature increase as ongoing Arctic warming enhances freshwater input—riverine discharge and/or precipitation—associated with the warmer summers (Extended Data Fig. 2). After 5 ka, central Arctic Ocean $\delta^{15}N_{N_p}$ declined in concert with summer insolation (Fig. 3c), indicating that central Arctic Ocean stratification weakened in the late Holocene (Fig. 4a). This probably resulted from a decrease in the same freshwater sources that maintained the earlier stratification.

**Implications for the future Arctic Ocean**

The rapid increase in nitrate consumption during the reconnection of the North Pacific and Arctic oceans by 11 ka demonstrates that the high degree of nitrate consumption in the modern western Arctic Ocean, occurring despite extensive sea-ice cover, is largely a result of strong stratification. In turn, the development of strong stratification in the western Arctic Ocean by 11 ka indicates that this stratification results from low-salinity inflow across the Bering Strait. In the central Arctic Ocean, greater nitrate consumption during the HTM indicates that stronger stratification characterized past warmer regional Arctic climates, which we suggest arose from greater freshwater input to the central Arctic Ocean in response to the warmer climate.

With regard to the future, climate models find that continued warming will lead to increased freshwater delivery to the Arctic Ocean and enhanced stratification, with limited nutrient supply triggering oligotrophy. By contrast, satellite-based estimates of Arctic Ocean productivity have increased during the past two decades. An important caveat is that observed productivity increases have largely occurred on the Arctic shelves where Pacific and North Atlantic inflows and weaker stratification have enhanced the nutrient supply. Our results provide insight into the factors controlling the nutrient supply to the extensive open Arctic Ocean, which is underrepresented in satellite-based estimates due to sea-ice cover.

The HTM provides a useful point of comparison for future Arctic change. A more strongly stratified central Arctic Ocean during the HTM (Fig. 4b) implies that stratification will probably increase as ongoing Arctic warming enhances freshwater input to the central Arctic Ocean. Such stronger future central Arctic Ocean stratification would be a reversal from the recently observed weakening of stratification and a return to conditions most recently experienced during the HTM. This enhanced stratification will limit the nutrient supply even as sea-ice retreat alleviates light limitation. Thus, our reconstructions imply that future productivity in the central Arctic Ocean will become more strongly constrained by nutrient supply, as predicted by climate models. This dynamic should reduce or prevent any productivity rise that might otherwise occur due to improved light availability with sea-ice loss.

In the western Arctic Ocean, the effect of global warming on water-column stratification may be less consequential. Global-warming-driven strengthening of the stratification would simply ensure that the western Arctic Ocean maintains the stratified, nutrient-limited conditions that have persisted since the flooding of the Bering Strait. In this sense, in the face of continued global warming, the open western basin will probably be the most biogeochemically stable region of the Arctic Ocean.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-021-00789-y.
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Methods

Sediment cores and chronology. The 1994 Arctic Ocean Section (or AOS94) collected Mark III box cores (40 x 40 x 60 cm) along a transect from the Mendeleev Ridge to the Lomonosov Ridge. Each box core was subsampled with 10 cm diameter plastic tubes. Our samples are sourced from the ‘B’ tube at site B8 (78.13° N, 176.74° W, 1.031 m water depth) and site B17 (81.27° N, 178.97° E, 2.217 m water depth) from the Mendeleev Ridge, and at site B28 (88.87° N, 140.18° E, 1.990 m water depth) from the Lomonosov Ridge. Sediment samples were taken every 1 cm. Approximately, 1,500 N. pachyderma sinistral (Ehrenberg) tests (~ 5–7 mg) were picked from the 212-300 µm size fraction using a binocular microscope.

Age models were created from existing 14C dates on N. pachyderma from B8, B17 and B28 (refs. 36-39). All existing dates were recalibrated using Marine20 (ref. 39) and no local reservoir correction was applied (that is, ΔR = 0 years). This choice of calibration scheme reflects several considerations:

1. While high-latitude oceans have sluggish air–sea 14C equilibration due to upwelling and/or sea-ice coverage, the upper Arctic Ocean is primarily ventilated along horizontal (advector) pathways and not local vertical mixing. The extremely old marine reservoir ages for the Arctic Ocean (>1,500 years) suggested by coarse-resolution ocean- circulation models are not consistent with the prevalence of well-ventilated Atlantic water inflow to the Arctic over the timespan of this study40-43, probably because such simulations do not capture these advective ventilation pathways.

2. Higher prebomb marine reservoir ages (of ~500 years) observed in near-shore western Arctic waters reflect the input of older Pacific-sourced waters transiting across the Bering Strait. Thus, there is an expectation that Arctic marine reservoir ages may have been younger when the Bering Strait was exposed44, in contrast with previous expectations for older marine reservoir ages at this time.

3. We conservatively choose not to assume a particular ΔR history given the few available constraints of past Arctic marine reservoir ages. Instead, we allow that our calculated ages may be imprecise due to past changes in ΔR and interpret our data on millennial- or longer timescales.

Age models (Extended Data Fig. 3) were created using Bayesian age-depth modelling of calibrated calendar ages in Bacon45 using an accumulation rate prior of 300 years cm-1, an accumulation shape prior of 1.5, a default section thickness of 5 cm and default autocorrelation priors of memory strength 4 and memory mean 0.7. For B28, all available 14C dates (number of samples, N = 15) from ref. 39 were incorporated into the age-depth model. For B8 and B17, combining 14C datasets from different studies resulted in poor mixing of the Markov Chain Monte Carlo age-depth iterations, as indicated by a Gelman and Rubin reduction factor46 of >1.05. This was addressed by using only 14C dates from ref. 39 in our age-depth models for B8 and B17. Disagreement between 14C ages is most pronounced for dates before 20 ka and may reflect that dates were obtained from different subsampled ‘push cores’ with 1–2 cm misalignments in the sample depths47. Nonetheless, our resulting age models show coherent Arctic Ocean sediments of season-ration patterns, with higher sedimentation rates of 0.5–2 cm per kyr during the Holocene and late Marine Isotope Stage 3, and lower sedimentation rates of 0.2–0.4 cm per kyr during Marine Isotope Stage 2, as observed previously44,48,49. Note that the higher sedimentation-rate uncertainty before 15 ka reflects the few available 14C dates and the low sedimentation rates during peak glacial conditions50. This uncertainty does not materially affect our interpretations as we do not interpret millennial-scale patterns before 15 ka.

Seawater nitrate isotope analyses. Seawater samples for nitrate isotope analyses were collected along the western Arctic Ocean GEOTRACES transect (ARC01). Collected samples were filtered through a 0.2 µm polyethersulfone membrane into pre-rinsed 60 ml high-density polyethylene bottles and were stored frozen until analysis. Nitrite was removed by sulfamic acid addition51 before analysis in samples in which nitrite was detected. Twenty nanomoles of nitrate were reduced to N2O and the measured ratio of the remaining nitrate and the nitrate supply, and δ falls, is the isotope effect of nitrate assimilation, which is set to 5% given available constraints52-54.

The δ15N of the organic matter preserved in N. pachyderma (δNpachy) as in the main text is observed to be ~2‰ elevated over δ15Ncont in the North Atlantic55, a region of complete nutrient consumption today (where f = 0, so equation (1) simplifies to δ15Naccumulated = δ15Ncont). The δ15N enrichment in non-spicate, symbiont-barren N. pachyderma is consistent with δ15N elevation observed in non-spicate, symbiont-barren foraminifera over thermocline nitrate δ15N in oligotrophic subtropical gyres with complete nutrient consumption55. Given N. pachyderma shows a strong seasonal flux bias to peak summer at high latitudes56, we assume that the diet of N. pachyderma reflects the biomass accumulated throughout the growing season57. This allows for calculating the degree of nutrient consumption (f) from δ15Ncont using the Rayleigh accumulated product model (equation (1))

\[ \delta^{15}N_{\text{Npachy}} = \delta^{15}N_{\text{Ncont}} + 5 \times f(1-f) \times \delta f \]

where δ15Ncont is the δ15N of the reactant nitrate source, f is the degree of seasonal nitrate consumption given by the concentration ratio between the remaining nitrate and the nitrate supply, and δf is the isotope effect of nitrate assimilation, which is set to 5% given available constraints52-54.

The δ15N of organic matter contained in N. pachyderma (δNpachy) is calculated through the isotope effect of nitrate assimilation from two δ15Ncont values from central Arctic Ocean site B28 with a bulk-sediment δ15N record at site PS2185-4 (87.5° N, 144.5° E), which is also located on the Lomonosov Ridge approximately 150 km to the south of site B2858. An age model for PS2185-4 was constructed from 15 accelerator mass spectrometry 14C dates on N. pachyderma59 using the above parameters (see ‘Sediment cores and chronology’). Both sites are >800 km from the nearest shelf area and should record comparable open central Arctic Ocean conditions. Extended Data Fig. 1 shows that, while site δ15Ncont data from site B28 and PS2185-4 bulk sediment δ15N data have similar values in the late Holocene and both increase between the last glacial period and the late Holocene, the two records otherwise have a very different structure. The differences may be explained by changes in the ratio of terrigenous to marine organic N in the sediment, which biases bulk sediment δ15N but does not affect δNpachy. Terrigenous organic material typically has a low δ15N, as do Mackenzie River sediments (1.4–2.8‰, ref. 60) and riverine dissolved organic nitrogen along the Laptev Sea shelf (2.1‰, ref. 61). Thus, lower values of bulk sediment δ15N compared with δNpachy before 5 ka may reflect a greater proportion of terrigenous nitrogen relative to marine organic nitrogen in the sediment (see ref. 7).
δ15N of AHW nitrate is primarily inherited from water masses that contribute to high-latitude North Atlantic subsurface waters. These include subtropical North Atlantic central waters (NACW), with low δ15N in the North Atlantic (δ15N in the North Atlantic), and Southern Ocean mode water (SAMW) and Antarctic intermediate water, which have higher δ15N due to partial nitrate consumption in the surface Southern Ocean. The resultant mixture of these source water masses imparts high-latitude North Atlantic subsurface waters and ultimately AHW with a δ15N of around 5‰, which is approximately equal to the mean deep ocean δ15N (ref. 2). Past changes in Atlantic nitrate δ15N could result from changing contributions of, or the δ15N of nitrate in, these source water masses. Foraminifer-bound δ15N records from the Atlantic basin inform us as to the δ15N of these water masses in the past (Extended Data Fig. 4a,b). Foraminifer-bound δ15N from the subtropical North Atlantic is elevated before 11 ka (ref. 3), indicating reduced regional N fixation and thus a higher δ15N of nitrate in NACW (Extended Data Fig. 4a). In isolation, higher δ15N in NACW would have decreased nitrate δ15N before 11 ka, the opposite sense of change that would explain our results. With regard to Southern Ocean contributions, nitrate consumption was more complete within the Southern Ocean source regions of mode and intermediate waters before 11 ka (ref. 4). (Extended Data Fig. 4b). However, high degrees of consumption in the Southern Ocean would have meant that δ15N residual nitrate that was input into the SAMW was at a lower nitrate concentration. As a consequence, this nitrate δ15N in Southern Ocean-sourced thermocline waters would have been quickly moderated downwards by mixing with underlying nitrate-rich deep water, with its nitrate δ15N of ~5‰ (ref. 5). Thus, the reconstructed Southern Ocean nitrate δ15N in the Holocene, which presumably had a limited capacity to change nitrate δ15N in SAMW or downstream in AHW.

Although direct reconstructions of past AHW δ15N are not currently possible given the confounding influence of changing nitrate consumption (for example, equation (2)), proximal data suggest relatively constant nitrate δ15N in the high-latitude North Atlantic source region of AHW (Extended Data Fig. 4c,d). A δ15N record from the subtropical North Atlantic (31°N) suggests a nitrate δ15N of ~5 in the North Atlantic Ocean upstream of the Arctic Ocean. Additionally, a foraminifer-bound δ15N record from the oligotrophic subtropical North Atlantic (31°N) during Heinrich Events 2 and 3, which are argued to reflect intervals of complete surface nitrate consumption due to strong stratification, given the 2–3‰ δ15N increase during Heinrich Events 2 and 3, which are argued to reflect intervals of complete surface nitrate consumption due to strong stratification, suggests a nitrate δ15N in the North Atlantic Ocean upstream of the Arctic Ocean of ~5‰. Any such increase in AHW δ15N before the Holocene is in the opposite sense of the dominant change in our δ15N records, in which δ15N rises from Marine Isotope Stage 2 to the Holocene (Fig. 3).

Holocene δ15Np, and Pacific water inflow. At western Arctic sites B8 and B17, δ15Np varies between 7.2 and 8.7‰ from 11 ka to the coretop (Fig. 3). These variations, despite being modest, may indicate changes in the position of the PHW–AHW front associated with varying input of Pacific water to the Arctic. At site B8, which presumably is most sensitive to Pacific water input due to its proximity to the Bering Strait (Fig. 1a), two intervals of elevated δ15Np values occurred between 8–7 ka and 6–5 ka. These times correspond to higher reconstructed phytoplankton productivity from opal and biogenic carbon mass accumulation rates, and to reduced sea-ice extent as demonstrated by reduced values of the phytoplankton marker IP25 index (IP25), at a core location proximal to the Bering Strait in the Chukchi Sea (Fig. 3). These biomarker changes are argued to reflect two intervals of enhanced Pacific water inflow to the Arctic Ocean (Fig. 1a). We propose that enhanced Pacific water inflow during these intervals changes the position of the Pacific–Arctic halocline front (PAHF), leading to an increased presence of PHW at site B8, higher δ15Np, and thus higher δ15Np under conditions of complete nitrate consumption. A late Holocene reduction of Pacific water input is further supported by the coeval δ15Np decline at site B17 after 5 ka (Fig. 3).

Data availability. Source data are provided with this paper. Foraminifera-bound nitrogen isotope data are available from the NCEI Paleoclimateography database (https://www.ncdc.noaa.gov/paleo-search/study/33272). Arctic Ocean seawater nitrate isotope data are available from BCO-DMO (https://www.bco-dmo.org/dataset/733109).
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**Author contributions**

J.R.F., D.M.S. and J.G. designed the study; J.R.F. and O.M.U. performed the δ¹⁵N analyses; J.G. performed the seawater nitrate δ¹⁵N analyses; T.M.C. provided the sediment samples; J.R.F., O.M.U. and T.M.C. provided chronology; J.R.F. and D.M.S. drafted the first version of the manuscript; all authors contributed to the interpretation of the data and preparation of the final manuscript.

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**Competing interests**

The authors declare no competing interests.

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Extended Data Fig. 1 | Comparison of δ¹⁵N_Np and N content from Site B28 (blue circles, this study) and bulk sediment δ¹⁵N and %TOC from Site PS2185-4 (brown triangles, ref. ¹). a, Prior to 15 ka, bulk sediment δ¹⁵N averages 4.1 ‰, which is 1.5 to 2 ‰ lower than δ¹⁵N_Np. Between 15 and 10 ka, bulk sediment δ¹⁵N increases by 1 ‰ while δ¹⁵N_Np increases by 2 ‰; the high δ¹⁵N_Np at 13 ka is absent in bulk sediment δ¹⁵N. Between 10 and 5 ka, bulk sediment δ¹⁵N continues to increase, including a rapid 1.5 ‰ increase between 6 and 5 ka; in contrast, δ¹⁵N_Np is constant through this time. After 5 ka, δ¹⁵N_Np declines by ~1 ‰ while bulk sediment δ¹⁵N is constant. b, N. pachyderma N content is constant whereas PS2185-4 percent total organic carbon (%TOC) declines downcore. The decline in bulk sediment %TOC might reflect progressive diagenetic organic matter loss with depth, with terrestrial organic carbon being more recalcitrant.
Extended Data Fig. 2 | Comparison to meltwater discharge and sea ice proxies. a, Arctic δ^15N\text{pp}, (colors as in Fig. 3), (b) N. pachyderma δ^18O from the Beaufort Slope indicating freshwater flooding events in the Arctic Ocean\textsuperscript{16}; greater freshwater discharge is upward. (c)–(f) Relative sea ice extent from c-e, PIP\textsubscript{35} biomarker index in the (c) Chukchi Sea\textsuperscript{9}, (d) Fram Strait\textsuperscript{9}, (e) Laptev Sea\textsuperscript{45}, and (f) open western Arctic Ocean sea ice coverage (months/year >50%) from dinocyst assemblages\textsuperscript{40} (locations in Fig. 1a). More extensive sea ice is downward. Vertical brown bar denotes the Younger Dryas; vertical blue bar indicates proposed timing of postglacial Bering Strait flooding\textsuperscript{33,34}. 
Extended Data Fig. 3 | Age models. Age-depth models for sediment cores B8 (a), B17 (b) and B28 (c). Black line in each panel is Bayesian age-depth model from Bacon59; gray shading indicates 95% confidence interval. Symbols indicate calibrated ¹⁴C dates on *N. pachyderma*. Data sources: a) dark diamonds⁵⁴, light diamonds⁵¹; b) diamonds⁵⁴, triangles⁵³, circles⁹³; c) diamonds⁵³.
Extended Data Fig. 4 | Foraminifera-bound $\delta^{15}N$ constraints on AHW nitrate $\delta^{15}N$ over the last 35,000 years. a, $\delta^{15}N$ from the tropical Atlantic, with higher values indicating weaker $N_2$ fixation during the last ice age. b, $\delta^{15}N$ from the Subantarctic Southern Ocean, with higher values indicating more complete surface ocean nitrate consumption during the last ice age. c, $\delta^{15}N_{N.p}$ from subpolar North Atlantic, interpreted in terms of changing nitrate consumption (dark gray bars at bottom); the data imply relatively constant $\delta^{15}N_{nitrate}$ if the Heinrich Stadial $\delta^{15}N_{N.p}$ peaks reached complete consumption (light gray bars for Heinrich Stadials 2 and 3, compared with light gray bar for the Holocene).
Extended Data Fig. 5 | Comparison to Holocene western Arctic productivity and sea ice proxies. a, Site B8 δ²⁰Ν_{N.p} (orange circles), (b) Chukchi Sea phytoplankton productivity from brassicasterol (green) and opal (blue) mass accumulation rates and (c) Chukchi Sea sea ice extent from PIP_{25} (blue) (ref. 91). Higher brassicasterol and opal MARs indicate higher phytoplankton productivity; lower PIP_{25} (plotted upward) indicates reduced sea ice extent. Gray shading denotes two intervals of higher Chukchi Sea productivity and reduced sea ice that have been attributed to increased Pacific water input to the Arctic Ocean91.