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Freshening, stratification and deep-water formation in the Nordic Seas during marine isotope stage 11

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ABSTRACT

The Atlantic meridional overturning circulation (AMOC) is a critical element of Earth's climate system and it is currently weakening. While this weakening is frequently explained by freshwater-driven disruptions to deep-water formation, uncertainties about the impacts of prolonged freshening limit our capacity to predict its future state. For example, during the warm and unusually long marine isotope stage (MIS) 11 interglacial, ~424 to 374 ka, several lines of evidence suggest that a strong AMOC persisted concomitant with fresher-than-present conditions in the Nordic Seas, challenging our current understanding of deep-water formation. Here, we present new foraminifer-bound nitrogen isotope data along with multiple additional geochemical reconstructions of upper-ocean hydrography in the Nordic Seas during this anomalous interval. Our data suggest that a weak summer stratification was driven by the prolonged upper-ocean accumulation of freshwater beginning at the onset of the climatic optimum, ~410 to 407 ka, which could have helped precondition the region for deep-water formation. A box model constrained by paleo-proxy data additionally suggests that the density gradient between the subpolar North Atlantic and Nordic Seas was favorable for the onset of deep-water formation in the Nordic Seas during the climatic optimum. It is thus likely that the Nordic Seas became a locus of deep-water formation around this time. Enhanced northern-hemisphere heating driven by deep-water formation in the Nordic Seas may have been important for delaying glacial conditions, thereby driving the extended warming characteristic of MIS 11. Such findings may also be relevant for near-future changes under a relatively fresher high-latitude North Atlantic.

1. Introduction

Deep-water formation in the high-latitude North Atlantic regulates the strength of the Atlantic meridional overturning circulation (AMOC), which is critically involved in heat, greenhouse gas and nutrient transport throughout the global ocean (e.g., Buckley and Marshall, 2016; Kuhlbrodt et al., 2007; Lozier et al., 2019; Pelegrí et al., 2006; Williams et al., 2011). Recent observations of a weakening AMOC (Caesar et al., 2018; Rahmstorf et al., 2015; Thibodeau et al., 2018b; Thornalley et al., 2018) and projections of near-future reductions in northern ocean convection (Rahmstorf et al., 2005) highlight the importance of developing a more complete understanding of the mechanisms that control overturning strength, such as prolonged freshwater input and its impact on upper-ocean hydrography.

Modern hydrographic conditions in the Nordic Seas vary seasonally. Summer warming produces stable upper-ocean stratification with a mixed-layer depth (MLD) of less than 30 m, which

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can be extended to reach a depth of ~300 m during winter cooling (Jeansson et al., 2015) (Fig. 1). Freshwater input is usually considered to be a key driver of upper-ocean stratification due to its role in lowering the density of surface waters. However, observations indicate that the summer MLD of all ocean basins has deepened under simultaneous warming and freshening over the last ~50 years (Sallée et al., 2021). Further, paleoceanographic evidence suggests that the accumulation of freshwater in the upper ocean hindered summer mixed-layer shoaling during past anomalously warm interglacial periods (Thibodeau et al., 2017). The hydrographic response of the polar northern ocean to long-term freshening expected from ongoing global warming therefore remains elusive, which may have implications for the fate of the AMOC and related climatic impacts.

Marine isotope stage (MIS) 11, ~424 to 374 ka, has been considered a potential analog for Earth's contemporary and future climate, owing to its similarities in orbital geometry (Berger and Loutre, 2002; Loutre and Berger, 2003) and preindustrial atmospheric greenhouse gas conditions (Raynaud et al., 2005; Siegenthaler et al., 2005). A global synthesis of paleoclimate data suggests that MIS 11 was an anomalously long and potentially warmer-than-present interval in Earth history (Candy et al., 2014). Several lines of evidence also indicate that a vigorous AMOC persisted throughout this interval (Dickson et al., 2009; Koutsodendris et al., 2014; Rodríguez-Tovar et al., 2015; Vázquez Riveiros et al., 2013) concomitant with colder and fresher-than-present conditions in the Nordic Seas (Bauch, 2013; Kandiano et al., 2012, 2016; Thibodeau et al., 2017). Indeed, the extended duration of MIS 11 has been previously attributed to an AMOC intensification beginning at ~415 ka (Dickson et al., 2009), which was hypothesized to facilitate enhanced heat transport to the northern hemisphere and delay the onset of glacial conditions (Dickson et al., 2009; Rachmayani et al., 2017).

Previous hydrographic reconstructions in the Nordic Seas suggest that the prolonged addition of freshwater limited the shoaling of the summer mixed layer during MIS 11 compared to the Holocene (Thibodeau et al., 2017). However, this interpretation was based upon the nitrogen isotopic composition of bulk sediment ($\delta^{15}N_{bulk}$). The $\delta^{15}N_{bulk}$ proxy has some limitations, such as its sensitivity to terrigenous input (Schubert et al., 2001) and post-burial organic matter mineralization (Sigman et al., 1999), rendering the interpretation of these data complicated. A more reliable proxy capable of capturing the full variability of upper-ocean structure during MIS 11 is therefore desired. Here, we present $\delta^{15}N$ measurements of organic matter bound within carbonate tests of the heterotrophic planktic foraminifer *Neogloboquadrina pachyderma* ($\delta^{15}N_{Np}$) (Ren et al., 2009), extracted from the central Nordic Seas core MD99-2277 (Fig. 1). We also present stable carbon and oxygen isotopic ratios ($\delta^{13}C$ and $\delta^{18}O$) in the planktic foraminifer, *Turborotalita quinqueloba*, and pair these measurements with previously analyzed isotopic ratios of *N. pachyderma* (Helmke et al., 2003) to further constrain primary productivity and upper-ocean structure in the Nordic Seas throughout MIS 11 (e.g., Simstich et al., 2012, 2003). Lastly, we use a simple thermohaline box model (Lambert et al., 2016) driven by paleo-reconstructed temperature and salinity gradients to test how thermohaline conditions might have affected deep-water formation in the Nordic Seas during MIS 11 (Text S1; Figs. S1 and S2).

2. Methods

2.1. Regional setting and chronostratigraphy

Core MD99-2277 was obtained from the central Nordic Seas (69.25 °N, 6.32 °W) at 2800 m water depth. Sea surface conditions at this site are influenced by the Norwegian Atlantic Current, an extension of the North Atlantic Current carrying warm and saline waters northward, as well as the East Greenland Current, which exports polar waters southward (Fig. 1). The age model at site MD99-2277 was first established by correlating carbonate content

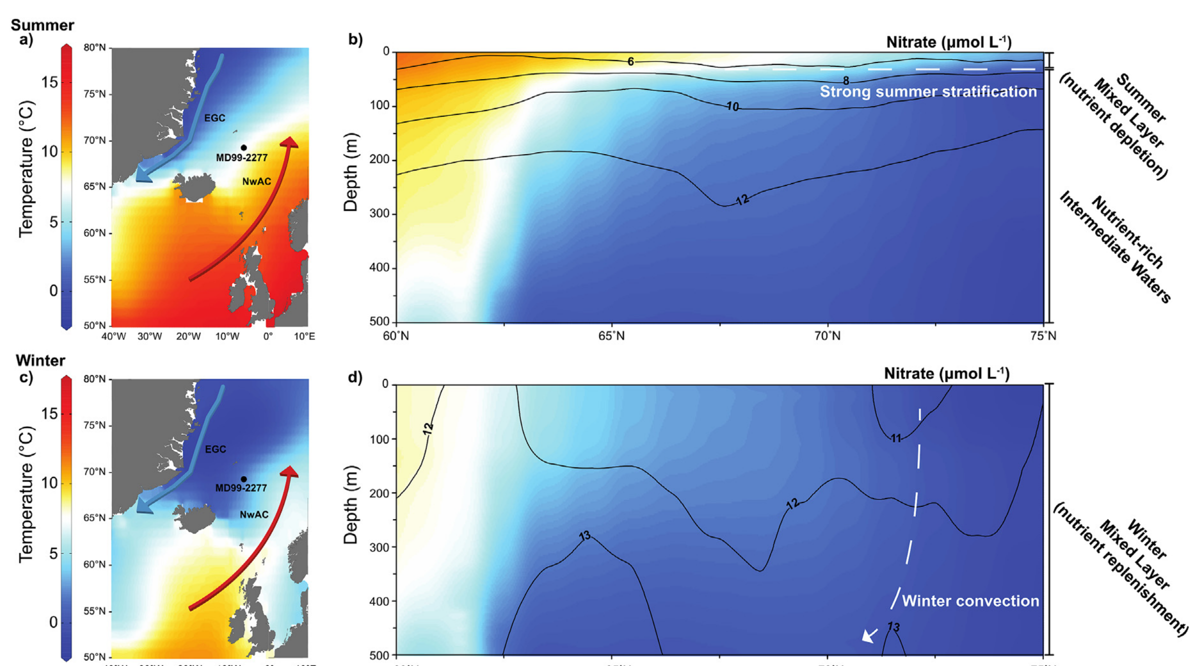

Fig. 1. Oceanographic setting. **(a)** Core site and mean July to September sea surface temperature; **(b)** July to September mean temperature (colored) and nitrate concentration (contour lines) at 0–500 m depth; **(c)** Core site and mean January to March sea surface temperature; **(d)** January to March mean temperature (colored) and nitrate concentration contours at 0–500 m depth. Currents depicted in **(a)** and **(c)** are: Norwegian Atlantic Current (NwAC) and East Greenland Current (EGC). All data presented here are mean values calculated from 1955 to 2012. Figure was prepared with World Ocean Atlas data using Ocean Data View Version 5.1.5 (Schlitzer, 2018).

and planktic $\delta^{18}O$ with a nearby sediment core (Helmke et al., 2005), and later improved by correlating benthic $\delta^{18}O$ measurements to other regional records (Kandiano et al., 2012). All data included here use the updated chronostratigraphy of Kandiano et al. (2012).

2.2. Foraminifer picking and cleaning

Approximately 10–30 *T. quinqueloba* specimens were picked from sediment corresponding to ~417 to 398 ka for $\delta^{13}C$ and $\delta^{18}O$ measurements at a temporal resolution of typically <1 ka. *N. pachyderma* specimens were also picked to obtain a target mass of ~6–8 mg for $\delta^{15}N$ measurements at a temporal resolution of typically <1 ka from ~419 to 384 ka, with duplicates or triplicates picked for every 2 to 3 samples. Both foraminifer species were picked from either the 125–250 μm sediment fraction or the 150–500 μm sediment fraction (see Text S2; Fig. S3). A previously published cleaning protocol (Ren et al., 2009) was implemented to remove external nitrogen before isotopic measurements. Briefly, samples were cleaned by 5-min ultrasonication in a 2% sodium hexametaphosphate solution and rinsed twice with Milli-Q water. Sodium hypochlorite (bleach) was then introduced with several agitations. Samples were soaked in bleach overnight, rinsed again 5 times with Milli-Q water, and oven-dried at 60 °C.

2.3. Isotopic analysis

Stable carbon and oxygen isotopic ratios of *T. quinqueloba* were analyzed on a MAT 253 isotope ratio mass spectrometer (IRMS) coupled to a Kiel IV carbonate preparation system in the Stable Isotope Lab housed in the College of Earth, Ocean, and Atmospheric Sciences at Oregon State University. Two calcium carbonate standards, NBS 19 and Wiley (in-house standard), were run during the analysis, which have expected $\delta^{13}C$ values of 1.95 and −0.41‰ respectively and expected $\delta^{18}O$ values of −2.20 and −7.20‰ vs. VPDB respectively. The Wiley standard was used to correct our data. Average standard deviations (1σ) for $\delta^{13}C$ and $\delta^{18}O$ were calculated to be 0.08 and 0.06‰ respectively based on four *T. quinqueloba* duplicates. Previously measured but unpublished carbon isotopic ratios of *N. pachyderma* are also reported here. Approximately 20 specimens from the 125–250 μm sediment fraction were picked for these measurements, which were conducted on a MAT 251 IRMS coupled to a Kiel device and reported vs. PDB. These measurements were performed on the same specimens used for $\delta^{18}O$ analysis published in Helmke et al. (2003).

Analysis of $\delta^{15}N$ in *N. pachyderma* followed the protocol of Ren et al. (2009). After oxidative cleaning, test-bound organic nitrogen was liberated by adding 30–60 μL of ultrapure 4-N HCl. Organic nitrogen was then converted to nitrate by adding an alkaline persulfate oxidizing reagent (potassium peroxydisulfate; "POR") and heating at 120 °C. The $\delta^{15}N$ of nitrate was measured after bacterial conversion to nitrous oxide (Sigman et al., 2001). Nitrous oxide produced from the carbonate samples was concentrated on a custom-built purge and trap system and analyzed on a Thermo Delta V Plus IRMS with a GasBench II interface housed at the Centre for Coastal Biogeochemistry, Southern Cross University. The contribution of nitrogen derived from the analytical procedure to sample nitrogen was quantified by analyzing blank POR samples. The $\delta^{15}N$ of blank nitrogen was calculated from coral powder standards with a known $\delta^{15}N$ using an isotope mixing model (Hayes, 2002). All samples were then corrected for the contribution of blank nitrogen, which was consistently <10% of the sample nitrogen. The analytical precision based on 12 replicate coral standards was 0.2‰. Three outliers (2 with anomalously high nitrogen concentrations, likely indicative of contamination) of 53 total samples (including replicates) were disregarded. An average standard deviation (1σ) was calculated to be 0.28‰ based on 14 replicates (duplicates or triplicates).

2.4. Calculation of $\delta^{18}O_{sw}$

To provide additional estimations of changes in upper-ocean salinity in the Nordic Seas throughout MIS 11, we calculated the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) from the oxygen isotopic composition of *N. pachyderma* specimens (Helmke et al., 2003) and temperature (T, in °C) reconstructed via modern analog technique (Kandiano et al., 2016). We used a previously published relationship describing the $\delta^{18}O$ of calcitic *N. pachyderma* tests precipitated in equilibrium with water ($\delta^{18}O_{Np}$) as a function both temperature and $\delta^{18}O_{sw}$ (Jonkers et al., 2010; Kim and O'Neil, 1997; King and Howard, 2005), which was rewritten in terms of $\delta^{18}O_{sw}$ and solved as:

$$\delta^{18}O_{sw} = \delta^{18}O_{Np} - \frac{4.64 - \sqrt{0.36T + 15.734}}{0.18}$$

2.5. Modeling thermohaline circulation during MIS 11

We constrained a three-box thermohaline model (Lambert et al., 2016; Thibodeau and Lambert, 2019) with previously reconstructed gradients of upper-ocean temperature and salinity between the subpolar North Atlantic and Nordic Seas (Kandiano et al., 2012, 2016, 2017) to simulate North Atlantic circulation throughout MIS 11. A full description of the model is presented in Text S1.

3. Results and discussion

3.1. Drivers of isotopic variability

$\delta^{15}N_{Np}$ values range from 1.87 to 6.14‰ (Fig. 2c). Relatively high values are observed during the initial phase of the interglacial period, followed by a steep decline during the onset of the climatic optimum (~410–407 ka, with the minimum at ~409 ka) and a return to pre-optimum-like values following this excursion. Because the $\delta^{15}N$ of heterotrophic foraminifera tracks upper-ocean nitrate dynamics, presumably via their consumption of phytoplankton (Smart et al., 2018), the nitrogen isotope excursion towards low-$\delta^{15}N$ values could have been caused by several physical, chemical and/or biological processes, which are discussed below.

Dinitrogen fixation is known to introduce low-$\delta^{15}N$ nitrate to the oceanic nitrogen pool, including in the subtropical Atlantic (Knapp et al., 2008) and potentially the Arctic (Harding et al., 2018). This nitrate is advected to the Nordic Seas (Pelegrí et al., 2006; Williams et al., 2011) and therefore could have influenced our $\delta^{15}N_{Np}$ record. However, foraminifer-bound $\delta^{15}N$ values from the Caribbean Sea suggest relatively stable intra-interglacial rates of dinitrogen fixation over the last 6 marine isotope stages (Ren et al., 2009; Straub et al., 2013a). Thus, without any evidence that dinitrogen fixation increased substantially within an interglacial, fixation is not likely to explain the observed excursion in $\delta^{15}N_{Np}$.

Alternatively, it is conceivable that variability in the strength of advected inflow waters could have influenced the concentration and baseline isotopic composition of seawater nitrate, and potentially also nutrient utilization, in the Nordic Seas. An increase in Atlantic inflow would be expected to increase both temperature and salinity. Indeed, maximum temperatures reconstructed via modern analog technique based on planktic foraminifer census counts are observed from ~407 to 405 ka (Fig. 2g), aligned with an increase in upper-ocean salinity that would likely be indicative of

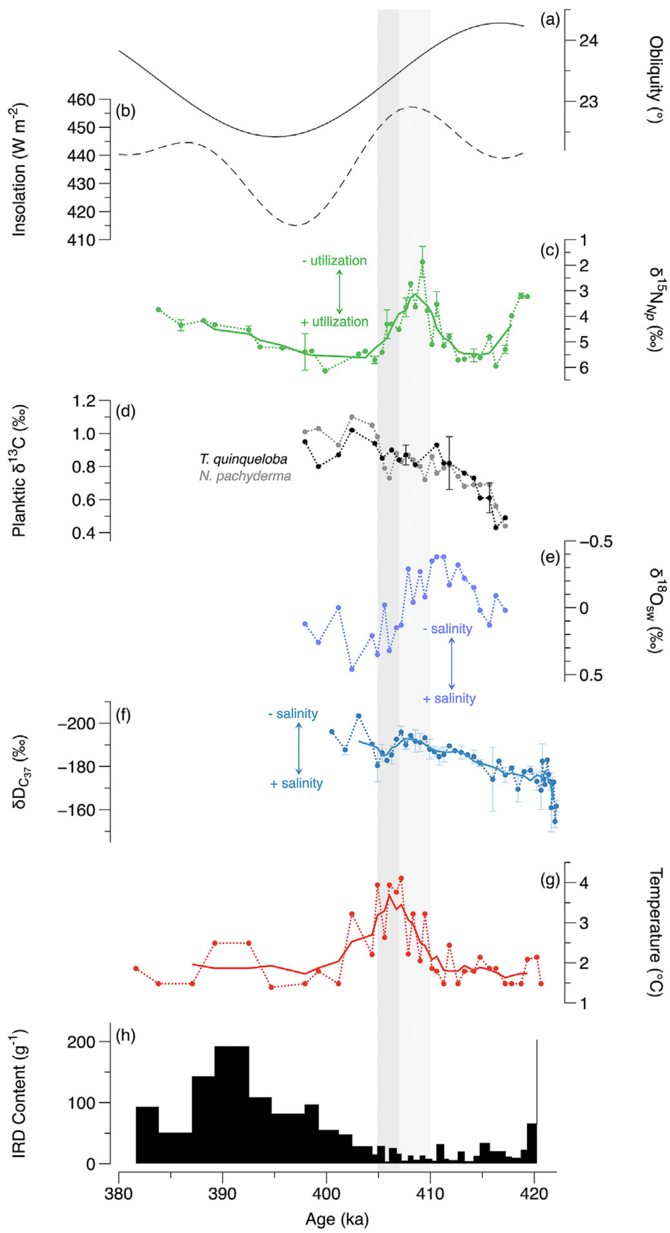

Fig. 2. Climatic and oceanographic trends. **(a)** Obliquity and **(b)** mid-July insolation at 65 °N (Berger and Loutre, 1991); **(c)** Stable nitrogen isotopic composition of *N. pachyderma* (this study); **(d)** Stable carbon isotopic composition of *N. pachyderma* and *T. quinqueloba* (this study); **(e)** $\delta^{18}O_{sw}$ calculated from the $\delta^{18}O$ of *N. pachyderma* (Helmke et al., 2003) and temperature reconstructed via modern analog technique (Kandiano et al., 2016); **(f)** Stable hydrogen isotopic composition of C_{37} alkenones, positively correlated with seawater salinity (Kandiano et al., 2016); **(g)** Upper-ocean temperature reconstructed via modern analog technique based on planktic foraminifer census counts (Kandiano et al., 2016); **(h)** Ice-rafted debris (IRD) content >250 μm (Kandiano et al., 2012). Five-point moving averages are depicted by the solid lines. The lighter-shaded vertical region corresponds to the onset of peak interglacial conditions whereas the darker-shaded vertical region corresponds to the temperature optimum, considered to also reflect enhanced Atlantic inflow as inferred from a simultaneous increase in reconstructed salinity.

enhanced North Atlantic inflow (Fig. 2e and 2f). However, because fresher and colder conditions persisted prior to 407 ka, Atlantic inflow during the $\delta^{15}N_{Np}$ excursion was likely mostly limited to a relatively deeper position as previously suggested (Thibodeau et al., 2017). Additional evidence of this deeper Atlantic inflow may be found in $\delta^{18}O$ offsets between the relatively deep-dwelling and polar-origin *N. pachyderma* and relatively shallow-dwelling and subpolar-origin (i.e., advected) *T. quinqueloba* foraminifers − a signal which has been previously used to reconstruct upper-ocean stratification in the Nordic Seas during the Holocene (Simstich et al., 2012). Specifically, the consistently reduced planktic $\delta^{18}O$ offsets during MIS 11 (Fig. 3) could reflect relatively closer habitat depths between the two species, which is consistent with a deeper Atlantic inflow that would force the otherwise near-surface-dwelling and subpolar-origin *T. quinqueloba* foraminifers to a position closer to that of the relatively deeper-dwelling *N. pachyderma* (e.g., Carstens et al., 1997; Pados and Spielhagen, 2014; Volkmann, 2000). An alternative explanation of the reduced planktic $\delta^{18}O$ offsets characteristic of MIS 11 may be that *T. quinqueloba* foraminifers grew *in-situ* in the Nordic Seas and, during MIS 11, vigorous upper-ocean mixing between the shallower position of *T. quinqueloba* and deeper position of *N. pachyderma* homogenized these upper waters and their oxygen isotopic compositions. However, this is a less likely explanation of our data since *T. quinqeuloba* foraminifers in modern polar settings are overwhelmingly found in distinct subpolar-origin water masses (e.g., Carstens et al., 1997; Pados and Spielhagen, 2014; Volkmann, 2000). Thus, this species is not likely to have predominately grown in the colder-than-present polar Nordic Seas. As such, these data reinforce the argument that cold and fresh upper-ocean conditions prevailed during the onset of the climatic optimum, thereby indicating a relatively minor influence of warm and saline Atlantic waters at the surface. Regardless of the specific mechanism that resulted in consistently lower-than-Holocene planktic $\delta^{18}O$ offsets, our data support the previous hypothesis of a deep mixed layer occurring in the Nordic Seas during MIS 11 compared to the Holocene, which likely also modulated variations in $\delta^{15}N_{Np}$ via its impact on nitrate supply and utilization (Fig. 4; Thibodeau et al., 2017).

Nitrate utilization by primary producers may affect the $\delta^{15}N$ of phytoplankton and therefore our $\delta^{15}N_{Np}$ record. Primary productivity can be reconstructed using planktic $\delta^{13}C$, which is driven by the $\delta^{13}C$ of the dissolved inorganic carbon (DIC) pool (e.g., Ravelo and Hillaire-Marcel, 2007). This is an imperfect proxy due to a variety of other non-biological processes that may impact the $\delta^{13}C$ of DIC, including source-water variability and carbon cycle dynamics (Ravelo and Hillaire-Marcel, 2007). However, Rayleigh distillation calculations suggest that a ~3× reduction in nitrate uptake would be required to produce the $\delta^{15}N_{Np}$ excursion at ~409 ka (Text S3; Fig. S4). If such a steep decrease in primary productivity drove this large decline in nutrient uptake, it is reasonable to assume that this would also impact the $\delta^{13}C$ of DIC and planktic $\delta^{13}C$ values despite other processes that could affect these values. Yet, relatively constant $\delta^{13}C$ values are observed in both planktic foraminifer records during this interval (Fig. 2d). Therefore, a large decrease in productivity and associated lower rate of nitrate utilization of the magnitude consistent with the $\delta^{15}N_{Np}$ reduction are not a likely explanation of our data.

Changes in vertical mixing could also affect nitrate utilization via its impact on the surface supply of nitrate. Indeed, previous foraminifer-bound $\delta^{15}N$ measurements in the subpolar North Atlantic indicate relatively minor changes in nutrient utilization over the last interglacial with the exception of pronounced peaks associated with Heinrich events (Straub et al., 2013b). As such, it was previously argued that summer mixed-layer shoaling and its impact on nutrient supply exerts the primary control on the isotopic composition of intra-interglacial variations in foraminifer-bound nitrogen in the subpolar North Atlantic. Such a mechanism is also the most reasonable driver of our Nordic Seas record, as the

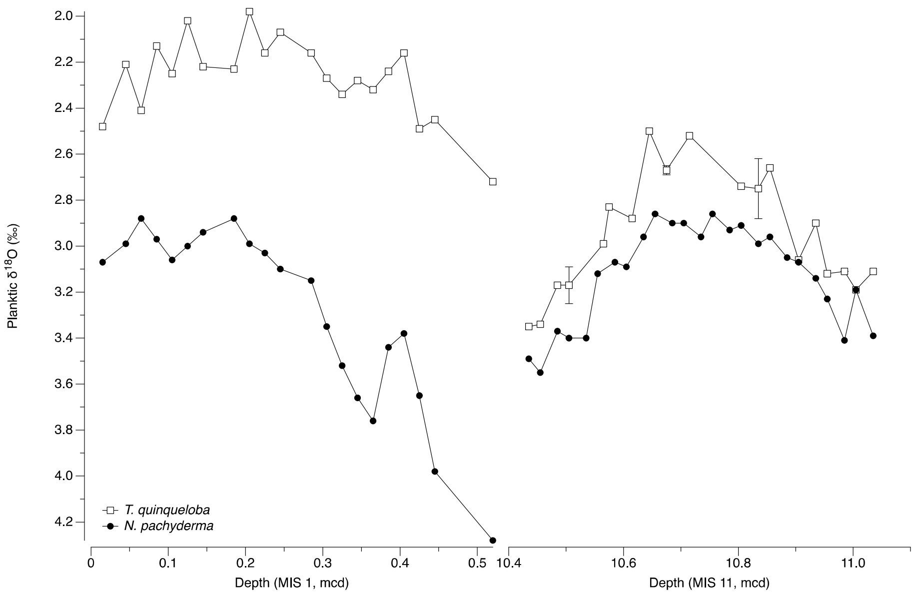

Fig. 3. Paired planktic $\delta^{18}O$. Oxygen isotopic ratios of *T. quinqueloba* (open squares) and *N. pachyderma* specimens (dots) for MIS 1 (left), derived from an MD99-2277 analog core (PS1243), and for MIS 11 (right), derived from MD99-2277. Data for MIS 1 were taken from Simstich et al. (2012), data for *N. pachyderma* of MIS 11 were taken from Helmke et al. (2003) and data for *T. quinqueloba* of MIS 11 are from this study.

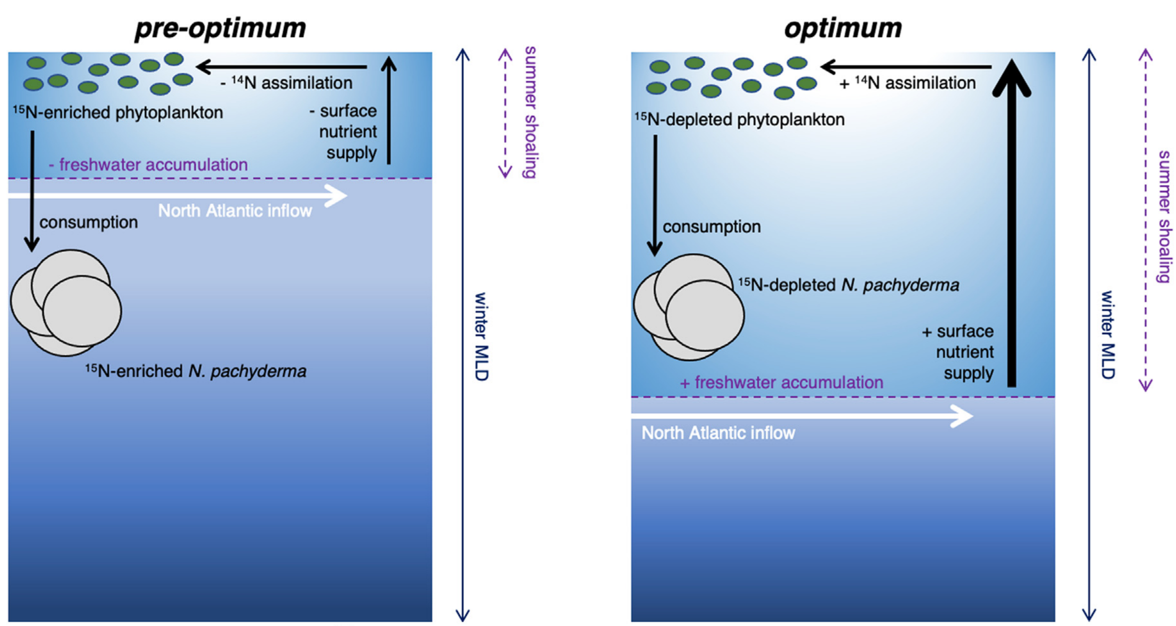

Fig. 4. Interpretation of $\delta^{15}N_{Np}$. Inflow from the North Atlantic occurred below the depth of the summer mixed layer during MIS 11. During the onset of the climatic optimum, open-ocean conditions and prolonged freshwater accumulation resulted in a relatively lesser degree of summer mixed-layer shoaling and thus provided the surface ocean with a relatively larger surplus of nitrate compared to pre- and post-optimum intervals. The preferential assimilation of ^{14}N-nitrate contributed to phytoplankton biomass depleted in the heavy isotope, and this isotopic signal was transmitted to *N. pachyderma* via its consumption of such phytoplankton.

degree of summer mixed-layer shoaling largely determines nutrient supply to the surface waters of the contemporary Nordic Seas, and thus also nutrient utilization (Fig. 4) (Jeansson et al., 2015; Swift and Aagaard, 1981; Thibodeau et al., 2017). While changes in winter mixing could conceivably act as an additional control on nutrient supply, Rayleigh distillation calculations constrained by modern nitrate hydrography in the Nordic Seas indicate that winter MLD variations on the order of hundreds of meters could only explain a maximum change of ~0.6‰ in the isotopic composition of biologically assimilated nitrogen (Text S2; Fig S5). By contrast, an increase of ~25–35 m in the summer MLD would be sufficient to explain the $\delta^{15}N_{Np}$ minimum in our record (Fig. S5). The lower sensitivity of $\delta^{15}N$ to winter mixing is due to the much lower vertical nitrate gradient that persists during the winter (Fig. 1d), thereby resulting in a relatively minor change in mixed nitrate concentration with depth compared to summer (Fig. S5). Thus, the available evidence indicates that nutrient utilization, controlled by variations in the summer MLD, is the primary driver of $\delta^{15}N_{Np}$ and raises a new question: what could have driven anomalously deep summer mixing during the onset of the MIS 11 climatic optimum?

Orbitally modulated solar forcing during MIS 11 is expected to induce warmer surface temperatures in the northern hemisphere (Dickson et al., 2009) and thus stronger stratification of the upper-ocean water column, which would increase nutrient utilization by limiting the availability of deeper nutrients mixed to the surface. Yet, high obliquity and insolation (Berger and Loutre, 1991) corresponded to the large decrease in nutrient utilization observed in our record during the onset of the climatic optimum (Fig. 2a–c), which suggests that thermal forcing via orbital geometry cannot explain the $\delta^{15}N_{Np}$ trend during this interval.

Surface freshwater input is usually expected to induce a shallower summer MLD in the context of intense and short-lived discharge events (Straub et al., 2013b). However, $\delta^{15}N_{bulk}$ data and the dominance of the polar-indicating *N. pachyderma* suggest that a relatively deep mixed layer persisted in the Nordic Seas during MIS 11 (Thibodeau et al., 2017) despite extensive surface-ocean freshening as reconstructed via $\delta^{18}O_{sw}$ and the δD composition of C_{37} alkenones (δD_{C37}; Kandiano et al., 2016) (Fig. 2e and 2f). Specifically, persistently lower-than-coretop δD_{C37} values throughout MIS 11 were interpreted to reflect increased freshwater input to the Nordic Seas relative to present (Kandiano et al., 2016). The 410 to 407 ka interval is characterized by particularly low $\delta^{18}O_{sw}$ and δD_{C37} values, indicating that the Nordic Seas experienced extensive freshening at the onset of the climatic optimum (Fig. 2e and 2f). Contrary to abrupt freshening events such as Heinrich stadials, the prolonged accumulation of freshwater in the upper ocean could result in a deeper mixed layer, thereby also increasing surface nutrient supply (Thibodeau et al., 2017, 2018a). During MIS 11, low values of bulk $\delta^{15}N$ were previously interpreted to reflect anomalously deep mixing in the Nordic Seas driven by prolonged ice melt and freshwater input compared to the Holocene (Thibodeau et al., 2017).

Yet, MLD does not appear to track ice melt throughout our $\delta^{15}N_{Np}$ record, as the notable minimum occurs concomitantly with a near-absence of ice-rafted debris (Fig. 2h). However, because ice-rafting events during peak interglacial periods were sparse in the Nordic Seas (Ruddiman, 1977), it is unlikely that *in-situ* freshwater derived from iceberg meltwater can explain the intense freshening and MLD variability during MIS 11. Instead, the mostly seasonally ice-free surface ocean during the onset of the climatic optimum could have allowed for northern-sourced freshwater derived from northern Greenland, Scandinavia and/or the Arctic Ocean to enter the Nordic Seas (Doherty and Thibodeau, 2018). Such a hypothesis is supported by several paleoceanographic studies reviewed in Doherty and Thibodeau (2018). High-magnitude temperature variability and continuous upper-ocean freshening were reconstructed in the mostly seasonally ice-free Nordic Seas after the ice sheet in southern Greenland had already melted, implicating these northern freshwater sources as important for regulating sea-surface properties of the Nordic Seas during MIS 11. This northern-sourced freshwater likely accumulated in the Nordic Seas and extended the depth of the summer mixed layer. Enhanced adiabatic processes driven by prolonged ocean-atmosphere contact could have further deepened the summer MLD as would be expected under lower-ice conditions (Lique et al., 2018; Lique and Thomas, 2018; Peralta-Ferriz and Woodgate, 2015). Indeed, wind-driven turbulence has been invoked to explain the global deepening of the mixed layer over the last ~50 years (Sallée et al., 2021). Because deep convection requires an initial breakdown of summer stratification (Killworth, 1983), this relatively deep summer MLD in the Nordic Seas may have also been relevant for changes in the AMOC during MIS 11 (Dickson et al., 2009).

3.2. Relevance for the AMOC

It was previously hypothesized that a reduction of Atlantic sea ice preceding the MIS 11 climatic optimum drove a northward extension of surface currents (Dickson et al., 2009). This northward migration allowed for a stronger AMOC and increased bottom-water ventilation at the onset of the climatic optimum, as reconstructed by benthic $\delta^{13}C$ (Dickson et al., 2009; Lisiecki, 2010, 2014). Such oceanographic changes may have further helped to sustain the continual melting of sea ice in the Nordic Seas, as modeling experiments indicate that an increase in ocean-heat transport driven by a stronger AMOC contributed to the melting of northern Greenland during MIS 11 (Rachmayani et al., 2017), which implies that this heat also reached the Nordic Seas. However, it is not understood if the fresh Nordic Seas also contributed to vigorous deep-water formation.

To better understand circulation dynamics during MIS 11, we constrained a three-box thermohaline model with paleo-reconstructions of temperature and salinity (Text S1). Our data-constrained model solutions suggest favorable conditions for overturning to occur in the Nordic Seas during the onset of the climatic optimum (Fig. 5), triggered by an increase in temperature and decrease in salinity differences between the Nordic Seas and the subpolar North Atlantic. Given such a favorable latitudinal density gradient in addition to the existence of a weak summer stratification, it is likely that the onset of Nordic Seas convection played a role in enhancing AMOC strength during this anomalously warm interglacial period despite its fresher-than-present status (Fig. 6). These findings may have implications for past interglacial AMOC variability and contextualizing the long-term fate of the future AMOC. However, due to the simplifications made in the

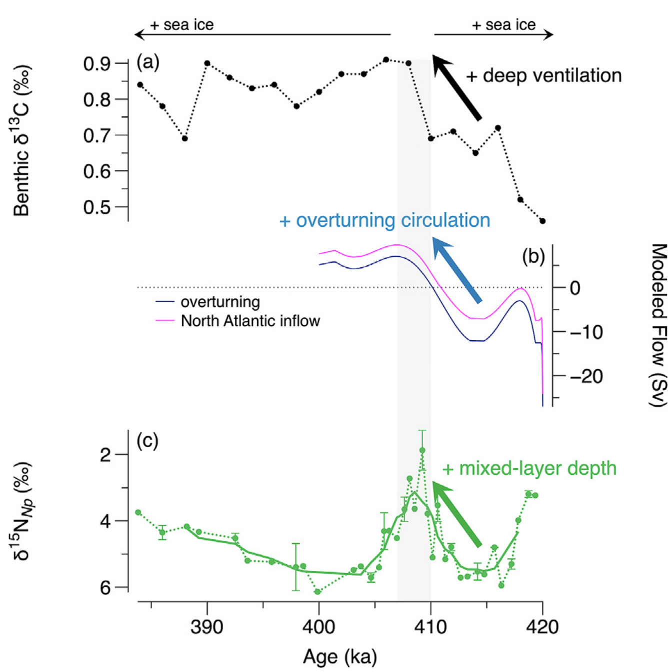

Fig. 5. Deep-water formation in the Nordic Seas. **(a)** Atlantic benthic carbon stack (Lisiecki, 2010) and **(b)** paleo-constrained model solutions for Atlantic inflow and overturning, plotted with **(c)** $\delta^{15}N_{Np}$. Positive flow values (the onset of North Atlantic inflow and overturning in the Nordic Seas) are marked by the horizontal dotted line. The shaded region is the same as in Fig. 2.

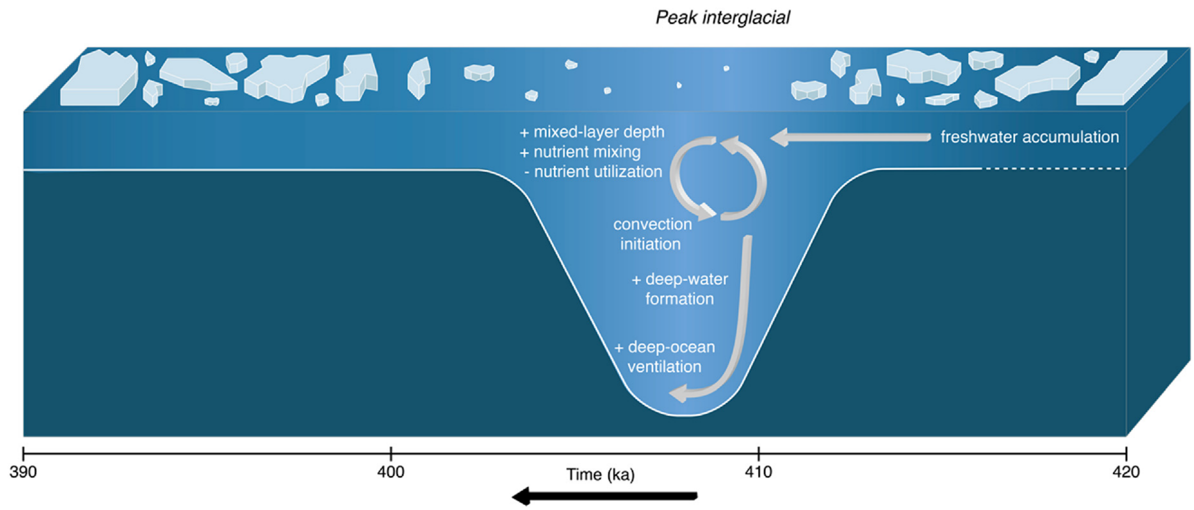

Fig. 6. Schematic diagram of convection in the Nordic Seas throughout MIS 11. During the peak interglacial, open-ocean conditions and prolonged freshwater accumulation extended the mixed layer to its maximum depth. At this time, the Nordic Seas became a locus of deep-water formation and deep-ocean ventilation.

model's configuration, our results should only be interpreted qualitatively. Future work should therefore aim to simulate more realistic freshwater fluxes during this period, which would require more sophisticated numerical approaches and additional paleo-constraints on upper-ocean salinity. Additionally, the stronger AMOC interpreted from benthic $\delta^{13}C$ outlasted the weakly stratified summer conditions in the Nordic Seas inferred from $\delta^{15}N_{Np}$ (Fig. 5). Yet, a planktic $\delta^{13}C$ increase beginning at ~407 ka (Fig. 2d) could be associated with increased productivity (among other phenomena; see Section 3.1), which may hinder our interpretation of the $\delta^{15}N_{Np}$ record as documenting changes to the summer MLD alone. Thus, it is not clear whether the Nordic Seas could have maintained its deep-water contribution following ~407 ka. However, if the Nordic Seas overturning branch was shut off after the onset of the climatic optimum, the persistently strong AMOC throughout MIS 11 would imply that deep-water formation must have been compensated for elsewhere in the subpolar and/or polar North Atlantic.

An interesting remaining question involves the influence, if any, of changes in the Labrador Sea on convection in the Nordic Seas during the MIS 11 climatic optimum. Convection in the Labrador Sea regulates the strength of the subpolar gyre such that enhanced Labrador Sea convection facilitates a stronger zonal orientation of the gyre, which inhibits relatively saline, subtropical-origin Atlantic waters from entering the high latitudes (Hátún et al., 2005). The accumulation of freshwater in the Nordic Seas could potentially indicate a limited role of high-salinity, subtropical-origin waters linked to strong zonal gyre circulation and vigorous Labrador Sea convection. This would be consistent with temperature reconstructions at site ODP 983, within the subpolar gyre, which indicate that relatively stable conditions persisted throughout the climatic optimum (Oppo et al., 1998). Given the importance of Labrador Sea convection in regulating climatic variability throughout the Holocene (Thornalley et al., 2009), understanding its potential role during MIS 11 is important for comparisons of the ocean-climate system between both interglacials. Interestingly, Labrador Sea convection has not been observed during other anomalously warm interglacials such as MIS 5e (Hillaire-Marcel et al., 2001) and MIS 31 (Aubry et al., 2016). Thus, investigating if deep-water formation in the Labrador Sea was maintained throughout MIS 11 would enhance our understanding of convection dynamics under high-latitude freshening and, potentially, the response of the AMOC to ongoing global warming.

4. Conclusions

Reductions in northern ocean convection predicted by various climate models are frequently attributed to increased freshwater fluxes in the high-latitude North Atlantic region (Bakker et al., 2016; Böning et al., 2016; Rahmstorf et al., 2005; Yang et al., 2016; Yu et al., 2016). While this may be true in the context of anthropogenic global warming, our study suggests that prolonged freshwater input does not always impede active deep-water formation. During MIS 11, the expansion of regional summer ice-free surface-ocean conditions allowed for simultaneous freshening and enhanced deep convection in the Nordic Seas (Fig. 5 and 6). This study is the first example of field data supporting deep convection under such a scenario, and further demonstrates that the rate of freshwater input alone cannot determine the strength of overturning circulation. Our discovery therefore bears significant implications for the 20th century weakening of the AMOC (Caesar et al., 2018; Rahmstorf et al., 2015; Thibodeau et al., 2018b; Thornalley et al., 2018) and raises a new question: will weakening continue under ongoing high-latitude warming and freshwater input, or will the AMOC reach a new steady state following a change in deep-water source regions? Numerical experiments suggest the latter (Lique et al., 2018; Lique and Thomas, 2018), which with our study highlight the key role that the Nordic Seas may play in the future AMOC, and reinforce the need to better constrain the dynamic interplay of ice melt, northward current extension and potential freshwater-induced hysteresis in climate models. Our study further suggests that AMOC recovery and strengthening following freshwater perturbations may be possible on interglacial timescales, which is useful for putting contemporary oceanographic changes in the context of long-term Earth-system forecasts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2021.107231.

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