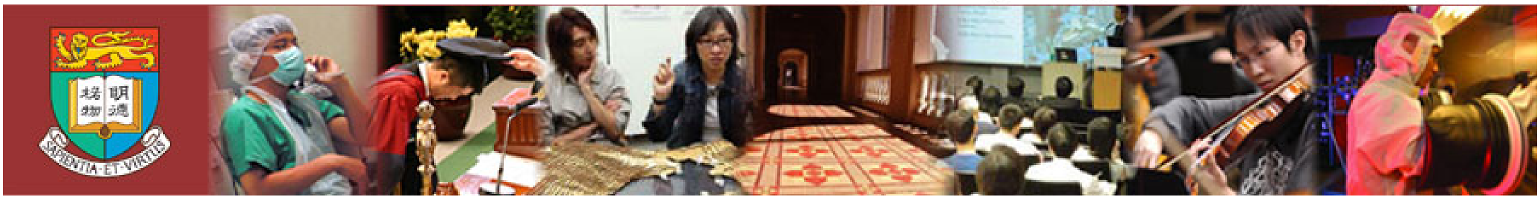
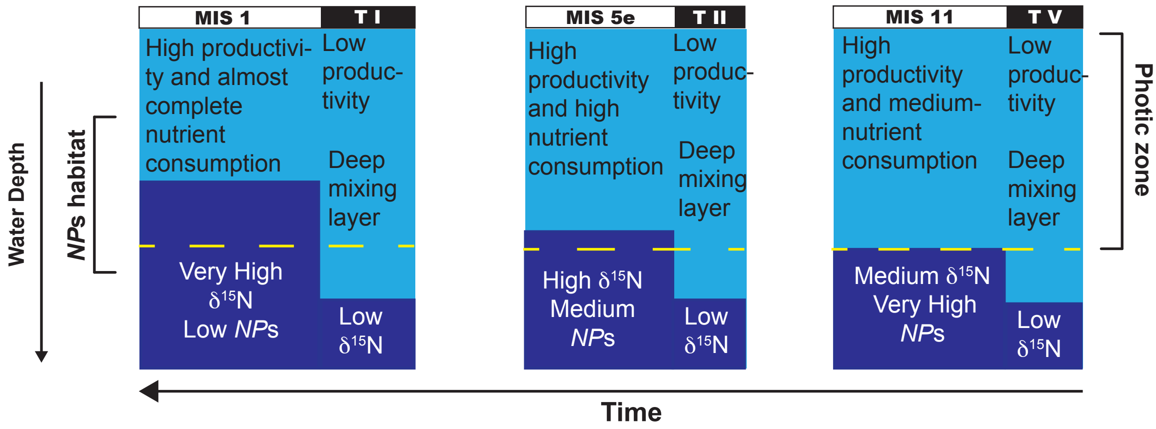


Title	Stratification-induced variations in nutrient utilization in the Polar North Atlantic during past interglacials
Author(s)	Thibodeau, B; Bauch, HA; Pedersen, TF
Citation	Earth and Planetary Science Letters, 2017, v. 457, p. 127-135
Issued Date	2017
URL	http://hdl.handle.net/10722/234563
Rights	Posting accepted manuscript (postprint): © 2017. This manuscript version is made available under the CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/

Highlights

- A thin mixed-layer and a strongly stratified upper-water characterized MIS1
- A thick mixed-layer prevailed during MIS11 and reduced nitrate utilization
- These contrasting results explain the weak expression of MIS11 in the polar latitudes
- Caution is needed when using older interglacials as near-future climate analogues


MIS 1
T I
High productivity and almost complete nutrient consumption
Low productivity
Deep mixing layer
Very High δ15N
Low NPs
Low δ15N
MIS 5e
T II
High productivity and high nutrient consumption
Low productivity
Deep mixing layer
High δ15N
Medium NPs
Low δ15N
MIS 11
T V
High productivity and medium-nutrient consumption
Low productivity
Deep mixing layer
Medium δ15N
Very High NPs
Low δ15N
Water Depth
NPs habitat
Photic zone
Time

Stratification-induced variations in nutrient utilization in the Polar North Atlantic during past interglacials

Authors: Benoit Thibodeau[1,2,5*], Henning A Bauch[3,4,5], Thomas F Pedersen[6]

Affiliations:

[1]Department of Earth Sciences, The University of Hong Kong, Pokfulam Road, Hong Kong SAR

[2]Swire Institute for Marine Science, The University of Hong Kong, Cape d'Aguilar Road, Shek O, Hong Kong SAR

[3]Alfred-Wegener-Institute for Polar and Marine Research, Columbusstrasse, 27568 Bremerhaven, Germany

[4] GEOMAR - Helmholtz Centre for Ocean Research, Wischhofstrasse 1-3, 24148 Kiel, Germany

[5]Academy of Science, Humanities and Literature, Geschwister-Schollstrasse 2, 55131 Mainz, Germany

[6]School of Earth and Ocean Sciences, Bob Wright Centre, University of Victoria 3800 Finnerty Road, Victoria, BC, V8P 5C2, Canada

*Correspondence to: Benoit Thibodeau, Department of Earth Sciences, University of Hong Kong, Pokfulam Road, Hong Kong SAR +852 3917 7834 bthib@hku.hk

Keywords: Stratification, Polar Seas, Global changes, Atlantic Meridional Overturning Circulation, freshwater discharge

Abstract: Vertical water mass structure in the Polar North Atlantic Ocean plays a critical role in planetary climate by influencing the formation rate of North Atlantic deepwater, which in turn affects surface heat transfer in the northern hemisphere, ventilation of the deep sea, and ocean circulation on a global scale. However, the response of upper stratification in the Nordic seas to near-future hydrologic forcing, as surface water warms and freshens due to global temperature rise and Greenland ice demise, remains poorly known. While past major interglacials are viewed as potential analogues of the present, recent findings suggest that very different surface ocean conditions prevailed in the Polar North Atlantic during Marine Isotope Stage (MIS) 5e and 11 compared to the Holocene. It is thus crucial to identify the causes of those differences in order to understand their role in climatic and oceanographic variability. To resolve this, we pair here bulk sediment $\delta^{15}N$ isotopic signatures with planktonic foraminiferal assemblages and their isotopic composition across major past interglacials. The comparison defines for the first time stratification-induced variations in nitrate utilization up to 25% between and within all of these warm periods that highlight changes in the thickness of the mixed-layer throughout the previous interglacials. That thickness directly controls the depth-level of Atlantic water inflow. The major changes of nitrate utilization recorded here thus suggest that a thicker mixed-layer prevailed during past interglacials, probably related to longer freshwater input associated with the preceding glacial termination. This would have caused the Atlantic water to flow at greater depth during MIS 5e and 11. These results call for caution when using older interglacials as modern or near-future climate analogues and contribute to the improvement of our general comprehension of the impact of freshwater input near a globally important deep-water formation site like the Nordic Seas. This is crucial when assessing the negative impacts on the Greenland Ice Sheet of climate change and global warming.

1. Introduction

Deepwater convection in the Nordic Seas relies on the inflow of warm, saline upper-ocean waters from the Atlantic. These gradually increase in density and sink as the waters move northward and cool (Hansen and Østerhus, 2000; Isachsen et al., 2007; Lohmann et al., 2014; Mauritzen, 1996; Swift and Aagaard, 1981). This convective process profoundly affects surface heat transfer in the northern hemisphere, ventilation of the deep sea, and ocean circulation on a global scale (Clark et al., 2002; Vellinga and Wood, 2002). While the general convective pattern differed during past glacial intervals and ensuing terminations (Lynch-Stieglitz et al., 2007), convection and deep ocean circulation during interglacials is thought to have been similar to that today (Bohm et al., 2015). However, it has been suggested that climatic and oceanic instabilities could have led to relatively abrupt variations in the strength of North Atlantic Deep Water (NADW) formation during the last interglacial (Marine Isotope Stage [MIS] 5e) and its associated termination (e.g., Fronval and Jansen, 1996; Galaasen et al., 2014; Seidenkrantz et al., 1995). In most cases NADW reduction events are thought to have been triggered by deglacial ice-sheet melting and sudden freshwater releases that rendered the surface water denser, thus altering the upper-ocean stratification at convection sites. While such events are considered to play a crucial role on planetary climate by influencing the strength of the Atlantic meridional overturning circulation (AMOC) (Rahmstorf, 2002; Rahmstorf et al., 2015), their frequency and estimated intensity remain poorly constrained beyond the Last Glacial Maximum, some 21,000 years ago. Since both warming and freshening of the Polar North Atlantic are expected during the next century (Dickson et al., 2007; Glessmer et al., 2014; Kirtman et al., 2013; Peterson et al., 2006), determining the sensitivity of upper water stratification in the Nordic Seas during pre-Holocene interglacial periods—when global temperatures were likely higher than today—

offers a way to forecast the impact of the warmer climate that greenhouse gas emissions are driving us toward.

Two key analogues of impending climate states are the Eemian or last interglaciation (MIS 5e) and the Holsteinian or Hoxnian (MIS 11), respectively centered around 125 ka and 400 ka. Both appear to represent near-future climate conditions that are similar to model projections for the end of this century: warmer-than-Holocene temperatures (+ 5°C) over most of Europe (Kaspar, 2005; Otto-Bliesner et al., 2006) and the Arctic, and widely reduced sea-ice cover (CAPE Last Interglacial Project Members, 2006). Moreover, the Holocene and the Holsteinian share similar orbital forcing characteristics (insolation) and initial greenhouse gas concentrations (Berger and Loutre, 1991; EPICA community members, 2004). Despite such overall similarities, growing evidence suggests that interactions between glacial ice-sheet size, deglaciation-specific traits and post-glacial sea level rise largely determine the water mass structure and climate (Bauch, 2013; Vázquez Riveiros et al., 2013). This is well illustrated by the cooler-than-Holocene reconstructed sea surface temperature in the Nordic Seas during both MIS 5e and 11 (Kandiano et al., 2012; Van Nieuwenhove et al., 2011) (Fig. 1). While the specifics of each period do not inhibit the unravelling of key influences on present and future climate, they call for caution when trying to understand important processes that drive the AMOC and heat delivery to the Polar region. It is therefore critical to evaluate independently the properties of upper ocean structure in the Polar North Atlantic during each analogue interval if we are to comprehend better the potential of past warm periods to act as exemplars for modern or near-future climate.

The modern upper-ocean structure of the Nordic Seas is dictated by seasonality. Surface water is well stratified during summer with a mixed-layer thinner than 30 m (Jeansson et al., 2015). The mixed-layer is thus well above the light penetration depth, which allow a near complete consumption of surface nitrate during this period (Fig 2a). During winter the cooling of salty Atlantic-derived surface water promotes deeper mixing, creating a mixed-layer that can reach up to 300 m in thickness (Fig 2b; Jeansson et al., 2015). This process is crucial in the formation of deep-water and to the replenishment of nitrate to surface water (Jeansson et al., 2015; Swift and Aagaard, 1981).

Reconstructing upper ocean water mass structure in Polar regions is not straightforward due to the difficulty in estimating mixed-layer thickness. Here, we propose a novel approach that overcomes this constraint, using the abundance of the polar water indicator foraminiferal species *Neogloboquadrina pachyderma* sinistral (*NP*s) in combination with the nitrogen isotopic composition of the host bulk sediment ($\delta^{15}N_{bulk}$). The isotopic signature of nitrate in subpolar and polar water surface waters is controlled by the degree of nitrate utilization (Schubert et al., 2001). Relative utilization affects the $\delta^{15}N$ of sinking particles; when nitrate is abundant (low relative utilization, and discrimination by phytoplankton against heavy nitrate) in the mixed layer, exported particulate organic matter is isotopically light. But when stratification inhibits mixing of "new" nitrate from below into the photic zone, relative nitrate utilization is higher and the exported particle flux is isotopically heavier (higher $\delta^{15}N$). In the subpolar North Atlantic the degree of relative utilization is controlled by the thickness of the mixed-layer and thus by the stratification of the upper water column (Straub et al., 2013b). A well-stratified upper water column (thus, thin mixed layer) in spring and summer will limit the nitrate flux to the photic zone during growth season, resulting in high utilization and high $\delta^{15}N$ of exported organic material, while a mixed-layer that extends below the photic zone during the same period will induce light limitation at depth and decrease nitrate utilization, leading to a lower aggregated $\delta^{15}N$ in sinking particles (Fig. 3). Coherent to the light limitation, a thick cold and fresh mixed-layer might hypothetically reduce the growth season by delaying the spring ice breakup, which could reinforce the decrease in nitrogen utilization. The $\delta^{15}N$ of sinking particles can also be affected by an increase in nitrate supply, which, taken alone, would tend to lower the nitrate utilization. However, since nitrate is fully utilized by the end of the summer (Jeansson et al., 2015), increased input would support an increase in primary productivity, which would have the opposite effect on utilization (Galbraith et al., 2008) and thus the final effect on the nitrate utilization would be minimal. Despite the influence of nitrate input and productivity being probably minimal on the nitrate utilization, we used the abundance of polar foraminiferal specie *Neogloboquadrina pachyderma* sinistral (*NP*s) to strengthen our interpretation of the mixed-layer depth. This species has been widely used as an inverse-indicator of Atlantic water in the Nordic Seas (e.g., Bauch et al., 1999). The abundance of *NP*s thus provides us with a qualitative estimate of the proportion of Polar and Atlantic water present between 0 and 100m, which is the preferred depth habitat for this species (Pados and Spielhagen, 2014). This implies that under a thin summer mixed-layer the *NP*s abundance will be diminished compared to a summer characterized by a thicker mixed-layer (Fig 3). Thus concurrent low $\delta^{15}N$ values and high *NP*s numbers are interpreted as indicating a thick-mixed layer originating from fresh and cold water inputs that limit nutrient utilization (Fig 3). This approach allows temporal variations in nitrate utilization to be traced, and it therefore defines the mixed-layer depth and the past surface and subsurface vertical water mass structure of the Nordic Sea.

2. **Materials and Methods**

We used a well-dated sediment core from the central Nordic Seas (PS1243, 69°22N/6°32W, 2710m water depth) to investigate surface water stratification over three specific intervals. The core chronostratigraphy was established based on the AMS-radiocarbon dated upper section of the core and cross correlation of benthic $\delta^{18}O$, carbonate content and sediment reflectance (Bauch et al., 2001). The three specific intervals of interest cover the deglacial terminal phases (Termination I, II, and V), the complete interglacials of the Holocene, Eemian, and Holsteinian, as well as the ensuing post-interglacial periods of glacial inception. This site registers the intrusion of warm, saline Atlantic Water northward to the Polar North Atlantic and ultimately the Arctic Ocean (Fig. 4). Interglacial intervals are clearly identifiable within the core by an absence of iceberg-rafted debris (IRD), depleted planktic foraminiferal $\delta^{18}O$ and lowered *Neogloboquadrina pachyderma* sinistral (*NP*s) abundance (Fig. 5). Records of $\delta^{15}N$, *NP*s and IRD covering those three intervals are scarce in this region mainly due to the low sedimentary nitrogen content. Between 300 and 500 foraminifers were counted in the >125µm fraction of washed sediment. Ice-rafted-debris was counted in the size fraction >250µm. Carbonate content and mass accumulation rate of carbonate are presented as they are considered proxy of productivity in this region (Bauch et al., 2001). For each oxygen isotope analysis about 28 similar-sized specimens of the polar planktic foraminifer *Neogloboquadrina pachyderma* sinistral were taken from the 125-250 µm size fraction. Isotope measurements were performed at the Leibniz-Laboratory (Kiel University) on a Finnigan MAT 251 mass spectrometer combined with an automated carbonate preparation device. The analytical precision of the MAT 251 system was ±0.08 ‰ for $\delta^{18}O$ based on multiple measurements of an internal standard. Most of the $\delta^{18}O$ data presented in this paper have been previously published, but the bulk-sediment nitrogen isotopic data are new and are used here to assess, for the first time, the thickness of the mixed-layer.

2.1. Nitrogen Isotope measurement

The bulk $\delta^{15}N$ measurements were performed at the Department of Earth and Ocean Sciences at the University of British Columbia. The N isotopic composition was analyzed using a Carlo-Erba CHN analyzer coupled to a VG prism mass spectrometer. The $\delta^{15}N$ values are reported relative to air N_2 with an analytical precision of ±0.2‰ based on multiple measurements of an acetanilide internal standard.

3. Results

3.1. Bulk $\delta^{15}N$

The $\delta^{15}N_{bulk}$ record shows the same pattern for each of the three termination-interglacial transition: increases of 1 to 2‰ before the end of each termination (Fig 5), which translate to increases in nutrient utilization of 13-19% (TI to MIS 1), 20-26% (TII to MIS 5e) and 16-20% (TV to MIS 11). These estimates assume an classic isotope effect of 5 to 8 ‰ for nitrate assimilation (DiFiore et al., 2006). However, the shapes of the increases differ slightly in each period; the $\delta^{15}N_{bulk}$ peak is already reached before the end of TI while it comes in the early or middle part of the interglacials during MIS 11 and 5e. While all interglacials are marked by the same pattern of enriched $\delta^{15}N$ compared to their respective terminations, the average value is significantly different for each (2σ, $P < 0.0001$, Kruskal-Wallis test performed with Prims6 software); the Holocene is the highest (~6.4 ‰, n = 23) while the Eemian (~5.2 ‰ n = 27) and the Holsteinian (~4.8 ‰, n = 39) are lower (Fig. 5). These translate to lower nitrate utilization rates of 13-19% (MIS 5e) and 17-25% (MIS 11) compared to the Holocene.

3.2. Potential alteration of $\delta^{15}N$

Most of the $\delta^{15}N_{bulk}$ values from the interglacial periods (Fig. 6) reflect the typical geochemical composition of marine algae (Meyers, 1997) , assuming a $\delta^{15}N > 4.5$‰ for the regional oceanic nitrate pool (Sigman et al., 2009). That suggests a very low content of allochthonous (terrestrial) carbon-rich organic matter in the majority of the samples (Fig 6a), an observation consistent with C/N weight ratios that are <12 (Fig. 6a). Moreover, the relationship between the total organic carbon and total nitrogen contents (Fig 6b) yields a very small intercept (0.005), suggesting that the fraction of inorganic nitrogen in our samples— from for example, input of ammonium adsorbed into illite—is trivially small. Thus, while we can predict from (Fig 6a) that the terrestrial organic component is minimal for almost all samples, we also note that if diagenesis had significantly altered the nitrogen-bearing compounds in the deposits, there should be a relationship between the $\delta^{15}N_{bulk}$ and the C/N ratio and total nitrogen. No such relationship is observed in the data (Fig 6a) or only weakly (6c). Futhermore, the C/N ratios of the three interglacial periods are very similar ($P = 0.8189$; Kruskal-Wallis test performed with Prims6 software), which argues against there being any major differences in either the source of nitrogen or alteration of nitrogen-bearing compounds between the interglacials. We therefore conclude that the $\delta^{15}N_{bulk}$ values primarily reflect the $\delta^{15}N$ of exported organic matter, assuming a constant diagenetic alteration through time (Robinson et al., 2012).

4. Discussion

4.1. $\delta^{15}N_{bulk}$ variations from terminations to interglacial stages

The $\delta^{15}N$ of sinking organic matter is enriched during each interglacial relative to the preceding termination, being at least 1‰ higher during the Holocene compared to Termination 1, and ~2 ‰ higher between Termination II / MIS 5e and Termination V / MIS 11 transitions. Similar enrichments in $\delta^{15}N$ between the Last Glacial Maximum and the Holocene were previously observed in both the subpolar North Atlantic—using organic-bound $\delta^{15}N$ of planktic foraminifera (Straub et al., 2013b)—and in the central Arctic using $\delta^{15}N_{bulk}$ (Schubert et al., 2001). In both regions, the increase in $\delta^{15}N$ during the Holocene was attributed to more complete nitrate consumption due to a shallower summer mixed-layer, thus enhanced stratification.

While nitrate utilization is the most probable factor controlling $\delta^{15}N$ in the polar region, another process could have induced changes: a varying rate of N fixation between glacial and interglacial times could have altered the nitrate $\delta^{15}N$ of the surface nitrate pool. We can discount this potential influence as it has already been demonstrated that potential changes in N fixation are of the opposite sign required to explain observed variations in $\delta^{15}N$ during glacial-to-interglacial transitions (Ren et al., 2009; Straub et al., 2013a, 2013b). Moreover, we can also discount enhanced input of nitrate to surface waters during glacials as that would be associated with increased biogenic material fluxes during glacial episodes, which are not observed (Fig. 7), assuming that nitrate is the limiting during glacials as well.

Thus, we interpret the increase in $\delta^{15}N_{bulk}$ during glacial-to-interglacial transitions as an indicator of a higher relative consumption of nitrate during the interglacial phase compared to the termination. This relationship holds for all three termination-to-interglacial intervals explored here (Fig. 7), and it highlights, for the first time, an apparent increase in nutrient utilization during each interglacial, most likely resulting from a thinner, well-illuminated summer mixed-layer. This is in accordance with results from the organic-bound $\delta^{15}N$ of planktic foraminifera and further illustrates that $\delta^{15}N_{bulk}$ can record upper-ocean stratification under certain conditions.

4.2. Inter-interglacial $\delta^{15}N_{bulk}$ variations

Within interglacials, we interpret differences in $\delta^{15}N_{bulk}$ as reflecting changes in the relative nutrient utilization linked to different surface stratification conditions. Biogenic carbonate mass accumulation rates suggest that MIS 11 and MIS 5e were characterized by lower productivity; lower average $\delta^{15}N_{bulk}$ assays during these times therefore do not reflect an enhanced supply of nitrate, which would have supported higher, not lower, productivity. The high mean $\delta^{15}N_{bulk}$ value in the Holocene thus implies that during that epoch a more stratified, more Atlantic-influenced oceanic structure with a very thin summer mixed-layer prevailed, conditions similar to those today (Fig 2). This hypothesis is supported by the decreasing interglacial dominance in our records of the polar foraminiferal species *NP*s (95 % average during MIS 11, 64 % during MIS 5e and only 44 % during the Holocene; Fig. 7). At face value the high percentages of *NP*s indicate that the water depth at which *NP*s usually resides was bathed in cold and relatively fresh polar water during the Holsteinian while higher proportions of warm, saltier Atlantic water were present at the same depth levels during the Eemian and, even more, during the Holocene.

Polar waters should be characterized by lighter oxygen isotope values but water temperature and ice-sheet volume also influence the *NP*s oxygen isotope signature and prevent a straightforward interpretation of the $\delta^{18}O$ record. While our $\delta^{18}O$ record is similar to the global $\delta^{18}O$ stack and thus cannot be used to estimate with confidence the relative importance of freshwater release and temperature regionally (Fig 5), the shapes of the curves suggest a quite different timeline of events for each interglacial (Fig 8). For example, the inference that a deeper cold mixed-layer prevailed during MIS 11 and MIS 5e (Fig. 7) could be explained by a prolonged meltwater release from the surrounding ice-sheets that freshened the surface layer and forced the saltier Atlantic core to flow at a greater water depth (Bauch, 2013; Van Nieuwenhove et al., 2011). This hypothesis is supported by the presence of IRD well into MIS 11 and, to a lesser extent, MIS 5e (Fig 7), and it is coherent with the hypothesized presence of an extremely large ice-sheet in MIS 12 (Rohling et al., 1998), that would have required a much longer time to completely melt. A change in the $\delta^{15}N$ of the source nitrate could be proposed to justify the lower $\delta^{15}N_{bulk}$ found for MIS 5e and MIS 11 but this would not explain the higher abundance of *NP*s during those two intervals, both of which are typically reported as being warmer than the Holocene climate (Melles et al., 2012). The collective evidence therefore supports our hypothesis that the abundance of *NP*s does not always relate directly to a more intense Atlantic Water inflow to the Nordic Seas but can be interpreted as reflecting the summer thickness of the cold mixed-layer and consequent changes in the depth of inflowing Atlantic Water. This hypothesis reconciles records suggesting a globally warmer-than-Holocene world with less ice over the high latitudes during MIS 5e and 11 (Bauch and Kandiano, 2007; de Vernal and Hillaire-Marcel, 2008; Melles et al., 2012; Otto-Bliesner et al., 2006; Vázquez Riveiros et al., 2013), with records indicating cooler SST in the Nordic seas and a low-saline halocline over the Vøring Plateau during the same intervals (Bauch et al., 2012; Kandiano et al., 2012; Van Nieuwenhove and Bauch, 2008) (Fig. 1). The deeper penetration depth of the Atlantic Water can also explain previously observed isotopically light benthic $\delta^{18}O$ spikes or bottom water temperature variations during deglacial periods (Bauch et al., 2012, 2000; Rasmussen et al., 2003) as the Atlantic inflow might have been, at least partially, replaced by a very thick cold and fresh mixed layer, even at depth.

4.3. Intra-interglacial $\delta^{15}N_{bulk}$ variation

In addition to differences in the average absolute value, each interglacial is unique in terms of $\delta^{15}N_{bulk}$ variability. This implies short-lived episodes of relative nutrient utilization and water mass structure variability within the Nordic Seas during every warm interval. During Termination V and early MIS 11, high $\delta^{15}N_{bulk}$ indicates that the upper layer of the Nordic Seas was dominated by a thick summer mixed-layer, which originated from the deglaciation following the extreme glacial conditions of MIS 12 (Rohling et al., 1998). The massively thick mixed-layer could have induced strong light limitation and low relative nutrient utilization initially, and later restrained advection of nutrients to the upper water, which contributed to the observed high $\delta^{15}N_{bulk}$ toward the end of Termination V and its increase during the early phase of MIS 11 (Fig. 5). Coming off an intense glacial and a

Termination marked by an exceptionally long Heinrich-event-like stadial with a prolonged collapse of the AMOC (Vázquez Riveiros et al., 2013), the early $\delta^{15}N_{bulk}$ peak and its subsequent high variability within the MIS 11 suggests a long period of surface water structure instability in the Nordic Seas during the entire interglacial (Fig. 7). Insolation changes were weak during the transition between MIS 12 and 11 and the observed variability in $\delta^{15}N_{bulk}$ therefore highlights the sensitivity of upper ocean stratification in the Nordic Seas to other, non solar-related parameters such as input of meltwater and surface ocean current reorganization.

Termination II is also marked by low relative nitrate utilization due to the presence of the thick layer of meltwater caused by the deglaciation that could have induced light limitation during summer time. A subsequent and progressive increase in nitrate utilization abruptly stopped during the early Eemian as input of meltwater waned and the summer mixed layer shoaled. At this time, relative nitrate utilization suddenly decreased (Fig. 7). This minimum is synchronous with the minimum abundance of the subpolar planktic foraminifer *Globogerinita uvula* (Fig 7; Bauch et al., 2012) indicating the coldest conditions of the whole interglacial. The intense cooling can be linked to a southward shift of the polar front, which would have delivered fresh, cold water and created a thick, cold mixed-layer at the surface, thus limiting nitrate utilization. Finally, the increase in nitrate utilization seen in the early to Late Eemian data is interpreted to represent a transition from initially deeper stratification caused by meltwater originating from the early Eemian deglacial to a more Atlantic-influenced circulation mode (Fig. 7) in the Nordic seas (Bauch and Erlenkeuser, 2008; Van Nieuwenhove and Bauch, 2008). Toward the glacial inception in the later part of the Eemian, the decrease in $\delta^{15}N_{bulk}$ to 5‰ reflects the progressive deepening of the summer mixed layer.

Like the previous terminations, a thick residual mixed-layer derived from the glacial period (Simstich et al., 2012) was present at the end of termination I. This quickly thinned during the very early stage of the Holocene indicating a higher influence of Atlantic water at our site (Fig. 7). The plateau of high relative nitrate utilization persisted until the mid-Holocene where the sudden drop in $\delta^{15}N_{bulk}$ is associated with a decrease in proportion of sub-polar foraminifera, indicating a thicker mixed-layer and a deeper Atlantic water inflow (Fig. 7). This sudden deepening of the mixed-layer might be linked to a sudden meltwater input or a southern shift of the East Greenland Current and it could be related to the so-called 8.2 ka event (Alley et al., 1997). During the Holocene thermal optimum relative nitrate utilization is high and is accompanied by a strong presence of Atlantic-derived species (Fig. 7), collectively indicating shoaling of the mixed-layer.

5. Conclusions

Our results support the hypothesis that nitrate utilization in the polar North Atlantic was lower during the last termination and subsequently increased at the beginning of the Holocene (Straub et al., 2013b). By extending the record to two older termination-interglacial periods within the Nordic Seas we have defined a similar pattern of steep increase in nitrate utilization. These results together imply a quick thinning of the summer mixed-layer at the beginning of interglacial periods, the likely cause being the accumulation of meltwater produced in the region during deglaciation. The potentially larger volume of meltwater discharged into the Nordic Seas well into MIS 11 explains why the summer mixed-layer thinning seems to have been relatively slowest during this period compared to the others. This is in agreement with our reconstructed summer mixed-layer depth during MIS 11, the thickest of the three interglacials studied here, which is consistent with the notion of the melting of an extremely large ice-sheet during Termination V (Rohling et al., 1998). The presence of a rather thick summer mixed-layer, and consequently a deeper Atlantic Water inflow, reconciles indications of a warmer general climate with the cooler SST in the Nordic

Seas during older interglacials (MIS 11 & 5e), compared to the Holocene (Fig 1). Moreover, it highlights that a thick summer mixed layer originating from the massive amount of freshwater water input that originated from the preceding glacial terminations did not inhibit the AMOC, since there is considerable evidence that AMOC was active throughout those interglacials (Bohm et al., 2015; Rodríguez-Tovar et al., 2015). Thus, the timing and location of important meltwater discharge events are probably the crucial factors in determining the effect of freshwater addition on the formation of deep-water. This new information needs to be considered when assessing the potential impact of the predicted demise of Greenland ice-sheet on regional oceanography.

Acknowledgments:

Data reported in the paper are available on Pangea (https://doi.pangaea.de/10.1594/PANGAEA.805366;https://doi.pangaea.de/10.1594/PANGAEA.780099). H.A.B., T.F.P. and B.T. developed the concept and designed the study. H.A.B. carried out samples preparation and contributed to the analysis. TFP thanks Kathy Gordon for conducting the nitrogen isotope measurements. B.T. interpreted the results and wrote the manuscript in collaboration with H.A.B. and T.F.P. Figure 1, 2 and 4 were created using Ocean Data View (Schlitzer, 2002). We are thankful to the editor H. Stoll and three anonymous reviewers for their comments and suggestions that improved the manuscript.

References

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability: A prominent, widespread event 8200 yr ago. Geology 25, 483.

Bauch, H.A., 2013. Interglacial climates and the Atlantic meridional overturning circulation:

is there an Arctic controversy? Quat. Sci. Rev. 63, 1–22.

Bauch, H.A., Erlenkeuser, H., 2008. A critical climatic evaluation of last interglacial (MIS 5e) records from the Norwegian Sea. Polar Res. 27, 135–151.

Bauch, H.A., Erlenkeuser, H., Fahl, K., Spielhagen, R.F., Weinelt, M.S., Andruleit, H., Henrich, R., 1999. Evidence for a steeper Eemian than Holocene sea surface temperature gradient between Arctic and sub-Arctic regions. Palaeogeogr. Palaeoclimatol. Palaeoecol. 145, 95–117.

Bauch, H.A., Erlenkeuser, H., Helmke, J.P., Struck, U., 2000. A paleoclimatic evaluation of marine oxygen isotope stage 11 in the high-northern Atlantic (Nordic seas). Glob. Planet. Change 24, 27–39.

Bauch, H.A., Erlenkeuser, H., Spielhagen, R.F., Struck, U., Matthiessen, J., Thiede, J., Heinemeier, J., 2001. A multiproxy reconstruction of the evolution of deep and surface waters in the subarctic Nordic seas over the last 30,000 yr. Quat. Sci. Rev. 20, 659–678.

Bauch, H.A., Kandiano, E.S., 2007. Evidence for early warming and cooling in North Atlantic surface waters during the last interglacial. Paleoceanography 22, PA1201.

Bauch, H.A., Kandiano, E.S., Helmke, J.P., 2012. Contrasting ocean changes between the subpolar and polar North Atlantic during the past 135 ka. Geophys. Res. Lett. 39.

Bauch, H.A., Struck, U., Thiede, J., 2001. Planktic and benthic foraminifera as indicators for past ocean changes in surface and deep waters of the Nordic seas. North. North Atl. a Chang. Environ.

Berger, A., Loutre, M.F., 1991. Insolation values for the climate of the last 10 million years. Quat. Sci. Rev. 10, 297–317.

Bohm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M.B., Deininger, M., 2015. Strong and deep Atlantic meridional overturning circulation during the last glacial cycle. Nature 517, 73–76.

CAPE Last Interglacial Project Members, 2006. Last Interglacial Arctic warmth confirms polar amplification of climate change. Quat. Sci. Rev. 25, 1383–1400.

Clark, P.U., Pisias, N.G., Stocker, T.F., Weaver, A.J., 2002. The role of the thermohaline circulation in abrupt climate change. Nature 415, 863–9.

de Vernal, A., Hillaire-Marcel, C., 2008. Natural variability of Greenland climate, vegetation, and ice volume during the past million years. Science 320, 1622–5.

Dickson, R., Rudels, B., Dye, S., Karcher, M., Meincke, J., Yashayaev, I., 2007. Current estimates of freshwater flux through Arctic and subarctic seas. Prog. Oceanogr. 73, 210–230.

DiFiore, P.J., Sigman, D.M., Trull, T.W., Lourey, M.J., Karsh, K., Cane, G., Ho, R., 2006. Nitrogen isotope constraints on subantarctic biogeochemistry. J. Geophys. Res. 111, C08016.

EPICA community members, 2004. Eight glacial cycles from an Antarctic ice core. Nature 429, 623–8.

Fronval, T., Jansen, E., 1996. Rapid changes in ocean circulation and heat flux in the Nordic seas during the last interglacial period. Nature 383, 806–810.

Galaasen, E.V., Ninnemann, U.S., Irvalı, N., Kleiven, H.K.F., Rosenthal, Y., Kissel, C., Hodell, D.A., 2014. Rapid reductions in North Atlantic Deep Water during the peak of the last interglacial period. Science 343, 1129–32.

Galbraith, E.D., Sigman, D.M., Robinson, R.S., Pedersen, T.F., 2008. Nitrogen in Past Marine Environments.

Glessmer, M.S., Eldevik, T., Våge, K., Øie Nilsen, J.E., Behrens, E., 2014. Atlantic origin of observed and modelled freshwater anomalies in the Nordic Seas. Nat. Geosci. 7, 801–805.

Hansen, B., Østerhus, S., 2000. North Atlantic-Nordic Seas exchanges. Prog. Oceanogr.

Isachsen, P.E., Mauritzen, C., Svendsen, H., 2007. Dense water formation in the Nordic Seas diagnosed from sea surface buoyancy fluxes. Deep Sea Res. Part I Oceanogr. Res. Pap. 54, 22–41.

Jeansson, E., Bellerby, R.G.J., Skjelvan, I., Frigstad, H., Ólafsdóttir, S.R., Olafsson, J., 2015. Fluxes of carbon and nutrients to the Iceland Sea surface layer and inferred primary productivity and stoichiometry. Biogeosciences 12, 875–885.

Kandiano, E.S., Bauch, H.A., Fahl, K., Helmke, J.P., Röhl, U., Pérez-Folgado, M., Cacho, I., 2012. The meridional temperature gradient in the eastern North Atlantic during MIS 11 and its link to the ocean–atmosphere system. Palaeogeogr. Palaeoclimatol. Palaeoecol. 333–334, 24–39.

Kaspar, F., 2005. A model-data comparison of European temperatures in the Eemian interglacial. Geophys. Res. Lett. 32, L11703.

Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G.J., Bojariu, R., Camilloni, I., Doblas-Reyes, F.J., Fiore, A.M., Kimoto, M., Meehl, G.A., Prather, M., Sarr, A., Schär, C., Sutton, R., Van Oldenborgh, G.J., Vecchi, G., Wang, H.J., 2013. Near-term Climate Change: Projections and Predictability. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 953–1028.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ 18 O records. Paleoceanography 20, 1–17.

Lohmann, K., Jungclaus, J.H., Matei, D., Mignot, J., Menary, M., Langehaug, H.R., Ba, J., Gao, Y., Otterå, O.H., Park, W., Lorenz, S., 2014. The role of subpolar deep water formation and Nordic Seas overflows in simulated multidecadal variability of the Atlantic meridional overturning circulation. Ocean Sci. 10, 227–241.

Lynch-Stieglitz, J., Adkins, J.F., Curry, W.B., Dokken, T., Hall, I.R., Herguera, J.C., Hirschi, J.J.-M., Ivanova, E. V, Kissel, C., Marchal, O., Marchitto, T.M., McCave, I.N., McManus, J.F., Mulitza, S., Ninnemann, U., Peeters, F., Yu, E.-F., Zahn, R., 2007. Atlantic meridional overturning circulation during the Last Glacial Maximum. Science 316, 66–9.

Mauritzen, C., 1996. Production of dense overflow waters feeding the North Atlantic across the Greenland-Scotland Ridge. Part 1: Evidence for a revised circulation scheme. Deep Sea Res. Part I Oceanogr. Res. Pap. 43, 769–806.

Melles, M., Brigham-Grette, J., Minyuk, P.S., Nowaczyk, N.R., Wennrich, V., DeConto, R.M., Anderson, P.M., Andreev, A.A., Coletti, A., Cook, T.L., Haltia-Hovi, E., Kukkonen, M., Lozhkin, A. V, Rosén, P., Tarasov, P., Vogel, H., Wagner, B., 2012. 2.8 million years of Arctic climate change from Lake El'gygytgyn, NE Russia. Science 337, 315–20.

Meyers, P.A., 1997. Organic geochemical proxies of paleoceanographic, paleolimnologic, and paleoclimatic processes. Org. Geochem. 27, 213–250.

Otto-Bliesner, B.L., Marshall, S.J., Overpeck, J.T., Miller, G.H., Hu, A., 2006. Simulating Arctic climate warmth and icefield retreat in the last interglaciation. Science 311, 1751–3.

Pados, T., Spielhagen, R.F., 2014. Species distribution and depth habitat of recent planktic foraminifera in Fram Strait, Arctic Ocean. Polar Res. 33.

Peterson, B.J., McClelland, J., Curry, R., Holmes, R.M., Walsh, J.E., Aagaard, K., 2006. Trajectory Shifts in the Arctic and Subarctic Freshwater Cycle. Sci. 313, 1061–1066.

Rahmstorf, S., 2002. Ocean circulation and climate during the past 120,000 years. Nature 419, 207–14.

Rahmstorf, S., Box, J.E., Feulner, G., Mann, M.E., Robinson, A., Rutherford, S., Schaffernicht, E.J., 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nat. Clim. Chang. 5, 475–480.

Rasmussen, T.L., Thomsen, E., Kuijpers, A., Wastegård, S., 2003. Late warming and early cooling of the sea surface in the Nordic seas during MIS 5e (Eemian Interglacial). Quat. Sci. Rev. 22, 809–821.

Ren, H., Sigman, D.M., Meckler, A.N., Plessen, B., Robinson, R.S., Rosenthal, Y., Haug, G.H., 2009. Foraminiferal isotope evidence of reduced nitrogen fixation in the ice age Atlantic Ocean. Science 323, 244–8.

Robinson, R.S., Kienast, M., Luiza Albuquerque, A., Altabet, M., Contreras, S., De Pol Holz, R., Dubois, N., Francois, R., Galbraith, E., Hsu, T.C., Ivanochko, T., Jaccard, S., Kao, S.J., Kiefer, T., Kienast, S., Lehmann, M., Martinez, P., McCarthy, M., M??bius, J., Pedersen, T., Quan, T.M., Ryabenko, E., Schmittner, A., Schneider, R., Schneider-Mor, A., Shigemitsu, M., Sinclair, D., Somes, C., Studer, A., Thunell, R., Yang, J.Y., 2012. A review of nitrogen isotopic alteration in marine sediments. Paleoceanography.

Rodríguez-Tovar, F.J., Dorador, J., Martin-Garcia, G.M., Sierro, F.J., Flores, J.A., Hodell, D.A., 2015. Response of macrobenthic and foraminifer communities to changes in deep-sea environmental conditions from Marine Isotope Stage (MIS) 12 to 11 at the "Shackleton Site." Glob. Planet. Change 133, 176–187.

Rohling, E.J., Fenton, M., Jorissen, F.J., Bertrand, P., Ganssen, G., Caulet, J.P., 1998. Magnitudes of sea-level lowstands of the past 500,000 years. Nature 394, 162–165.

Schlitzer, R., 2002. Interactive analysis and visualization of geoscience data with Ocean Data View. Comput. Geosci. 28, 1211–1218.

Schubert, C.J., Stein, R., Calvert, S.E., 2001. Tracking nutrient and productivity variations over the Last Deglaciation in the Arctic Ocean. Paleoceanography 16, 199–211.

Seidenkrantz, M.S., Kristensen, P., Knudsen, K.L., 1995. Marine evidence for climatic instability during the last interglacial in shelf records from northwest Europe. J. Quat.

Sci.

Sigman, D.M., Difiore, P.J., Hain, M.P., Deutsch, C., Wang, Y., Karl, D.M., Knapp, A.N., Lehmann, M.F., Pantoja, S., 2009. Deep-Sea Research I The dual isotopes of deep nitrate as a constraint on the cycle and budget of oceanic fixed nitrogen. Deep. Res. Part I 56, 1419–1439.

Simstich, J., Lorenz, S.J., Bauch, H.A., 2012. Evaluation of past stratification changes in the Nordic Seas by comparing planktonic foraminiferal δ18O with a solar-forced model. Mar. Micropaleontol. 94–95, 91–96.

Straub, M., Sigman, D.M., Ren, H., Martinez-Garcia, A., Meckler, A.N., Hain, M.P., Haug, G.H., 2013a. Changes in North Atlantic nitrogen fixation controlled by ocean circulation. Nature 501, 200–+.

Straub, M., Tremblay, M.M., Sigman, D.M., Studer, A.S., Ren, H., Toggweiler, J.R., Haug, G.H., 2013b. Nutrient conditions in the subpolar North Atlantic during the last glacial period reconstructed from foraminifera-bound nitrogen isotopes. Paleoceanography 28, 79–90.

Swift, J.H., Aagaard, K., 1981. Seasonal transitions and water mass formation in the Iceland and Greenland seas. Deep Sea Res. Part A. Oceanogr. Res. Pap. 28, 1107–1129.

Van Nieuwenhove, N., Bauch, H.A., 2008. Last interglacial (MIS 5e) surface water conditions at the Vring Plateau (Norwegian Sea), based on dinoflagellate cysts. Polar Res. 27, 175–186.

Van Nieuwenhove, N., Bauch, H.A., Eynaud, F., Kandiano, E., Cortijo, E., Turon, J.-L., 2011. Evidence for delayed poleward expansion of North Atlantic surface waters during the last interglacial (MIS 5e). Quat. Sci. Rev. 30, 934–946.

Vázquez Riveiros, N., Waelbroeck, C., Skinner, L., Duplessy, J.-C., McManus, J.F., Kandiano, E.S., Bauch, H.A., 2013. The “MIS 11 paradox” and ocean circulation: Role of millennial scale events. Earth Planet. Sci. Lett. 371–372, 258–268.

Vellinga, M., Wood, R.A., 2002. Global climatic impacts of a collapse of the atlantic thermohaline circulation. Clim. Change 54, 251–267.

Fig. 1. Heat distribution within the Nordic Seas during interglacials. Comparison of averaged alkenone-derived sea surface temperature reconstruction (Kandiano et al., 2012; Van Nieuwenhove et al., 2011) during MIS 1 and MIS 11 (note that core PS1243 [this study] and MD99-2277 were retrieve from approximately the same site). Color of the dots represent alkenone-derived sea surface temperature. Gray scale represent bathymetry.

Fig 2. Modern seasonal upper-ocean temperature structure and dissolved nitrate content of surface waters and the upper-water column the Nordic Seas with the location of the mixed-layer. The star represents our coring site.

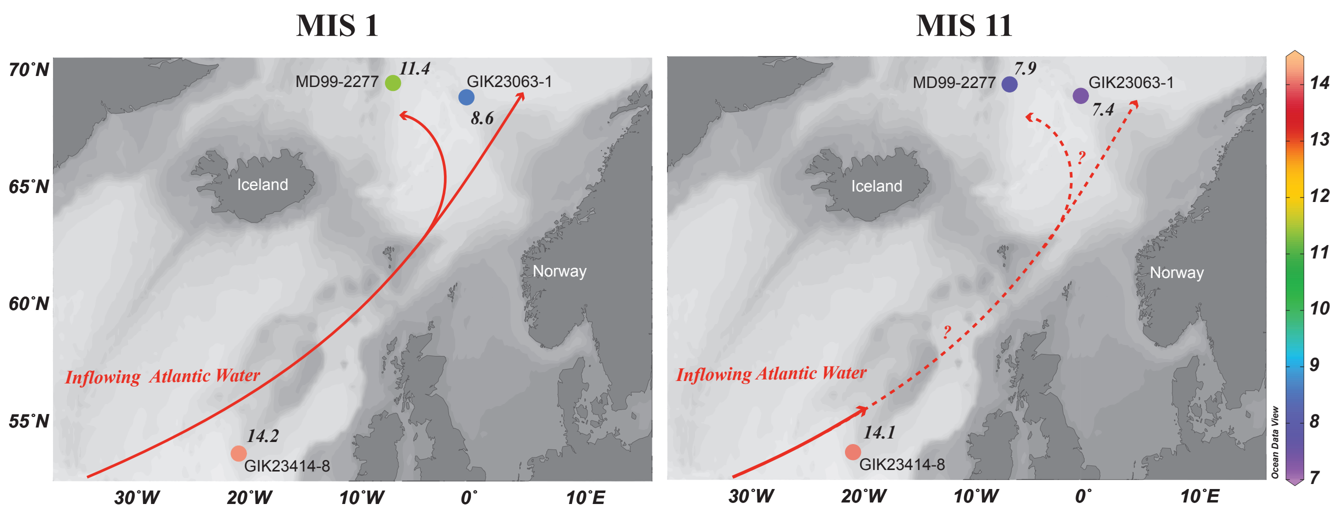
Fig 3. Conceptual relationships among nitrate utilization, $\delta^{15}N$ of exported organic matter and abundance of *Neogloboquadrina pachyderma* sinistral (*NP*s), with respect to the thickness of the summer mixed-layer (light blue).

Fig. 4. Water-mass and temperature distributions as a function of depth in the Nordic Sea region. The core location north of Iceland is shown by the black star.

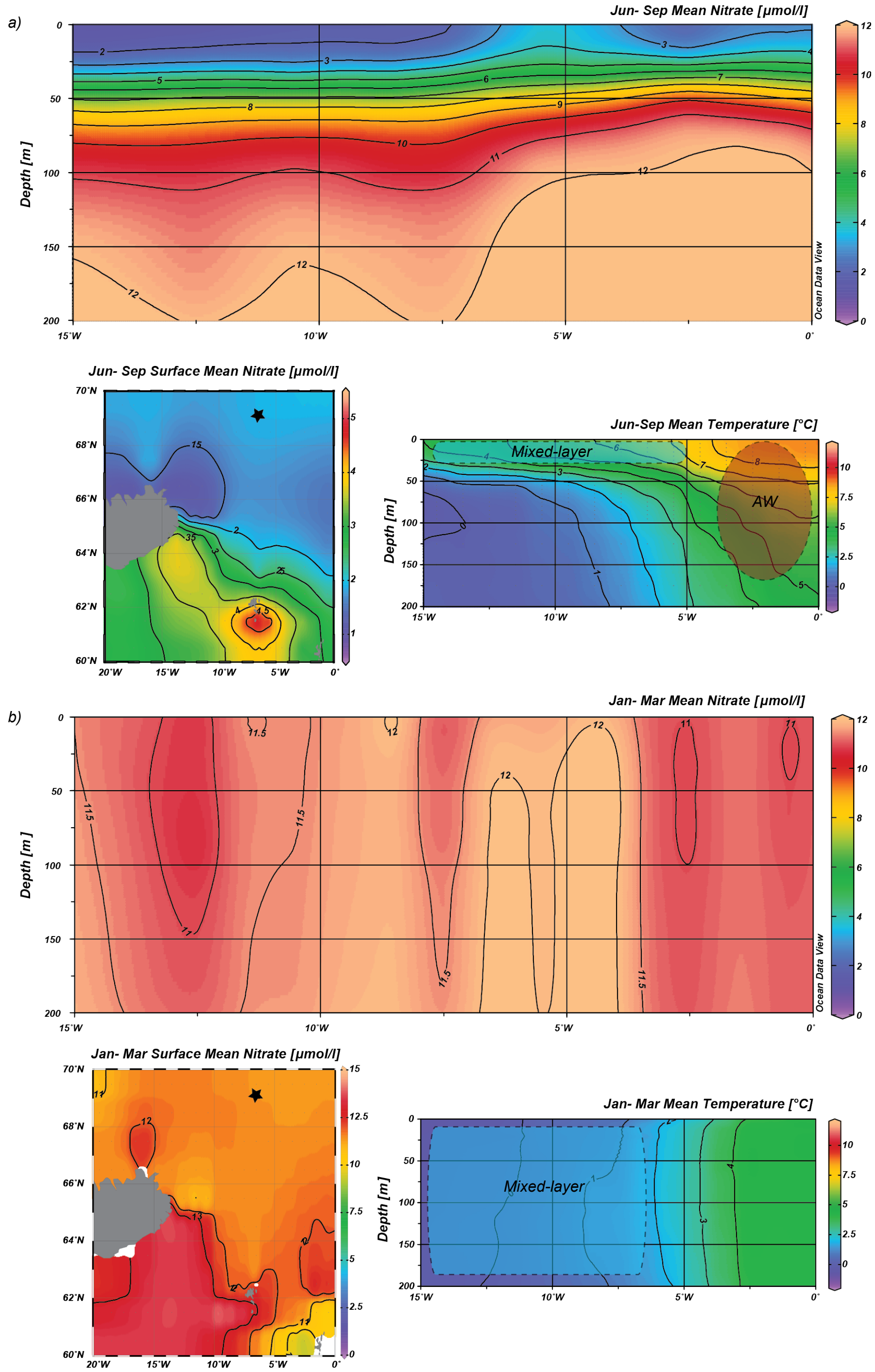
Fig 5. Data from core PS1243 plotted against age and compared to global $\delta^{18}O$ stack in black (Lisiecki and Raymo, 2005). Complete $\delta^{18}O$ *NP*s, $\delta^{15}N_{bulk}$, *NP*s, IRD record and carbonate content and accumulation rate are plotted in function of age (ky) for core PS1243 (top). The pale blue bars represent terminations, while the vertical yellow bars represent interglacial intervals. The bottom panel is a close-up of the radiocarbon dated part of the core.

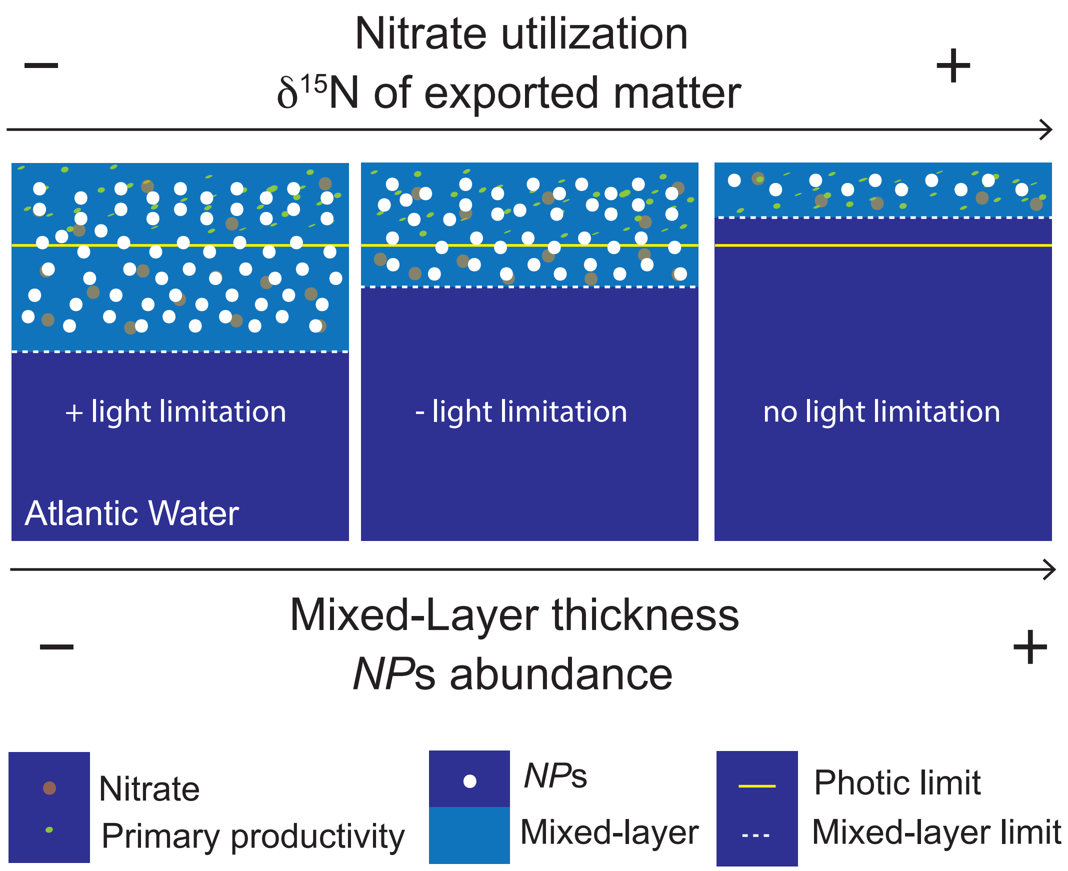
Fig. 6. Relationships among δ^{15}Nbulk, total N and C contents and the C/N weight ratio in the deposits. The colors define specific interglacial stages.

Fig. 7. Stratification during interglacial and termination. Interglacial and termination δ^{18}O *NP*s, $\delta^{15}N_{bulk}$, *NP*s, *G. uvula* and *T. quiqueloba* abundance, carbonate content and accumulation rate and IRD record are plotted in function of age (ky) for core PS1243 (top) along our $\delta^{15}N_{bulk}$ and *NP*s-based qualitative estimate of mixed-layer depth (bottom). Our mixed-layer depth estimate represents only the general trend for each interglacial without the inclusion of short-lived episodes and aims at visualizing the differences in the mixed-layer thickness variability and its impact on our proxies in each period.

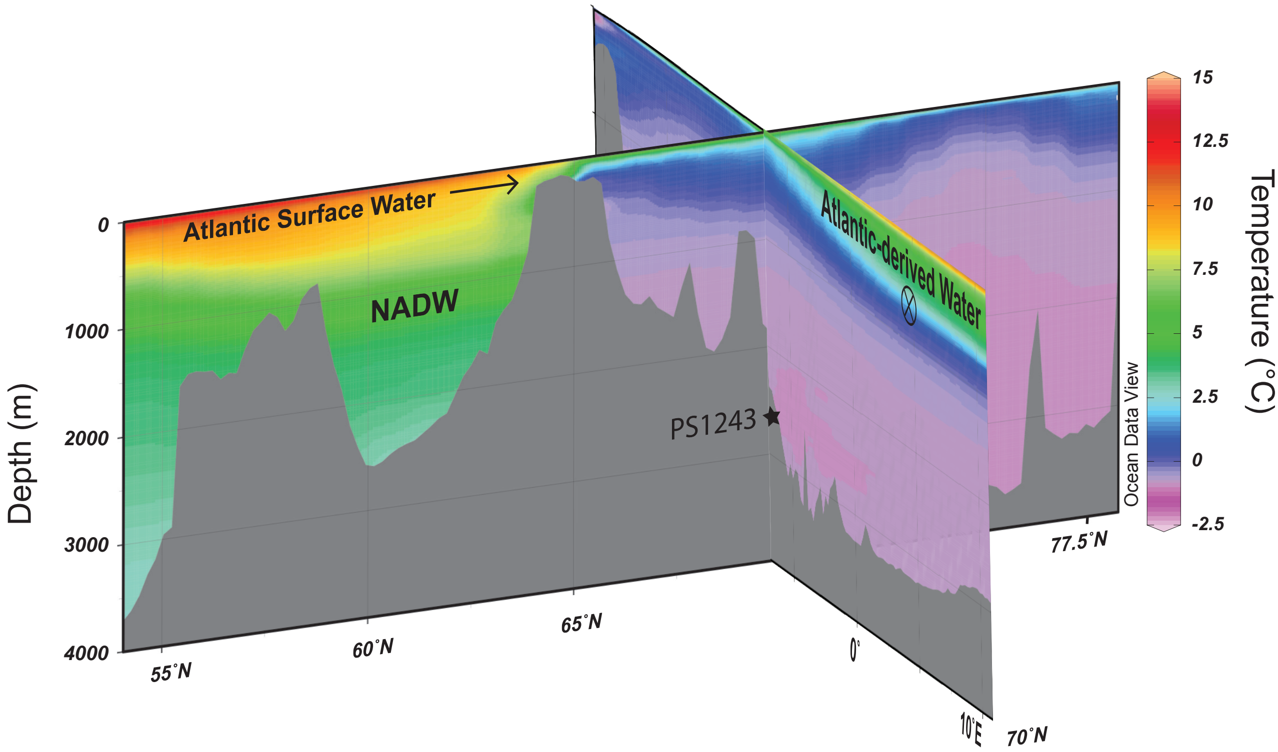


MIS 1
MIS 11
70˚N
65˚N
60˚N
55˚N
30˚W
20˚W
10˚W
0˚
10˚E
MD99-2277
11.4
GIK23063-1
8.6
Iceland
Norway
Inflowing Atlantic Water
14.2
GIK23414-8
7.9
7.4
14.1
?
14
13
12
11
10
9
8
7
Ocean Data View

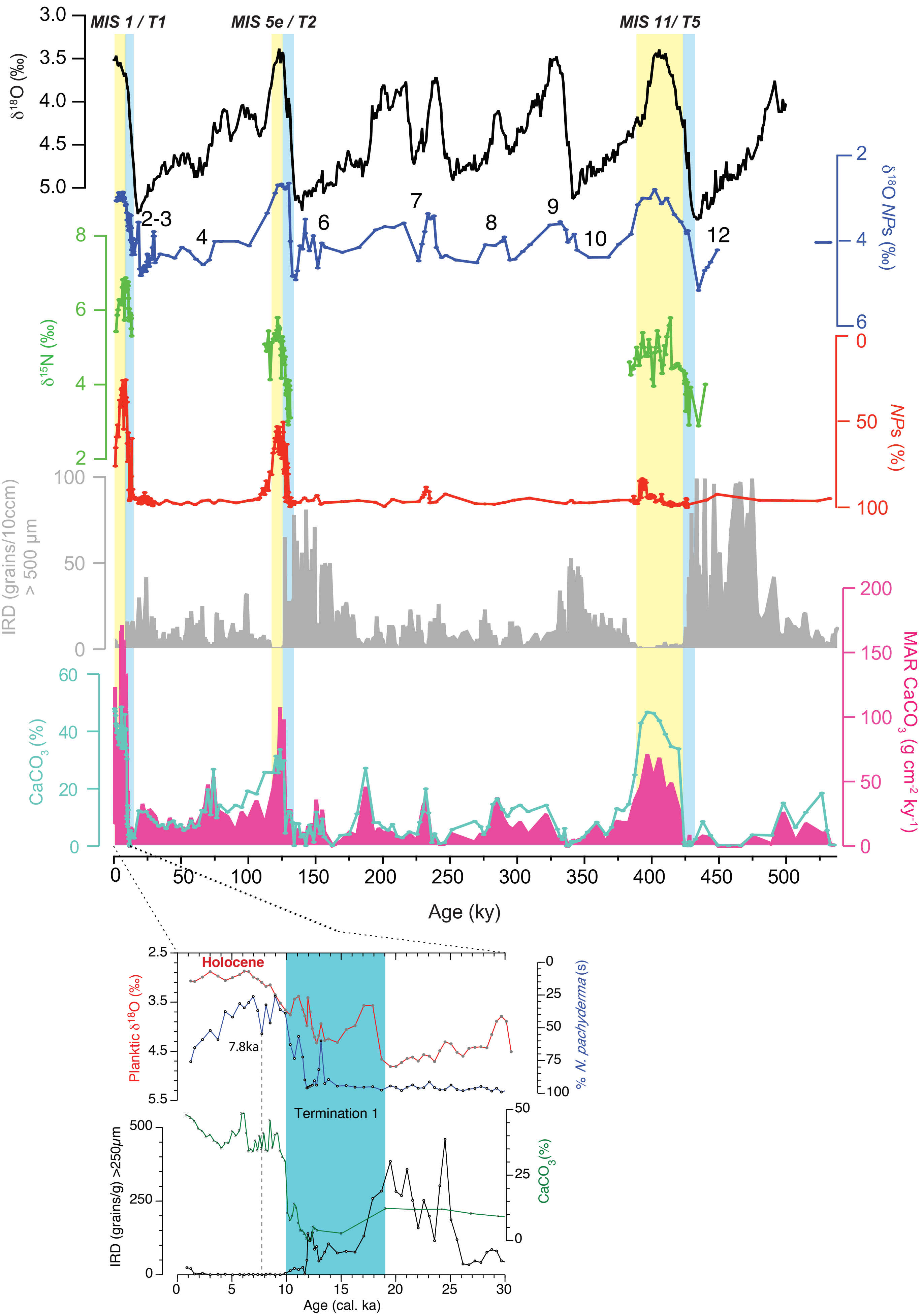

a)
Jun- Sep Mean Nitrate [µmol/l]
Depth [m]
Ocean Data View
15°W
10°W
5°W
0°
Jun- Sep Surface Mean Nitrate [µmol/l]
70°N
68°N
66°N
64°N
62°N
60°N
20°W
Jun-Sep Mean Temperature [°C]
Mixed-layer
AW
b)
Jan- Mar Mean Nitrate [µmol/l]
Jan- Mar Surface Mean Nitrate [µmol/l]
Jan- Mar Mean Temperature [°C]

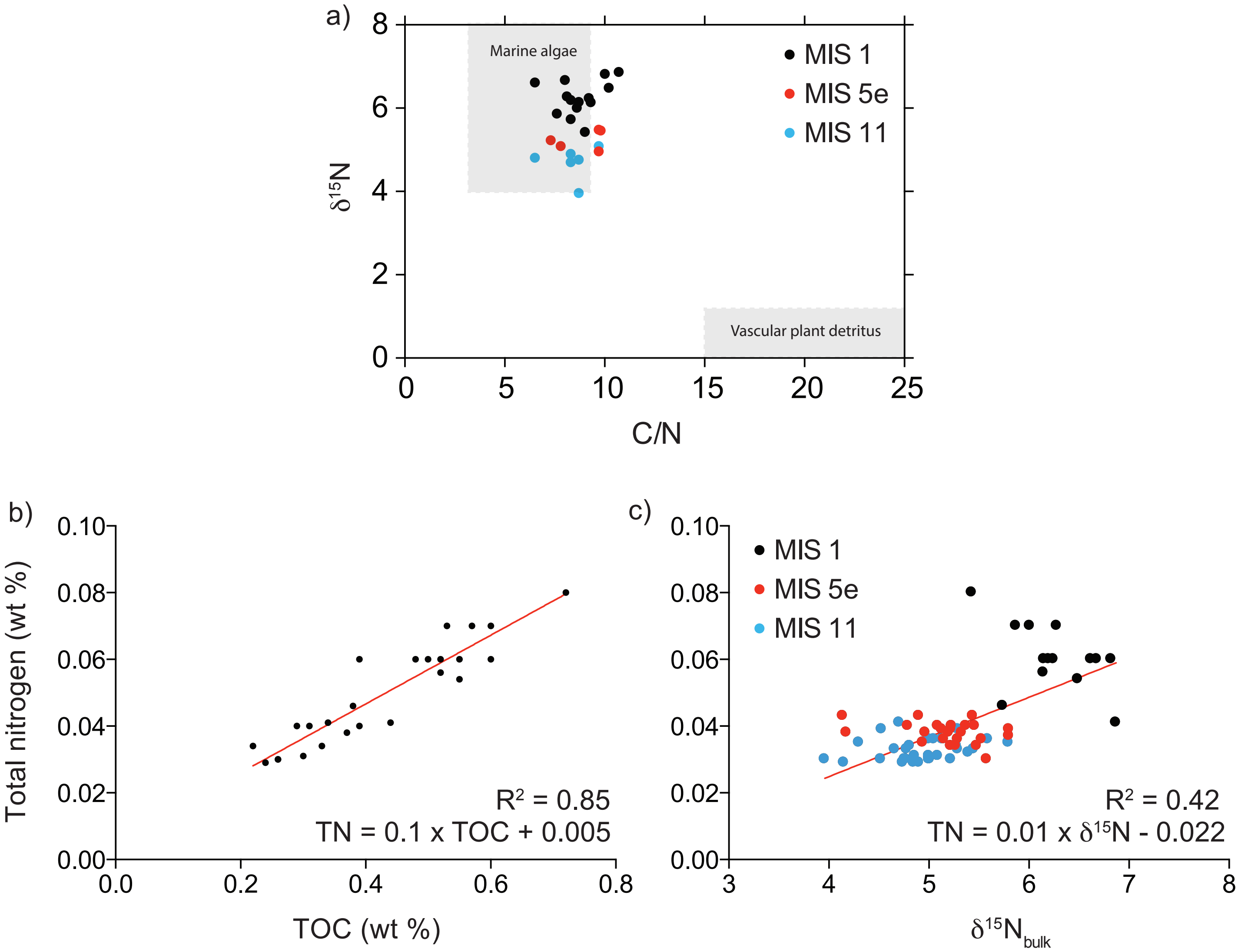


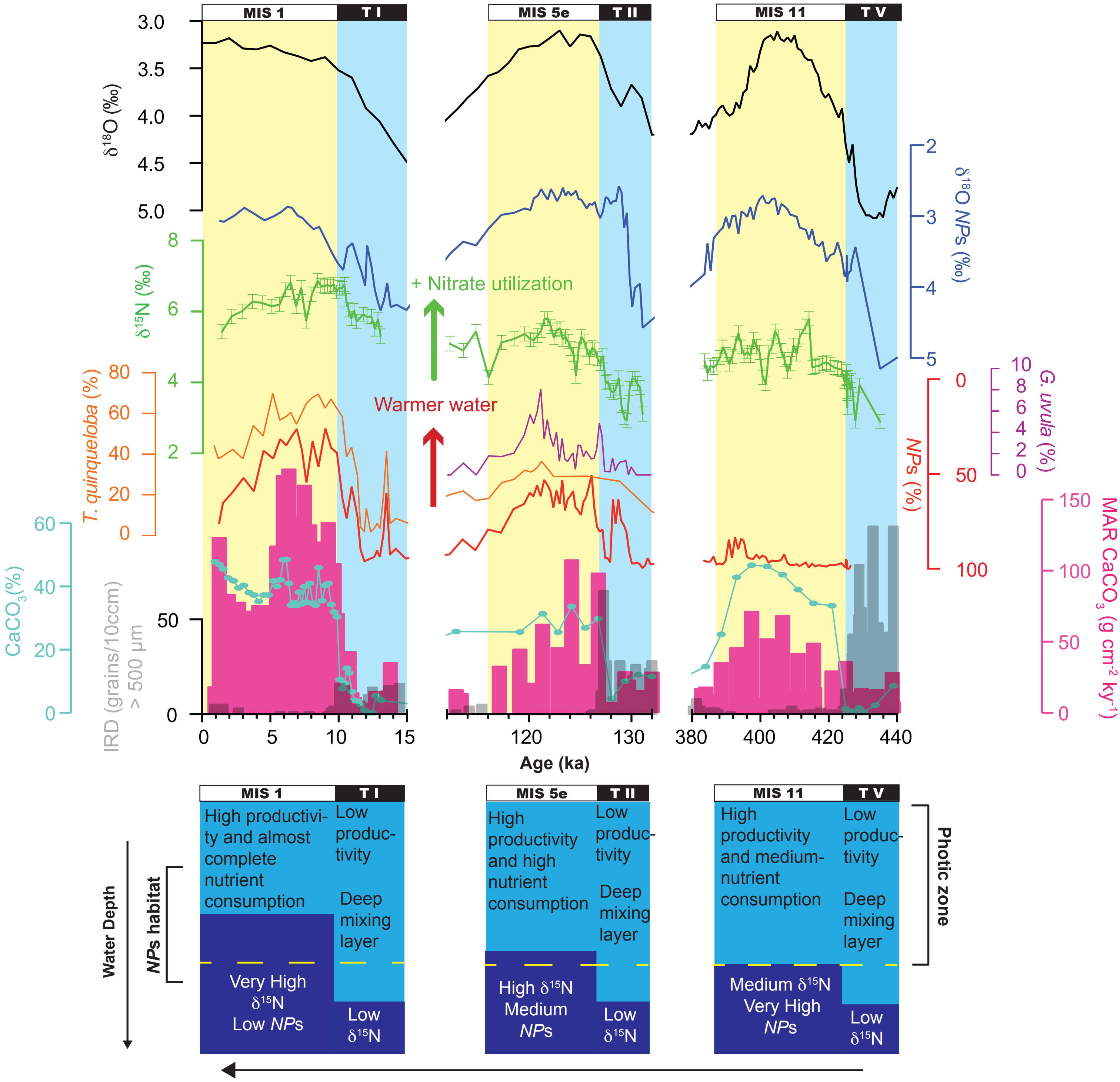
Nitrate utilization
δ15N of exported matter
–
+
+ light limitation
- light limitation
no light limitation
Atlantic Water
Mixed-Layer thickness
*NP*s abundance
–
+
Nitrate
Primary productivity
*NP*s
Mixed-layer
Photic limit
Mixed-layer limit



Atlantic Surface Water
NADW
Atlantic-derived Water
PS1243
Depth (m)
0
1000
2000
3000
4000
55˚N
60˚N
65˚N
0˚
10˚E
70˚N
77.5˚N
Ocean Data View
Temperature (°C)
15
12.5
10
7.5
5
2.5
0
-2.5


MIS 1 / T1
MIS 5e / T2
MIS 11/ T5
δ18O (‰)
δ18O NPs (‰)
δ15N (‰)
NPs (%)
IRD (grains/10ccm) > 500 µm
MAR CaCO3 (g cm-2 ky-1)
CaCO3 (%)
Age (ky)
2-3
4
6
7
8
9
10
12
Holocene
Planktic δ18O (‰)
% N. pachyderma (s)
7.8ka
Termination 1
IRD (grains/g) >250µm
CaCO3 (%)
Age (cal. ka)


a)
Marine algae
Vascular plant detritus
MIS 1
MIS 5e
MIS 11
δ15N
C/N
b)
Total nitrogen (wt %)
TOC (wt %)
R2 = 0.85
TN = 0.1 x TOC + 0.005
c)
MIS 1
MIS 5e
MIS 11
R2 = 0.42
TN = 0.01 x δ15N - 0.022
δ15Nbulk



MIS 1
T I
MIS 5e
T II
MIS 11
T V
δ18O (‰)
δ18O NPs (‰)
δ15N (‰)
+ Nitrate utilization
Warmer water
T. quinqueloba (%)
NPs (%)
G. uvula (%)
CaCO3 (%)
IRD (grains/10ccm) > 500 µm
MAR CaCO3 (g cm-2 ky-1)
Age (ka)
High productivity and almost complete nutrient consumption
Low productivity
Deep mixing layer
High productivity and high nutrient consumption
High productivity and medium-nutrient consumption
Very High δ15N Low NPs
High δ15N Medium NPs
Medium δ15N Very High NPs
Low δ15N
Water Depth
NPs habitat
Photic zone