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Semi-quantitative reconstruction of early to late Holocene spring and summer sea ice conditions in the northern Barents Sea

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Abstract

Semi-quantitative estimates of early to late Holocene spring sea ice concentration (SpSIC) and occurrence of summer sea ice for the northern Barents Sea have been obtained by analysing the biomarkers IP\textsubscript{25}, brassicasterol and a tri-unsaturated highly branched isoprenoid lipid in a Holocene marine sediment core. Sub-surface water mass variations were derived from planktic foraminiferal assemblages and stable isotopes (δ\textsuperscript{18}O, δ\textsuperscript{13}C). The record indicates paleoceanographic changes over three intervals. During Period I (ca. 9500–5900 cal a BP), the study location experienced the lowest recorded SpSIC (ca. 25%) with short spring seasons and long productive summers, resulting partly from increased Atlantic Water inflow that caused a stronger ocean-atmosphere heat exchange. Throughout Period II (ca. 5900–2700 cal a BP), the winter sea ice margin migrated southwards and an overall cooling trend resulted in higher SpSIC (ca. 60%) and increased delivery of cold Arctic Water. During Period III (ca. 2700 cal a BP–present), SpSIC increased further (ca. 75%) and some sea ice remained during summer months. A sub-surface warming likely indicates a decoupling of heat exchange between the ocean and the atmosphere. Longer springs and shorter summers were accompanied by the most southerly location of the winter sea ice margin.

Keywords

Sea ice, biomarker, proxy data, Holocene, Arctic
Introduction

The Barents Sea is a relatively small and shallow sea, yet it plays a crucial role in the Arctic climate system, in part, because of significant heat exchange between the ocean and the atmosphere (Serreze et al., 2007). Oceanic heat is brought into the Barents Sea via the inflow of warm Atlantic water and, due to shallow depths, heat loss to the atmosphere is very efficient. Further, it has been suggested that ocean advection strongly influences sea ice conditions in the Barents Sea, so the region is central to understanding ocean-sea ice-atmosphere interactions (Vinje, 2001).

Recently, many Arctic regions have experienced an abrupt decline in sea ice conditions, with the northern Barents Sea and the Chukchi Sea identified as the most affected areas during the last three to four decades (Screen and Simmonds, 2010; Stroeve et al., 2007, 2012). Present day sea ice variations within the Barents Sea have been attributed to different processes (e.g. atmospheric circulation variability, local wind patterns, ice import from the Arctic interior to the Barents Sea), although the role of oceanic heat advection is often emphasized as one of the most important factors (e.g. Årthun et al., 2012; Ivanov et al., 2012; Smedsrud et al., 2013). For example, Årthun et al. (2012) argued that recent increases in Atlantic Water inflow to the Barents Sea has contributed to a further decline in sea ice conditions in the Barents Sea. Similarly, the northerly inflow of Pacific Water has been suggested as a contributing factor to reduced sea ice conditions in the Chukchi Sea in recent times (e.g. Shimada et al., 2006; Woodgate et al., 2010) and during the Holocene (Stein et al., 2016a).

Since the impacts of Arctic amplification and the associated sea ice decline (Serreze and Francis, 2006; Screen and Simmonds, 2010) reach far beyond the Arctic region (Yang and Christensen, 2012), it is clearly necessary to better understand the interaction between sea ice production and water mass conditions, together with any natural variability that occurs between them over longer time frames. Instrumental and observational records of past climate variations in the Barents Sea reach back only ca. 100–150 years (Divine and Dick, 2006; Smedsrud et al., 2013), so longer-term records of sea ice and water mass conditions need to be derived from proxy climate indicators archived in marine sediment cores. Such records from the northern Barents Sea (e.g. Duplessy et al., 2001; Lubinski et al., 2001; Risebrobakken et al., 2011; Klitgaard Kristensen et al., 2013), the western Barents Sea (Berben et al., 2014) and the Svalbard margin (e.g. Slubowska et al., 2005; Rasmussen et al., 2013) are critical for understanding the evolution of past climatic conditions and for predicting future changes in sea ice conditions.
2007; Spielhagen et al., 2011; Müller et al., 2012; Werner et al., 2013) have demonstrated various fluctuations of both the influence of Atlantic Water inflow to the Barents Sea and sea ice conditions throughout the Holocene. The observed Holocene changes in the region have mainly been attributed to insolation changes and further factors such as land-cover feedbacks and coupled atmospheric-oceanic dynamics, in particular the northward penetration of relatively warm Atlantic Water (Berger, 1978; Koç et al., 1993; Kaufman et al., 2004). Additionally, insolation forcing has also been attributed to the long-term sea ice variability (Müller et al., 2012; Cabelo-Sanz et al., 2016b). However, few of these reconstructions have employed a specific proxy for sea ice or have provided detailed descriptions of sea ice conditions, including semi-quantitative estimates of spring sea ice concentration (SpSIC) or summer sea ice occurrence.

In this study, the biomarkers IP$_{25}$, brassicasterol and a tri-unsaturated highly branched isoprenoid (HBI) lipid (HBI III) have been analyzed in a marine sediment core from the Olga Basin in order to reconstruct a detailed record of sea ice conditions for the early to late Holocene in the northern Barents Sea (Fig. 1). The biomarker concentration data were presented previously by Belt et al. (2015), but were not discussed in detail. In the current study, therefore, we provide a more in-depth discussion of the individual and combined (i.e. PIP$_{25}$) biomarker data, including, for the first time, semi-quantitative estimates of SpSIC based on the recent calibration study by Smik et al. (2016). In addition, and similar to Werner et al. (2013, 2014), planktic foraminiferal fauna assemblages and stable carbon and oxygen isotopes ($\delta^{18}$O, $\delta^{13}$C) have also been measured to obtain a combined multiproxy record of sea ice conditions and sub-surface water masses, thus demonstrating the interaction of sea ice and inflow of Atlantic Water. The study site is located between the Atlantic Water characterized southern Barents Sea and the central Arctic Ocean and is, therefore, influenced by Atlantic derived water masses (Abrahamsen et al., 2006) but also experiences seasonal sea ice conditions (Fig. 1). As such, it represents a key location for reconstructing Holocene changes in sea ice conditions and Atlantic Water inflow. Using our Holocene proxy data, we also propose different oceanographic scenarios that emphasize the changing interactions between sea ice conditions and near-surface waters and these are discussed further by comparing the proxy data with outcomes from previous studies from the region.

*Sea ice biomarker background information*
Following the initial discovery of the Arctic sea ice proxy IP$_{25}$ (Belt et al., 2007), analysis of this biomarker has subsequently led to sea ice reconstructions for various sub-Arctic and Arctic regions: the central Arctic Ocean (Xiao et al., 2015a, 2015b), the Labrador Sea (Weckström et al., 2013), the Canadian Arctic (Vare et al., 2009), the Bering Sea/North Pacific (Méheust et al., 2013, 2015), the Chukchi Sea (Polyak et al., 2016; Stein et al., 2016a), the East Siberian Sea (Stein et al., 2013), the Laptev Sea (Fahl and Stein 2012; Xiao et al., 2013), the Barents Sea (Vare et al., 2010; Berben et al., 2014), the Fram Strait (Müller et al., 2009, 2012; Cabedo-Sanz et al., 2013, 2016a; Knies et al., 2014; Müller and Stein, 2014) and the Greenland/Norwegian Seas (Massé et al., 2008; Cabedo-Sanz et al., 2016b).

Furthermore, IP$_{25}$ appears stable within Arctic sediments to permit sea ice reconstructions over even longer timescales (e.g. going back into the Pliocene (Knies et al., 2014) and the Miocene (Stein et al., 2016b). IP$_{25}$ is biosynthesized by certain Arctic sea ice diatoms and is thus usually found in areas with seasonal sea ice conditions (e.g. Belt et al., 2007; Brown et al., 2011, 2014; Belt and Müller, 2013). In order to provide complementary information regarding open water conditions, Müller et al. (2009) proposed the additional measurement of phytoplankton biomarkers, such as brassicasterol. In addition, by combining IP$_{25}$ and phytoplankton biomarker concentrations, in the form of the so-called PIP$_{25}$ index, a method of elucidating semi-quantitative estimates of sea ice conditions has been proposed (Müller et al., 2011). However, application of the PIP$_{25}$ method is not always straightforward because some phytoplankton markers such as brassicasterol may also have non-pelagic sources and their generally higher concentration compared to IP$_{25}$ requires the use of a balance factor in the calculation of PIP$_{25}$, which can be problematic (for a detailed discussion, see Belt and Müller, 2013; Navarro-Rodriguez et al., 2013; Belt et al., 2015; Xiao et al., 2015a; Smik et al., 2016).

A recent study by Belt et al. (2015), however, demonstrated that a further phytoplankton-derived HBI biomarker, more specifically HBI III, was relatively abundant for locations within the marginal ice zone or close to the winter ice margin in the Barents Sea, thus representing an alternative indicator of open water conditions. In addition, since HBI III has a more constrained source (diatoms) and has sedimentary concentrations much closer to those of IP$_{25}$, some of the problems associated with using some other phytoplankton biomarkers can potentially be avoided. In a subsequent study, Smik et al. (2016) also demonstrated that PIP$_{25}$ values based on IP$_{25}$ and HBI III could provide realistic estimates of SpSIC for the Barents Sea, while a threshold value of 0.8 was suggested as providing evidence for the presence of summer sea ice (>5% summer sea ice concentration (SuSIC)).
Study area and oceanographic setting

The Barents Sea is an epicontinental shelf located between the Norwegian-Russian coast, Novaya Zemlya and the Svalbard and Franz Josef Land archipelagos (Fig. 1). The northern boundary of the Barents Sea is defined by the Nansen Basin continental slope (Jakobsson et al., 2004). The Barents Sea is characterized by several water masses and represents a major passage for Atlantic Water entering the Arctic Ocean (Carmack et al., 2006; Rudels et al., 2014).

The Norwegian Atlantic Current transports relatively warm and saline Atlantic Water towards the high latitude North Atlantic Ocean (Hopkins, 1991) (Fig. 1a). Before entering the Barents Sea, the Norwegian Atlantic Current splits into two different branches, the West Spitsbergen Current and the North Cape Current, respectively (Fig. 1a). Both of these currents transport the warm saline Atlantic Water into the Arctic Ocean (Rudels et al., 2014). Within the Barents Sea, Atlantic Water is entered from both the north and the southwest. The West Spitsbergen Current flows northwards along the western Barents Sea slope and splits into three branches in the Fram Strait; the Return Atlantic Current, the Yermak Branch and the Svalbard Branch (Fig. 1a) (e.g. Manley, 1995). The latter enters the Arctic Ocean north of Svalbard as a sub-surface current flowing eastward and beyond the Franz Victoria and St. Anna Troughs (Abrahamsen et al., 2006; Rudels et al., 2014). A sub-surface inflow of Atlantic Water derived from the Svalbard Branch enters the Barents Sea via the Northern Barents Sea Opening (Fig. 1a). Subsequently, Atlantic Water is advected south-westwards into the northern Barents Sea and has been observed year-round in the Olga Basin (Abrahamsen et al., 2006) where the studied sediment core is located. Although the major sub-surface water mass in the Olga Basin is Atlantic Water derived from the Svalbard Branch (Gammelsrød et al., 2009; Klitgaard Kristensen et al., 2013), the area is furthermore influenced by Atlantic Water that enters as a submerged flow from the south (e.g. Novitskiy, 1961; Loeng, 1991; Pfirman et al., 1994; Aksenov et al., 2010). The latter is brought to the area by the North Cape Current flowing northwards via the Barents Sea Opening into the southern Barents Sea, parallel to the coastal current system (Loeng, 1991; Loeng et al., 1993; Midttun, 1985; Rudels, 1987) (Fig. 1a). After mixing and heat loss, Atlantic Water exits the Barents Sea via the Barents Sea Exit and reaches the Arctic Ocean via the St. Anna Trough (e.g. Schauer et al., 2002; Rudels et al., 2014) (Fig. 1a).
In addition to relatively warm Atlantic Water, the Barents Sea is also influenced by Polar
Water that is brought from the Arctic Ocean into the Barents Sea through the Franz Victoria
and St. Anna Troughs, via the East Spitsbergen Current and the Bear Island Current,
respectively (Hopkins, 1991) (Fig. 1a). Arctic Water is formed when relatively warm Atlantic
Water converges and merges with cold, less saline and ice loaded Polar Water (Hopkins,
1991). Hence, surface water in the north-eastern Barents Sea is, in contrast to the Atlantic
Water dominated south-western Barents Sea, dominated by Arctic Water characterized by
reduced temperature and salinity, as well as seasonal sea ice conditions (Hopkins, 1991). A
CTD profile taken at the core location illustrates the presence of Arctic Water at the surface,
with Atlantic Water below ca. 150 m (Fig. 1c; Table S1).

The oceanic fronts dividing these different water masses are one of the main oceanographic
features of the near-surface waters of the Barents Sea (Pfirman et al., 1994). Defined as a
sharp climatic gradient in terms of temperature, salinity and sea ice conditions, the Polar and
Arctic fronts are the respective boundaries between Polar/Arctic and Arctic/Atlantic waters.
The positions of the Polar and Arctic fronts are closely related to the overall sea ice conditions
and, in particular, align with the average summer and winter sea ice margins, respectively
(Vinje, 1977). Although sea ice advection from the Arctic Ocean does occur, sea ice within
the Barents Sea is mainly formed locally during autumn and winter (Loeng, 1991). The
southward extent of the oceanic fronts, and hence the sea ice conditions in particular, are
regulated by the inflow of Atlantic Water into the western Barents Sea, which controls the
mainly ice-free Atlantic domain in the south-western Barents Sea (Årthun et al., 2012). In
contrast, the north-eastern Barents Sea experiences large changes in seasonal sea ice
conditions (Vinje, 2001; Sorteberg and Kvingedal, 2006) with maximum sea ice conditions
during March/April and minimum occurring throughout August/September (Fig. 1b). Annual
sea ice variability during recent decades might be explained by factors such as cyclone
activity, which cause fluctuations in sea ice transport, to and from the Arctic Ocean into the
north-eastern Barents Sea (Kwok et al., 2005; Sorteberg and Kvingedal, 2006; Ellingsen et
al., 2009; Kwok, 2009).

The interplay between water masses and other influences that impact sea ice formation in the
Barents Sea determine the position of the marginal ice zone, an area characterized by high
surface productivity during the summer season (e.g. Smith and Sakshaug, 1990). Within the
Barents Sea, enhanced primary production results from a peak algal bloom along the ice
margin during spring as sea ice retreats (Sakshaug et al., 1992). In addition, the advection of
Atlantic Water contributes to longer productive seasons, compared to other Arctic areas (Wassmann, 2011). Consequently, the Barents Sea is one of the most productive areas of the Arctic Seas (Wassmann et al., 2006; Wassmann, 2011).

Material and methods

A 245 cm long marine sediment core NP05-11-70GC was retrieved in 2005 by the RV Lance south of Kong Karls Land (Olga Basin) within the northern Barents Sea (78.40° N, 32.42° E; 293 m water depth) using a gravity coring device (Fig. 1). The upper section of the core (0–124 cm; 1-cm intervals) was investigated in the current study and was characterized by homogeneous sediments rich in silty clay deposited in a marine environment.

Chronology

A depth-age model for NP05-11-70GC was developed using linear interpolation between three calibrated AMS $^{14}C$ dates obtained from mixed benthic foraminifera as described by Berben (2014) and Belt et al. (2015) (Fig. 2; Table 1; Table S2). In order to try and improve the age control, attempts to obtain more $^{14}C$ dates were made by collecting all benthic foraminifera at each core level selected for microfossil analyses (i.e. every cm). Unfortunately, additional $^{14}C$ measurements were prevented due to the very low numbers of foraminifera (and thus insufficient amounts of CaCO$_3$ (Fig. 4)). Nonetheless, the lithological description of a marine sediment core from a very nearby location in the northern Barents Sea also indicate a well-defined homogeneous unit corresponding to Holocene sediments (Klitgaard Kristensen et al., 2013). Thus, based on lithological similarities, together with some younger AMS $^{14}C$ dates (<2000 cal a BP) in a nearby core, the NP05-11-70GC core top is assumed to represent modern age. The AMS $^{14}C$ dates were calibrated using Calib 6.1.1 (Stuiver and Reimer, 1993) and the Marine09 calibration curve (Reimer et al., 2009). A local reservoir age (ΔR) of 105±24 suggested for the Svalbard area by Mangerud et al. (2006) was used in the calibration (Table 1).

Biomarker analysis
To reconstruct past sea ice conditions, the seasonal sea ice biomarker IP$_{25}$ and the open water phytoplankton biomarkers (brassicasterol and HBI III) were analysed in 49 sub-samples (ca. 1 g taken from the same bulk sediment samples used for foraminiferal analysis). Prior to analysis, sub-samples were freeze-dried and stored at -20 °C. The general methodology for biomarker extraction, purification and analysis was as previously described by Belt et al. (2012) and Brown and Belt (2012). Analytical reproducibility was monitored using a sediment with known biomarker concentrations for every 10–12 extracted sediment samples (analytical error <6%, n=5). Lipid quantification was conducted using the integrated peak areas of each biomarker and the internal standard, an instrumental response factor, and the masses of the extracted sediment and internal standard (Belt et al., 2012). Biomarker concentrations, normalized to dry weight sediment mass (µg/g sed.) as presented previously (Belt et al., 2015), were further normalized to total organic carbon (µg/g TOC) in order to compensate possible regional differences in production and degradation in sediments (Belt and Müller, 2013). The weight percentages (wt. %) of TOC (n=43) were determined using a Carlo Erba EA 1110 elemental analyzer at Plymouth University. In order to remove any inorganic carbonate, ca. 100 mg of freeze-dried sediment was digested in HCl (1mL; 18h).

To investigate past sea ice conditions more quantitatively, IP$_{25}$ and phytoplankton biomarkers were used to calculate the so-called P$_{IP_{25}}$ and P$_{III_{IP_{25}}}$ indices (i.e. PIP$_{25}$ based on brassicasterol and HBI III, respectively) (Müller et al., 2011; Belt et al., 2015). Calculation of the P$_{IP_{25}}$ index was achieved using Eq. 1, which includes a concentration balance factor (c; Eq. 2) to compensate for the significant concentration difference between IP$_{25}$ and brassicasterol (Müller et al., 2011).

\[
P_{IP_{25}} = \frac{IP_{25}}{IP_{25} + (brassicasterol \times c)} \quad \text{[Eq. 1]}
\]

\[
c = \frac{\text{mean } IP_{25}}{\text{mean brassicasterol}} \quad \text{[Eq. 2]}
\]

Calculation of P$_{IIIIP_{25}}$ indices was achieved by replacing brassicasterol concentrations (Eq. 1) with those of HBI III. The balance factor, c, was calculated according to the relative mean concentrations of IP$_{25}$ and HBI III (i.e. as per brassicasterol; Eq. 2) and we also used a value of 0.63, derived from a regional calibration of surface sediments from the Barents Sea (Belt et al., 2015; Smik et al., 2016). In practice, P$_{IIIIP_{25}}$ values using a c term based on Eq. 2 (0.84) were very similar to those using the value of c derived from the surface sediment calibration (0.63; Smik et al., 2016). For simplicity, we present data using the surface sediment calibration.
calibration only. Semi-quantitative estimates of SpSIC were also made using the $P_{III}IP_{25}$ data and the calibration of Smik et al. (2016) (Eq. 3) (for more background information, see Introduction).

$$SpSIC(\%) = \frac{P_{III}IP_{25} - 0.0692}{0.0107} \quad \text{[Eq. 3]}$$

Planktic foraminifera

The sediment core was opened, and the sediments were sampled and frozen within 48 hours. Sediment samples were freeze-dried, wet-sieved through three different size fractions (1000, 100 and 63 µm), and dried at 40 °C. Planktic foraminiferal assemblages were determined for 123 samples using the 100–1000 µm size fraction following Knudsen (1998). Following Forcino (2012), the relative abundances (%) of each species were calculated for samples containing more than 25 specimens (82 samples). Identification of Neogloboquadrina pachyderma and Neogloboquadrina incompta species was achieved following Cifelli (1961) and Darling et al. (2006), and planktic foraminiferal concentrations (#/g sed.) were calculated. As the planktic foraminiferal assemblages might be affected by carbonate dissolution, it is important to assess the impact of preservation changes on the planktic foraminiferal data (e.g. Zamelczyk et al., 2013). Here, the preservation conditions were investigated by analysing preservation indicators such as the mean shell weight of $N. pachyderma$ and the percentage of fragmentation of planktic foraminiferal tests. A loss in the mean shell weight can be used to identify dissolution in the water column and sediment surface (Broecker and Clark, 2001; Barker and Elderfield, 2002; Barker et al., 2004). Hence, 25 well preserved (visually) and square shaped $N. pachyderma$ specimens were picked from each sample from a narrow size range (150–250 µm) in order to reduce problems of ontogeny and size difference induced variability (Barker et al., 2004). It was possible to obtain a mean shell weight (µg) of the 25 picked specimens per sample of $N. pachyderma$ using a Mettler Toledo microbalance (0.1 µg sensitivity; 110 samples). Further, the degree of fragmentation indicates the dissolution induced weakening of the tests as well as dissolution processes within the sediment (Conan et al., 2002). The fragmentation (%) of planktic foraminiferal tests was calculated for the 82 samples that contained a total number of >25 specimens within the 100–1000 µm size fraction. The fragmentation was calculated using the equation proposed by Pfuhl and Shackleton (2004) (Eq. 4).
Fragmentation = ((#fragments/g) / ((#fragments/g/3) + (#tests/g))) * 10  \[Eq. 4\]

**Stable carbon and oxygen isotope analysis**

The stable carbon and oxygen isotopic compositions of planktic foraminiferal shells (δ¹⁸O, δ¹³C) are widely used to reflect the ambient sea water mass properties in which they have been calcified. In particular, δ¹⁸O is a proxy for temperature and salinity, whereas δ¹³C variations reflect primary production and stratification changes (e.g. Spielhagen and Erlenkeuser, 1994; Katz et al., 2010). The δ¹⁸O and δ¹³C analyses were performed on the foraminiferal tests of *N. pachyderma*. All specimens were selected from a narrow size range (150–250 µm) in order to minimize size dependent effects on isotopic composition (Aksu and Vilks, 1988; Keigwin and Boyle, 1989; Oppo and Fairbanks, 1989; Donner and Wefer, 1994; Bauch et al., 2000). Sufficient amount of specimens were obtained from 105 samples. Samples were analysed using a Finnigan MAT 253 mass spectrometer coupled to an automated Kiel IV Carbonate Preparation Device at the Geological Mass Spectrometer (GMS) Laboratory at the University of Bergen. These measurements were conducted with a reproducibility of ±0.06 ‰ (δ¹⁸O) and ±0.03 ‰ (δ¹³C). Data are reported on the ‰ versus VPDB scale calibrated with NBS-19. Corrections for the ice volume effect were applied on the measured δ¹⁸O values according to Fairbanks (1989). No vital effect corrections were applied for the isotope measurements in this study as published estimates of species-specific vital effects are often inconsistent (e.g. Kohfeld et al., 1996; Bauch et al., 1997; Stangeew, 2001; Simstich et al., 2003), possibly due to seasonal changes of the apparent vital effect (Jonkers et al., 2010).

**Results**

The resulting depth-age model ranges between the present and ca. 9400 cal a BP (Fig. 2). The depth-age model presented here has its limitations (for a detailed discussion, see Chronology) and hence, for this reason, assigned ages should be taken with caution. Therefore, all data plots presenting the results of this study also include a depth scale, although the results are described with respect to age to enable us to place them into a wider context, both spatially and temporally, when comparing them with previously published results. Despite the
limitations of the age control, which prevents the determination of centennial-scale changes, we believe it is nonetheless feasible to describe the general early to late Holocene changes with some confidence.

Biomarker data

The initial decrease in IP$_{25}$ concentrations (2 data points) followed by low values, coincides with increased concentrations of both brassicasterol and HBI III ca. 9500–8500 cal a BP (Fig. 3a-c; Table S3). Hereafter, IP$_{25}$ concentrations show slightly higher values, whereas brassicasterol and HBI III show decreased concentrations towards ca. 5900 cal a BP (Fig. 3a-c). During this entire time interval (i.e. ca. 9500–5900 cal a BP), a decreasing trend in TOC is also observed, although values remain relatively high (Fig. 3d; Table S3). From ca. 5900–2700 cal a BP, the concentration of IP$_{25}$ increases further, while brassicasterol and HBI III both decrease although TOC values remain relatively stable (Fig. 3a-d). The last ca. 2700 cal a BP are characterized by the highest concentrations of IP$_{25}$ and relatively low (but stable) concentrations of brassicasterol and HBI III (Fig. 3a-c). Although the TOC values fluctuate somewhat throughout this period, the absolute values are the lowest within the entire record (Fig. 3d).

Both P$_{B}$IP$_{25}$ and P$_{III}$IP$_{25}$ indices, as well as the estimated SpSIC (which is linearly related to P$_{III}$IP$_{25}$; Smik et al., 2016), follow the same trends throughout the entire record (Fig. 3e-g; Table S3). After the initial lowest values at ca. 9000 cal a BP, each of P$_{B}$IP$_{25}$, P$_{III}$IP$_{25}$ and SpSIC show increasing (although still relatively low) values towards ca. 5900 cal a BP (Fig. 3e-g). The mean SpSIC estimate ca. 9500–5900 cal a BP is ca. 25% (Fig. 3g). From ca. 5900–2700 cal a BP, the P$_{B}$IP$_{25}$, P$_{III}$IP$_{25}$ and SpSIC records continue their increasing trend, albeit more gradually. The estimated SpSIC shows a mean value of ca. 60% throughout this time interval (Fig. 3g) with highest values towards ca. 2700 cal a BP. The P$_{B}$IP$_{25}$ reaches its highest value at the core top, whereas the P$_{III}$IP$_{25}$ records a maximum value at ca. 1600 cal a BP after which it remains high until the present (Fig. 3e-f). Estimates of SpSIC show a mean value of ca. 75% (Fig. 3g). According to the threshold limit (P$_{III}$IP$_{25}$>0.8) suggested by Smik et al. (2016), the occurrence of summer sea ice (SuSIC>5%) is estimated to have begun ca. 2700 cal a BP and remained a consistent feature thereafter, until the present (Fig. 3f).
Planktic foraminiferal preservation

From ca. 9500–7300 cal a BP, the absolute abundances of planktic foraminifera remain relatively low where after, they increase towards 5900 cal a BP (Fig. 4a; Table S4). From ca. 5900–2700 cal a BP, the planktic foraminiferal concentration has a broader range (Fig. 4a), while in the last ca. 2700 cal a BP, three episodes of increased planktic foraminiferal concentration values are observed ca. 2400–2000 cal a BP, ca. 1600–700 cal a BP, and ca. 400 cal a BP–present (Fig. 4a).

From ca. 9500–5900 cal a BP, the extent of fragmentation shows a mean value of 32%, whereas the mean shell weight is highly variable until ca. 7300 cal a BP, followed by more stable values (ca. 7.5 µg) towards ca. 5900 cal a BP (Fig. 4b-c; Table S4). The mean shell weight remains relatively stable (ca. 7 µg) ca. 5900–2700 cal a BP, while the fragmentation record exhibits an overall decrease (Fig. 4b-c). During the last ca. 2700 cal a BP, the degree of fragmentation shows a small overall increase although there is mainly an increase in the amplitude (i.e. minima and maxima between ca. 9–83%) (Fig. 4b). At the same time, the mean shell weight shows a general decrease (Fig. 4c).

Planktic foraminiferal fauna

The planktic foraminiferal record is characterized by the presence of polar (*N. pachyderma*) and sub-polar (*N. incompta, Turborotalita quinqueloba, Globigerinita glutinata, Globigerina bulloides* and *Globigerinita uvula*) species with *N. pachyderma* generally dominating the assemblages (Fig. 4d-i; Table S4). From ca. 9500–7300 cal a BP, the fauna is dominated by *N. pachyderma* (ca. 95%) followed by a period (ca. 7300–5900 cal a BP) with increased relative abundances of *T. quinqueloba, N. incompta* and *G. glutinata* up to ca. 24, 27 and 4%, respectively (Fig. 4d-g). After ca. 5900 cal a BP, the relative abundances of *T. quinqueloba* and *N. incompta* decrease and remain relatively stable (ca. 3–4%) towards ca. 2700 cal a BP, while *N. pachyderma* clearly dominates the planktic foraminiferal fauna (Fig. 4d-f).

Throughout the last ca. 2700 cal a BP, a reduction in *N. pachyderma* (towards ca. 65%) is accompanied by increasing relative abundances of *G. glutinata* (ca. 5%) and *G. bulloides* (ca. 8%), whereas *T. quinqueloba* and *N. incompta* reach their highest values between ca. 2400–2000 cal a BP, ca. 1600–700 cal a BP and ca. 400 cal a BP–present (Fig. 4d-h). The period
from ca. 400 cal a BP–present is characterized by a clear increase of *G. glutinata* (ca. 7%) and *G. bulloides* (ca. 6%), in addition to a remarkable increase of *G. uvula* (ca. 7%) (Fig. 4g-i).

### Stable carbon and oxygen isotope data

From ca. 9500–8800 cal a BP, the δ¹⁸O (*N. pachyderma*) record has a mean value of 3.8 ‰ followed by a period (ca. 8800–7300 cal a BP) characterized by lighter values (Fig. 5a; Table S5). A significant increase in δ¹⁸O ca. 7600–7300 cal a BP is followed by heavier values that fluctuate around ca. 3.7 ‰ until ca. 5900 cal a BP. The δ¹⁸O record remains relatively stable ca. 5900–2700 cal a BP with relatively heavy values (Fig. 5a). Throughout the last ca. 2700 cal a BP, the δ¹⁸O record shows decreased values in the range 3.5–4.0 ‰ (Fig. 5a).

The δ¹³C record shows a decrease from 0.4 to 0.0 ‰ ca. 9500–8500 cal a BP (Fig. 5b; Table S5). This trend is reversed at ca. 8500 cal a BP, with heavier δ¹³C values towards ca. 5900 cal a BP followed by an increase towards 0.9 ‰ ca. 5900–2700 cal a BP (Fig. 5b). The last ca. 2700 cal a BP are then characterized by a decreasing trend with δ¹³C values in the range 0.3–0.8 ‰ (Fig. 5b).

### Discussion

Throughout the early to late Holocene, the palaeoceanographic record in NP05-11-70GC shows an overall increase in sea ice reflecting the decline in solar insolation (Fig. 6a-d). Related IP25-based reconstructions have been reported for other Arctic and sub-Arctic regions such as the Fram Strait, the Laptev Sea, the East Siberian Sea and the Chukchi Sea (Stein *et al.*, 2016a), as well as for the Canadian Arctic (Vare *et al.*, 2009; Belt *et al.*, 2010) and North Iceland (Cabdeto-Sanz *et al.*, 2016b). However, for some other regions, including the Alaskan margin (Polyak *et al.*, 2016) and the western Barents Sea (Berben *et al.*, 2014), this long-term trend is not as evident. The record presented here for the northern Barents Sea is described in terms of individual time intervals reflecting the main stages of sea ice conditions and Atlantic Water inflow. The intervals are: Period I (ca. 9500–5900 cal a BP), Period II (ca. 5900–2700 cal a BP) and Period III (ca. 2700 cal a BP–present), although the interpretation of the timing of the exact boundaries between these intervals should be considered with caution due to the limitations of the age-depth model (see Chronology).
Climate and oceanographic variations during these periods are discussed and set into further context by comparison with previously published records from the region.

Our interpretation of the sea ice conditions involves the identification of previously unavailable semi-quantitative estimates of SpSIC and summer sea ice occurrence using a recently calibrated biomarker approach, which has also permitted the proposal of different sea ice scenarios. To obtain realistic representations for such sea ice conditions, known scenarios derived from modern and historical observations of the Barents Sea (NSIDC) have been considered (Fig. 1b). For example, the modern sea ice conditions have been derived from maximum (March) and seasonal variability (April/August) in sea ice using satellite data obtained between 1981 and 2010 (NSIDC) (Fig. 7c). In terms of temporal changes, historical data from the Barents Sea show variations in the mean sea ice margin position in April for four sub-periods between 1870 and 2002 (Divine and Dick, 2006). A north-easterly retreat of the sea ice margin since the second half of the 19th century occurred after a significant cooling in the second half of the 18th century (Divine and Dick, 2006) (Fig. 1b). This historical data from the Barents Sea illustrates that the decadal migration pattern of the sea ice margins associated with climatic conditions can reflect observed sea ice changes on an annual and/or seasonal time scale. Therefore, this key dataset provides precedent for the proposed sea ice scenarios (and changes to these) within the Barents Sea during the early to late Holocene.

With respect to the planktic foraminiferal preservation conditions, the proxy data is interpreted as follows. Better calcium carbonate preservation has been associated with increased production of organic matter in regions impacted by Atlantic Water (e.g. Hebbeln et al. 1998; Henrich et al. 2002). In particular, for areas with enhanced Atlantic Water inflow towards the Fram Strait, ocean currents appear to have a positive influence on the preservation of organic matter in sediments (Birgel and Stein, 2004; Birgel et al., 2004). The wide range in both fragmentation and mean shell weight could therefore reflect variable environmental control, preservation conditions or a combination of both. The high mean shell weight ca. 7300–5900 cal a BP indicates better preservation conditions, possibly related to an increased influence of Atlantic Water (Fig. 4c). In contrast, throughout the last ca. 2700 cal a BP, the preservation indicators (i.e. low mean shell weight and highly fluctuating fragmentation) show an overall change towards enhanced dissolution (Fig. 4b-c). This may be caused by an increased influence of sea ice formation and brine rejection which may form corrosive bottom water masses causing dissolution at the sea floor (e.g. Midttun 1985; Steinsund and Hald 1994). Further, the low planktic foraminiferal concentrations may seem to
indicate poor preservation conditions, however studies of recent planktic foraminifera show that low planktic foraminiferal concentrations can be found within environments characterized by sea ice conditions (Carstens et al. 1997; Pados and Spielhagen 2014). In addition, the data in this study is consistent with planktic foraminiferal concentrations from the Barents Sea region (e.g. Klitgaard Kristensen et al. 2013; Duplessy et al. 2001). When compared with other studies from the region (e.g. Zamelczyk et al. 2012, 2013; Berben et al. 2014), however, the current fragmentation and mean shell weight data indicate good preservation, especially throughout the early part of the record. Therefore, the generally low planktic foraminiferal concentrations are attributed here to the environmental conditions such as the shallow shelf environment influenced by Arctic Water with a reduced salinity and the proximity of the sea ice margin.

Regarding the planktic foraminiferal oxygen isotope signal, studies of recent foraminiferal calcite and the isotopic composition of water masses by Lubinski et al. (2001) demonstrate that, in the Barents Sea, these are controlled mainly by temperature changes rather than salinity. However, the water masses in the region are also influenced by meltwater and reduced salinities, especially during the earliest part of the Holocene, although this influence probably diminished around ca. 11 000 cal a BP (Klitgaard Kristensen et al., 2013). Therefore, it is further assumed that the stable isotope record has been mainly controlled by temperature.

**Period I (ca. 9500–5900 cal a BP): minimum sea ice conditions with reduced SpSIC (ca. 25%)**

During Period I, low IP$_{25}$ concentrations reflect reduced seasonal sea ice, while high brassicasterol and HBI III concentrations are indicative of open water and sea ice margin conditions, respectively (Fig. 3a-c). At the same time, the lowest P$_3$IP$_{25}$ and P$_{III}IP_{25}$ values indicate reduced spring sea ice conditions, with longer (warmer) summers suitable for phytoplankton production (Müller et al., 2011; Belt et al., 2015; Smik et al., 2016) (Fig. 3e-f), which is also reflected by the generally higher TOC values (Fig. 3d). Maximum HBI III concentrations indicate decreasing winter ice margin conditions from ca. 9500–8500 cal a BP (Belt et al., 2015), with SpSIC estimates consistently less than 50% (mean ca. 25%) (Fig. 3g) and an absence of summer sea ice (Fig. 3f-g). The occurrence of reduced SpSIC and longer (ice-free) summers is consistent with longer ice-free seasons and a retreated ice margin.
observed in the northern Barents Sea (Duplessy et al., 2001) and increased phytoplankton production in the northern Fram Strait (Müller et al., 2009, 2012) (for location of these study sites please refer to Fig. 1). Reduced spring sea ice conditions likely indicate the occurrence of the Holocene Thermal Maximum as recorded at the sea surface ca. 9300–6500 cal a BP. The subsequent increase in IP$_{25}$ concentration after ca. 6500 cal a BP reflects a general enhancement in sea ice conditions probably marking the gradual transition of the Holocene Thermal Maximum towards Neoglacial conditions (Fig. 6b). Similar conclusions regarding timing and termination of the Holocene Thermal Maximum based on IP$_{25}$ records have been made for the Fram Strait (until ca. 8400 cal a BP; (Müller et al., 2009)) and the West Svalbard margin, where the last phase of the Holocene Thermal Maximum was recorded ca. 8500–7000 cal a BP (Müller et al., 2012). Furthermore, the observed disappearance of sea ice in the western Barents Sea from ca. 10 700–7700 cal a BP has been linked previously to the Holocene Thermal Maximum (Sarnthein et al., 2003).

The light δ$^{18}$O (N. pachyderma) values ca. 8800–7300 cal a BP indicate a small temperature rise, possibly reflecting a gradual shift towards a warmer sub-surface water mass due to increased Atlantic Water inflow (Fig. 6e). The relatively light δ$^{18}$O values also coincide with high insolation, thereby reflecting the Holocene Thermal Maximum at the core site (Fig. 6e). The strong increase in δ$^{18}$O values ca. 7600–7300 cal a BP probably reflects its termination, a conclusion consistent with observations of Duplessy et al. (2001) for a nearby location. Furthermore, Hald et al. (2007) presented a time-transgressive Atlantic Water inflow from south to north along the Norwegian and Svalbard margins. Risebrobakken et al. (2011) suggested that this time-transgressive northward intensified heat advection resulted from major reorganization of the ocean circulation following the deglaciation. Hence, throughout the Holocene Thermal Maximum, high latitude radiative forcing was not responsible for the overall conditions of the water column and ocean dynamics, although it might have further enhanced the transport of warm salty water (Risebrobakken et al., 2011). Within the broader study area, Lubinski et al. (2001) associated decreasing δ$^{18}$O values ca. 10 000–6800 cal a BP with a possible increase of surface water temperatures due to a return inflow of warm water. A stronger Atlantic Water inflow delivered by the Svalbard Branch has also been recorded at the western and northern Svalbard margins ca. 8000 cal a BP (Slubowska et al., 2005; Werner et al., 2013) and in the Franz Victoria Trough ca. 7500 cal a BP (Duplessy et al., 2001). However, since the δ$^{18}$O values do not correspond to the observed time-transgressive pattern of the Svalbard Branch, it is assumed that the core site was influenced by Atlantic Water
inflow entering the Barents Sea via the North Cape Current. This is consistent with decreased
δ¹⁸O observations in the southern Barents Sea ca. 11 000–9800 cal a BP (Risebrobakken et
al., 2010), the western Barents Sea ca. 10 000 cal a BP (Berben et al., 2014) and the north-
western Barents Sea ca. 7000 cal a BP (Klitgaard Kristensen et al., 2013) (for study locations
please refer to Fig. 1).

During Period I, the overall high relative abundances of N. pachyderma, in particular ca.
9500–7300 cal a BP, suggest a dominance of Arctic Water masses and cold conditions at the
study site (Volkmann, 2000). However, from ca. 7300–5900 cal a BP, the increased
abundances of sub-polar species as well as of total planktic foraminifera indicate a
pronounced influence of relatively warm Atlantic Water inflow at the core site (Bé and
Tolderlund, 1971; Johannessen et al., 1994; Carstens et al., 1997) (Fig. 6f-g).
Correspondingly, elevated planktic foraminiferal concentrations were recorded in the north-
eastern Barents Sea and linked to an intrusion of Atlantic Water (Duplessy et al., 2001).
Similar interpretations were made for the northern Barents Sea (Klitgaard Kristensen et al.,
2013) and the western Barents Sea (Sarnthein et al., 2003; Berben et al., 2014).

Nonetheless, the timing of changes in Atlantic Water inflow based on planktic foraminiferal
assemblages (ca. 7300–5900 cal a BP) differs from that based on δ¹⁸O (ca. 8800–7300 cal a
BP). In the Arctic Ocean, the calcification of N. pachyderma is linked to phytoplankton
blooms occurring mainly in August (Kohfeld et al., 1996; Volkmann, 2000), whereas the
planktic foraminiferal fauna reflects an annual signal. Additionally, sea ice conditions can
result in a shift in the growing season (e.g. Farmer et al., 2008) and a species-specific change
in its calcification depth. Therefore, the δ¹⁸O of N. pachyderma reflects a different
temperature compared to the total foraminiferal assemblage (Simstich et al., 2003) and might
reflect a different signal with respect to seasonality and/or water depth. Furthermore, the
faunal response depends on more factors than temperature and salinity. For example, T.
quinqueloba also depends on the available food supply (e.g. Volkmann, 2000) and is
characteristic of Arctic Front conditions in the western Barents Sea (Burhol, 1994). An
increased nutrition availability associated with oceanic front conditions might have followed
later in time. Indeed, such a delay in food supply is suggested by increasing δ¹³C values ca.
7300–5800 cal a BP which likely reflect enhanced primary production, possibly associated
with increased seasonal sea ice conditions, as suggested from the IP₂₅ data. Hence, the timing
of increased relative abundances of sub-polar species is probably related to a combination of
enhanced Atlantic Water inflow and increased nutrition availability, as seen previously in the northern Barents Sea (Duplessy et al., 2001).

For Period I, the new proxy data, combined with outcomes from previous studies, indicate that the study site was characterized by reduced sea ice conditions during relatively short spring seasons, enhanced phytoplankton production within the proximity of the sea ice margin, and a winter sea ice margin in the proximity of the core site at ca. 78° N (Fig. 7a). These sea surface conditions were likely influenced by maximum insolation, while the sub-surface water masses were probably controlled more by oceanic dynamics (Andersson et al., 2010; Risebrobakken et al., 2011). In particular, a time-transgressive Atlantic Water inflow resulted in initially cold water masses followed by warmer Atlantic Water at the study site. The strengthening of Atlantic Water inflow might have additionally contributed to the reduced sea ice conditions as seen during modern times in the Barents Sea (Årthun et al., 2012). Such a proposed sea ice scenario implies that water masses south of the study area were ice free, consistent with open water conditions observed in the western Barents Sea (Sarnthein et al., 2003; Berben et al., 2014) and the West Svalbard margin (Müller et al., 2012) (Fig. 7a) during the early Holocene.

**Period II (ca. 5900–2700 cal a BP): marginal ice zone conditions with increasing SpSIC (ca. 60%)**

Throughout Period II, higher IP$_{25}$ concentrations and parallel decreases in brassicasterol and HBI III concentrations reflect increased seasonal sea ice with less open water conditions (Fig. 3a-c). Increasing P$_{III}$IP$_{25}$ and P$_{III}$IP$_{25}$ values indicate marginal ice zone conditions at the study site (Müller et al., 2011; Belt et al., 2015) (Fig. 3e-f) with a mean SpSIC of ca. 60% but increasing throughout this interval to ca. 70% (Fig. 6d). Despite a general increase in SpSIC, however, the P$_{III}$IP$_{25}$ data suggest that the site was probably ice free throughout the summer months (Smik et al., 2016) (Fig. 6c). Similar IP$_{25}$-based reconstructions of sea ice conditions have been attributed to mid Holocene Neoglacial cooling for the northern Fram Strait (Müller et al., 2009) and the West Svalbard margin (Müller et al., 2012).

The heavy δ$^{18}$O (N. pachyderma) values during Period II indicate lower temperatures and a decreased influence of Atlantic Water (Fig. 6e), consistent with previous observations from the region (Duplessy et al., 2001; Klitgaard Kristensen et al., 2013). It has also been
suggested that Arctic Water from the north-eastern Barents Sea might have influenced the western Barents Sea due to less heat advection from the south (Hald et al., 2007).

The dominance of *N. pachyderma*, along with decreased abundances of sub-polar foraminifera, such as *T. quinqueloba* and *N. incompta* indicate the prevailing presence of colder Arctic Water at the core site (Volkmann, 2000) (Fig. 6f-g). This is consistent with foraminifera-based observations of cold conditions after ca. 5200 cal a BP in the eastern Fram Strait (Werner et al., 2013) and reduced Atlantic Water inflow in the western Barents Sea (Sarnthein et al., 2003).

Combined, the biomarker and microfossil proxy data indicate a continuous cooling trend during Period II with a dominance of cold Arctic Water and an accompanying increase in SpSIC, likely as a result of decreasing summer insolation and a cooler surface water layer. Consequently, the strongly reduced Atlantic Water inflow could not have affected the sea ice conditions in the same way as was proposed for Period I. In addition, our data suggest that the maximum winter sea ice margin was probably located ca. 76–77° N or, at least, further south compared to the Period I (Fig. 7a-b). This is in good agreement with sea ice conditions at the continental slope of western Svalbard (Müller et al., 2012), although sea ice did not extend as far as the western Barents Sea (Berben et al., 2014) (Fig. 7b). With respect to the position of the summer sea ice margin, the increased P$_{III}$IP$_{25}$ values also suggest a location further south compared to Period I, consistent with previous observations in the northern Barents Sea after ca. 6000 cal a BP (Duplessy et al., 2001; Klitgaard Kristensen et al., 2013) (Fig. 7b).

**Period III (ca. 2700 cal a BP–present): Arctic frontal conditions with high SpSIC (ca. 75%) and summer sea ice**

Increases to IP$_{25}$, P$_{III}$IP$_{25}$ and P$_{III}$IP$_{25}$ reflect further increases in spring sea ice conditions during Period III (Fig. 3a; e-f), while lower brassicasterol and HBI III concentrations indicate less open water phytoplankton production consistent with lower TOC values (Fig. 3b-d). These results point to Arctic frontal conditions that are similar to the modern setting (Müller et al., 2011; Belt et al., 2015). Indeed, the P$_{III}$IP$_{25}$-based SpSIC estimates (ca. 75%) align closely with contemporary values derived from satellite records (Smik et al., 2016) (Fig. 6c-d), while P$_{III}$IP$_{25}$ values generally >0.8 are also indicative of the occurrence of summer sea ice (Smik et al., 2016), also a feature of the modern setting. Consistent with these findings,
extended sea ice conditions have been reported for the Fram Strait for the last ca. 3000 cal a BP (Müller et al., 2012).

The mainly light, but variable, δ^{18}O (N. pachyderma) values, are most likely indicative of a generally increased influence of Atlantic Water inflow (Fig. 6e), consistent with previous reports of episodic increases in Atlantic Water for the northern Barents Sea (Duplessy et al., 2001; Lubinski et al., 2001), the western Barents Sea (Wilson et al., 2011; Berben et al., 2014) and the Svalbard margin (Jernas et al., 2013; Werner et al., 2013) during the late Holocene.

The decrease in N. pachyderma and increased relative abundance of sub-polar foraminifera, especially G. bulloides, which is usually associated with the warmest parts of the Norwegian Atlantic Current (Johannessen et al., 1994) also reflect the generally increasing influence of Atlantic Water during this period (Fig. 6f-g). However, the fluctuations in the faunal data throughout Period III still indicate variability in the influence of Atlantic Water consistent with previous findings from the western Barents Sea (Sarnthein et al., 2003).

The increase in sea ice conditions reflects an overall cooling trend recorded previously in various Arctic terrestrial (e.g. Bjune et al., 2009; Kaufman et al., 2009), ice core (e.g. Kaufman et al., 2009; Divine et al., 2011) and marine records (e.g. Slubowska et al., 2005; Skirbekk et al., 2010), likely resulting from lower insolation affecting the sea surface. A negative solar irradiance anomaly ca. 2850–2600 cal a BP may also have resulted in decreased ventilation of the sub-surface waters, as corroborated by modelling experiments (Renssen et al., 2006). Meanwhile, the increased influence of Atlantic Water inflow might be attributed to stronger stratification among the upper layers as seen in previous studies of the Barents Sea (Lubinski et al., 2001; Duplessy et al., 2005; Risebrobakken et al., 2010; Wilson et al., 2011) and the Svalbard margin (Jernas et al., 2013; Werner et al., 2013).

The occurrence of sea surface cooling and sub-surface warming indicates that Period III was most likely characterized by a strong vertical stratification and a decoupling between the atmosphere and the oceanic sub-surface. Summer insolation was at its lowest during Period III (Fig. 6a), resulting in cooler atmospheric temperatures and potentially enhanced sea ice production and/or reduced sea ice melt. In addition to the stronger vertical stratification of the water column, the increased sea ice conditions probably also limited the heat exchange between the atmosphere and the sub-surface water masses. In terms of seasonality, we suggest that relatively long spring seasons with extensive sea ice conditions would have been
accompanied by shorter (and probably cooler) summers with lower phytoplankton production (Fig. 7c). Overall, the site was characterized by extensive sea ice conditions (SpSIC typically ca. 75%) with at least partial sea ice occurrence in the summer months (Fig. 7c). Such interpretations are also consistent with previous qualitative reports of intensified sea ice occurrence in the northern Barents Sea (Duplessy et al., 2001; Klitgaard Kristensen et al., 2013), increasing sea ice conditions in the Fram Strait (Müller et al., 2009, 2012; Werner et al., 2014) and in the western Barents Sea throughout the last ca. 1100 cal a BP (Berben et al., 2014). Hence, the data suggest a south-westwards transgression of the sea ice margin (Fig. 7c). Finally, the sea ice conditions most likely exceeded the modern sea ice margin during the (pre-industrial) late Holocene (Fig. 7c). A slight reversal in the extent of spring sea ice conditions during recent decades and a return to more open water conditions during summer (c.f. Period II) is evident during the last ca. 100 yr from observational records (Divine and Dick, 2006).

Conclusions

Early to late Holocene semi-quantitative estimates of SpSIC and the qualitative occurrence of summer sea ice in the northern Barents Sea have been reconstructed based on the variability of source-specific biomarkers within a marine sediment core taken from the Olga Basin. Additional proxy data based on planktic foraminifera that reflect the sub-surface water masses have demonstrated the evolution of Atlantic Water inflow to the Barents Sea. The major palaeoceanographic evolution can be summarised as follows: During Period I (ca. 9500–5900 cal a BP), reduced SpSIC (ca. 25%) was controlled, primarily, by relatively high summer insolation. The core site was also influenced by Atlantic Water entering the Barents Sea via the North Cape Current which caused an increased heat exchange between the ocean and the atmosphere and likely contributed to reduced sea ice conditions. The site was probably located close to the maximum winter sea ice margin, such that it experienced only relatively short periods of sea ice during the spring together with long (ice-free) productive summers.

An overall cooling trend characterized Period II (ca. 5900–2700 cal a BP), with increased SpSIC (ca. 60%) and delivery of cold Arctic Water. This interval was also characterized by a general southward advance of the winter and summer sea ice margins, although, summer months were still ice free.
Period III (ca. 2700 cal a BP–present) was marked by extensive SpSIC (ca. 75%), partial
summer sea ice occurrence and increased Atlantic Water inflow. Increased sea ice conditions
were probably induced by progressively lower insolation, while sub-surface warming due to
increased Atlantic Water demonstrates a likely decoupling between the atmosphere and the
ocean. The maximum winter sea ice margin was probably at its most southerly location within
the record, with long spring seasons of extensive sea ice conditions followed by shorter and
less productive summers. A slight retreat in the position of the winter sea ice margin is
proposed for recent decades based on observational records.

Supporting information

Additional supporting information related to this article may be found in the online version of
this article.

Table S1. CTD data presented in Fig. 1

Table S2. Age model presented in Fig. 2

Table S3. Biomarker data presented in Fig. 3

Table S4. Foraminiferal fauna data presented in Fig. 4

Table S5. Stable isotope data presented in Fig. 5

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Figure captions

Table 1. Depth-age model of NP05-11-70GC calibrated using Calib 6.1.1 (Stuiver and Reimer, 1993), the Marine09 calibration curve (Reimer et al., 2009) and a local reservoir age (ΔR) of 105±24 after Mangerud et al. (2006).

Figure 1. The modern oceanography is presented on a bathymetric map of the Barents Sea area. The core location of NP05-11-70GC is indicated by a black star, whereas previously published records are indicated by number: (1) Risebrobakken et al. (2010), (2) Wilson et al. (2011), (3) Berben et al. (2014), (4) Rasmussen et al. (2007), (5) Müller et al. (2012), Werner et al. (2013), (6) Skirbekk et al. (2010); Jernas et al. (2013), (7) Müller et al. (2009), (8) Slubowska et al. (2005); Jernas et al. (2013), (9) Kliitgaard Kristensen et al. (2013), (10) Lubinski et al. (2001), (11) Duplessy et al. (2001); (2005), (12) Risebrobakken et al. (2011), and (13) Duplessy et al. (2005). Northern Barents Sea Opening (NBSO), Barents Sea Opening (BSO), Barents Sea Exit (BSX). (a) The main surface currents (Hopkins, 1991). Atlantic Water (red): Norwegian Atlantic Current (NwAC), North Cape Current (NCaC), West Spitsbergen Current (WSC), Return Atlantic Current (RAC), Yermak Branch (YB) and Svalbard Branch (SB). Polar Water (blue): Bear Island Current (BIC) and East Spitsbergen Current (ESC). Coastal Water (black). (b) Seasonal sea ice margins (April (purple) and August (orange)) for the period 1981–2010 (National Snow and Ice Data Centre (NSIDC) Boulder Colorado, www.nsidc.com). The observed sea ice margin for April (dotted) and August (dashed) from historical data for four sub-periods between 1870 and 2002: 1870–1920 (red), 1921–1961 (yellow), 1962–1988 (pink) and 1989–2002 (black) (Divine and Dick, 2006). (c) Temperature (black) and Salinity (grey) profile at the NP05-11-70GC core site (78.40° N, 32.42° E). Water masses are defined according Gammelsrød et al. (2009).

Figure 2. Depth-age model of NP05-11-70GC. Calibrated radiocarbon ages versus depth with a linear interpolation between the dated levels. Error bars indicate the sampled depth intervals and a 2-σ error on the calibrated ages.

Figure 3. Biomarker analysis versus cal a BP and core depth. The black diamonds on the Y-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) Sea ice biomarker IP25 versus age. (b) Phytoplankton biomarker brassicasterol versus age. (c) Phytoplankton-derived HBI III biomarker versus age. Biomarker concentrations are normalized to total organic carbon (black) and to sediment mass (grey). (d) Total organic carbon versus age. (e) PBIP25 versus age. (f) PBIP25 versus age. >5% summer sea ice concentration (SuSIC) is also indicated when PBIP25 exceeds a value of 0.8 (Smik et al., 2016). (g) Estimated spring sea ice concentration (SpSIC) versus age.

Figure 4. Planktic foraminiferal fauna and preservation indicator analysis versus cal a BP and core depth. The black diamonds on the Y-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) Total planktic foraminiferal concentration versus age. (b) Planktic foraminiferal fragmentation versus age. (c) Mean shell weight of N. pachyderma versus age. (d-i) Species-specific relative abundance versus age.

Figure 5. Stable isotopes analysis performed on N. pachyderma versus cal a BP and core depth. The black diamonds on the X-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) δ18O measurements corrected for ice volume effect after Fairbanks (1989) (black) and uncorrected δ18O measurements (grey) versus age. (b) δ13C measurements versus age.

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Figure 6. Multi-proxy analysis versus cal a BP and core depth. The black diamonds on the Y-axis denote the AMS $^{14}$C converted to calibrated radiocarbon ages. (a) July insolation at 78° N (Laskar et al., 2004) (note the reversed axis) versus age. (b) Sea ice biomarker IP$_{25}$ versus age. Concentrations are normalized to total organic carbon (black line) and to sediment mass (grey line). (c) P$_{III}$IP$_{25}$ versus age. >5% summer sea ice concentration (SuSIC) is also indicated when P$_{III}$IP$_{25}$ exceeds a value of 0.8 (Smik et al., 2016). (d) Estimated spring sea ice concentration (SpSIC) versus age. (e) $\delta^{18}$O measurements corrected for ice volume effect after Fairbanks (1989) versus age. (f) Relative abundance of N. pachyderma versus age. (g) Planktic foraminiferal concentration versus age. (b-d) The in dark grey highlighted period reflects decreased sea ice conditions, whereas the in light grey highlighted periods indicate increased sea ice conditions. (e-g) The in grey highlighted periods are characterized by an increased influence of Atlantic Water.

Figure 7. Illustrations of the proposed seasonal sea ice scenarios at the NP05-11-70GC core location (black star). The shaded areas surrounding the dotted lines represent the proposed variability of the sea ice margin for March (black), April (purple) and August (orange), whereas the numbers indicate the core locations of previous studies: (1) Berben et al. (2014), (2) Müller et al. (2012), (3) Müller et al. (2009), (4) Klitgaard Kristensen et al. (2013), and (5) Duplessy et al. (2001). (a) Period I. (b) Period II. (c) Period III (dotted lines with shaded areas) and present day situation (full lines) based on mean sea ice margins (1981–2010) (National Snow and Ice Data Centre (NSIDC) Boulder Colorado, www.nsidc.com).
### Table 1

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<td>30</td>
<td>2281—2496</td>
<td>2389</td>
</tr>
<tr>
<td>Beta-346803</td>
<td>67 - 72</td>
<td>Benthic foraminifera</td>
<td>6110</td>
<td>40</td>
<td>6298—6536</td>
<td>6417</td>
</tr>
<tr>
<td>Beta-331328</td>
<td>122 - 127</td>
<td>Benthic foraminifera</td>
<td>8870</td>
<td>50</td>
<td>9307—9527</td>
<td>9417</td>
</tr>
<tr>
<td>Beta-331329</td>
<td>213 - 230</td>
<td>Benthic foraminifera</td>
<td>&gt; 43500</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. The modern oceanography is presented on a bathymetric map of the Barents Sea area. The core location of NP05-11-70GC is indicated by a black star, whereas previously published records are indicated by number: (1) Risebrobakken et al. (2010), (2) Wilson et al. (2011), (3) Berben et al. (2014), (4) Rasmussen et al. (2007), (5) Müller et al. (2012); Werner et al. (2013); Skirbekk et al. (2010); Jernas et al. (2013), (7) Müller et al. (2009), (8) Slubowska et al. (2005); Jernas et al. (2013), (9) Klitgaard Kristensen et al. (2013), (10) Lubinski et al. (2001), (11) Duplessy et al. (2001); (2005), (12) Risebrobakken et al. (2011), and (13) Duplessy et al. (2005). Northern Barents Sea Opening (NBSO), Barents Sea Opening (BSO), Barents Sea Exit (BSX). (a) The main surface currents (Hopkins, 1991). Atlantic Water (red): Norwegian Atlantic Current (NwAC), North Cape Current (NCC), West Spitsbergen Current (WSC), Return Atlantic Current (RAC), Yermak Branch (YB) and Svalbard Branch (SB). Polar Water (blue): Bear Island Current (BIC) and East Spitsbergen Current (ESC). Coastal Water (black). (b) Seasonal sea ice margins (April (purple) and August (orange)) for the period 1981–2010 (National Snow and Ice Data Centre (NSIDC) Boulder Colorado, www.nsidc.com). The observed sea ice margin for April (dotted) and August (dashed) from historical data for four sub-periods between 1870 and 2002: 1870–1920 (red), 1921–1961 (yellow), 1962–1988 (pink) and 1989–2002 (black) (Divine and Dick, 2006). (c) Temperature (black) and Salinity (grey) profile at the NP05-11-70GC core site (78.40° N, 32.42° E). Water masses are defined according Gammelsrød et al. (2009).

210x202mm (300 x 300 DPI)
Figure 2. Depth-age model of NP05-11-70GC. Calibrated radiocarbon ages versus depth with a linear interpolation between the dated levels. Error bars indicate the sampled depth intervals and a 2-σ error on the calibrated ages.
Figure 3. Biomarker analysis versus cal a BP and core depth. The black diamonds on the Y-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) Sea ice biomarker IP25 versus age. (b) Phytoplankton biomarker brassicasterol versus age. (c) Phytoplankton-derived HBI III biomarker versus age. Biomarker concentrations are normalized to total organic carbon (black) and to sediment mass (grey). (d) Total organic carbon versus age. (e) PBIP25 versus age. (f) PIIIIP25 versus age. >5% summer sea ice concentration (SuSIC) is also indicated when PIIIIP25 exceeds a value of 0.8 (Smik et al., 2016). (g) Estimated spring sea ice concentration (SpSIC) versus age.
Figure 4. Planktic foraminiferal fauna and preservation indicator analysis versus cal a BP and core depth. The black diamonds on the Y-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) Total planktic foraminiferal concentration versus age. (b) Planktic foraminiferal fragmentation versus age. (c) Mean shell weight of N. pachyderma versus age. (d-i) Species-specific relative abundance versus age.

198x334mm (300 x 300 DPI)
Figure 5. Stable isotopes analysis performed on N. pachyderma versus cal a BP and core depth. The black diamonds on the X-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) $\delta^{18}O$ measurements corrected for ice volume effect after Fairbanks (1989) (black) and uncorrected $\delta^{18}O$ measurements (grey) versus age. (b) $\delta^{13}C$ measurements versus age.
Figure 6. Multi-proxy analysis versus cal a BP and core depth. The black diamonds on the Y-axis denote the AMS 14C converted to calibrated radiocarbon ages. (a) July insolation at 78° N (Laskar et al., 2004) (note the reversed axis) versus age. (b) Sea ice biomarker IP25 versus age. Concentrations are normalized to total organic carbon (black line) and to sediment mass (grey line). (c) PIIIIP25 versus age. >5% summer sea ice concentration (SuSIC) is also indicated when PIIIIP25 exceeds a value of 0.8 (Smik et al., 2016). (d) Estimated spring sea ice concentration (SpSIC) versus age. (e) δ18O measurements corrected for ice volume effect after Fairbanks (1989) versus age. (f) Relative abundance of N. pachyderma versus age. (g) Planktic foraminiferal concentration versus age. (b-d) The in dark grey highlighted period reflects decreased sea ice conditions, whereas the in light grey highlighted periods indicate increased sea ice conditions. (e-g) The in grey highlighted periods are characterized by an increased influence of Atlantic Water.
Figure 7. Illustrations of the proposed seasonal sea ice scenarios at the NP05-11-70GC core location (black star). The shaded areas surrounding the dotted lines represent the proposed variability of the sea ice margin for March (black), April (purple) and August (orange), whereas the numbers indicate the core locations of previous studies: (1) Berben et al. (2014), (2) Müller et al. (2012), (3) Müller et al. (2009), (4) Klitgaard Kristensen et al. (2013), and (5) Duplessy et al. (2001). (a) Period I. (b) Period II. (c) Period III (dotted lines with shaded areas) and present day situation (full lines) based on mean sea ice margins (1981–2010) (National Snow and Ice Data Centre (NSIDC) Boulder Colorado, www.nsidc.com).

210x296mm (300 x 300 DPI)