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Short note

A first southern Lomonosov Ridge (Arctic Ocean) 60 ka IP_{25} sea-ice record

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Abstract: Here, we present a low-resolution biomarker sea-ice record from the High Arctic (southern Lomonosov Ridge), going back in time to about 60 ka (MIS 3 to MIS 1). Variable concentrations of the sea-ice diatom-specific highly branched isoprenoid (HBI) with 25 carbon atoms ("IP_{25}"), in combination with the phytoplankton biomarker brassicasterol, suggest variable seasonal sea-ice coverage and open-water productivity during MIS 3. During most of MIS 2, the spring to summer sea-ice margin significantly extended towards the south, resulting in a drastic decrease in phytoplankton productivity. During the Early Holocene Climate Optimum, brassicasterol reached its maximum, interpreted as signal for elevated phytoplankton productivity due to a significantly reduced sea-ice cover. During the mid-late Holocene, IP_{25} increased and brassicasterol decreased, indicating extended sea-ice cover and reduced phytoplankton productivity, respectively. The HBI diene/IP_{25} ratios probably reached maximum values during the Bølling-Allerød warm period and decreased during the Holocene, suggesting a correlation with sea-surface temperature.

Zusammenfassung: Mit dieser Pilotstudie wurde erstmals der neue Biomarker für Meereis (IP_{25}) in bis zu 60,000 Jahre alten Sedimenten vom südlichen Lomonosov-Rücken nahe des ostsibirischen Kontinentalrandes nachgewiesen. Obwohl weder die zeitliche Auflösung der Datenpunkte noch das Altersmodell dieser Studie hochaufgelöste Klimarekonstruktionen erlauben, ist es möglich, wichtige erste generelle Aussagen über die Veränderung der Meereisbedeckung in der hohen Arktis im Verlauf der Marinen Isotopenstadien (MIS) 3 bis 1 zu machen. Im MIS 3 weisen Minima und Maxima der untersuchten Biomarker auf eine kurzfristige Variabilität der Meereisbedeckung und Primärproduktition hin, die auf kurzfristige Klimaschwankungen zurückzuführen sein könnten. Im letzten Glazial führte eine ausgedehnte Meereisbedeckung wahrscheinlich zu einer deutlichen Abnahme der Primärproduktion. Während der Bølling-Allerød-Warm-Periode deuten dagegen minimale IP_{25}-Werte und maximale Werte für Phytoplankton-Biomarker auf eine drastisch reduzierte Eisbedeckung und erhöhte Primärproduktion hin. Im weiteren Verlauf des Holozäns nimmt dann die Meereisbedeckung wieder zu. Parallel dazu weist der Phytoplankton-Biomarker auf eine Abnahme der Primärproduktion. Das Verhältnis C_{25}-HBI dien/IP_{25} erreicht maximale Werte in der Bølling-Allerød-Warmperiode und nimmt dann – parallel mit der holozänen Klimaabkühlung – ab, was auf eine Korrelation zwischen diesem Verhältnis und der Oberflächenwassertemperatur hinweisen mag.

INTRODUCTION

A most prominent characteristic of the modern Arctic Ocean is the sea-ice cover with its strong seasonal variability in the marginal (shelf) seas (Fig. 1; e.g., JOHANNESSEN et al. 2004), STROEVE et al. 2007, STEIN 2008 for review). Furthermore, sea ice is a critical component in the climate system, contributing to changes in Earth's albedo, biological processes and deep-water formation, a driving mechanism of the global thermohaline circulation. Despite the importance of sea ice, however, detailed information about the extent and variability of sea ice in the geological past is still very sparse. In this context, a novel biomarker approach which is based on the determination of sea-ice diatom specific highly branched isoprenoids (HBI) with 25 carbon atoms (C_{25} HBIs - "IP_{25}"; BELT et al. 2007; for background information see also STEIN et al. this vol.), seems to be a major step forward in getting more qualitative and – especially in combination with other open-water phytoplankton biomarkers such as brassicasterol and/or dinosterol (MÜLLER et al. 2009, 2011) – even more quantitative data on paleo-sea-ice distributions.

In following-up studies, the identification of this new sea-ice proxy IP_{25} in marine sediment cores from the Canadian Arctic Archipelago (BELT et al. 2010, VARE et al. 2009, GREGORY et al. 2010), the shelf north of Iceland (MASSÉ et al. 2008), the Barents Sea (VARE et al. 2010), northern Fram Strait and off East Greenland (MÜLLER et al. 2009, 2011, 2012), and the Lomonosov Ridge in the central Arctic Ocean (FAHL & STEIN 2012) allowed reconstructions of the ancient sea-ice variability in these regions during the last 30 Cal. kyrs. BP (ka).

As result of this first study, we present a first IP_{25} record from the High Arctic, going back in time to about 60 ka.

METHODS AND MATERIAL

Core PS2767-4 (79°44.6' N, 144°00.4' E) was recovered at the interception of the southern Lomonosov Ridge and the East Siberian Sea continental margin at a water depth of 584 m during RV "Polarstern" Expedition ARK-XI/1 in 1995 (RACHOR 1997), located close to the modern September ice edge (Fig. 1). This core – together with several other cores from the Laptev Sea continental margin – has already been studied in order to identify organic-carbon sources (i.e., primary productivity *versus* terrigenous input) and their variations related to climate change, using organic geochemical bulk parameters and selected biomarkers (*n*-alkanes) (STEIN et al. 2001). For the Holocene to postglacial time interval, the age model of the sediment cores was primarily based on AMS^{14}C datings and magnetic susceptibility records (STEIN et al. 2001). In most of the cores, the base of the Holocene is characterized by a prominent decrease in magnetic susceptibility that can be used to correlate all the cores from the Laptev Sea continental margin (e.g., STEIN & FAHL 2000). For the sediment cores representing older, pre-Holocene intervals, the stratigraphy is based on oxygen isotope stratigraphy, magnetostratigraphy, biostratigraphy (especially dinoflagellates), lithostratigraphy, and magnetic susceptibility records (STEIN et al. 2001 and further references therein). As the number of AMS^{14}C datings is very limited and no further new chronological data have been produced so far, the existing age model is still tentative. Based on this age model, core PS2767-4 probably represents the last about 60 ka.

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For biomarker analyses we follow the procedure published by Müller et al. (2011) and Fahl & Stein (2012). Briefly summarized, the extraction of the freeze-dried sediments was carried out by an Accelerated Solvent Extractor. For quantification the internal standards 7-hexylnonadecane, squalane and cholesterol-d_6 (cholest-5-en-3β-ol-D_6) were added prior to analytical treatment. Separation of the hydrocarbons and sterol fractions was carried out via open-column chromatography (for further details and instrumental conditions see Fahl & Stein 2012 and further references therein). Individual compound identification was based on comparisons of their retention times with that of reference compounds and published mass spectra. The details about the quantification of the C_{25}-HBI alkenes (i.e., IP_{25} and HBI diene) and brassicasterol (24-methylcholesta-5,22E-dien-3β-ol) are described in Fahl & Stein (2012) and Fahl & Stein (1999), respectively.

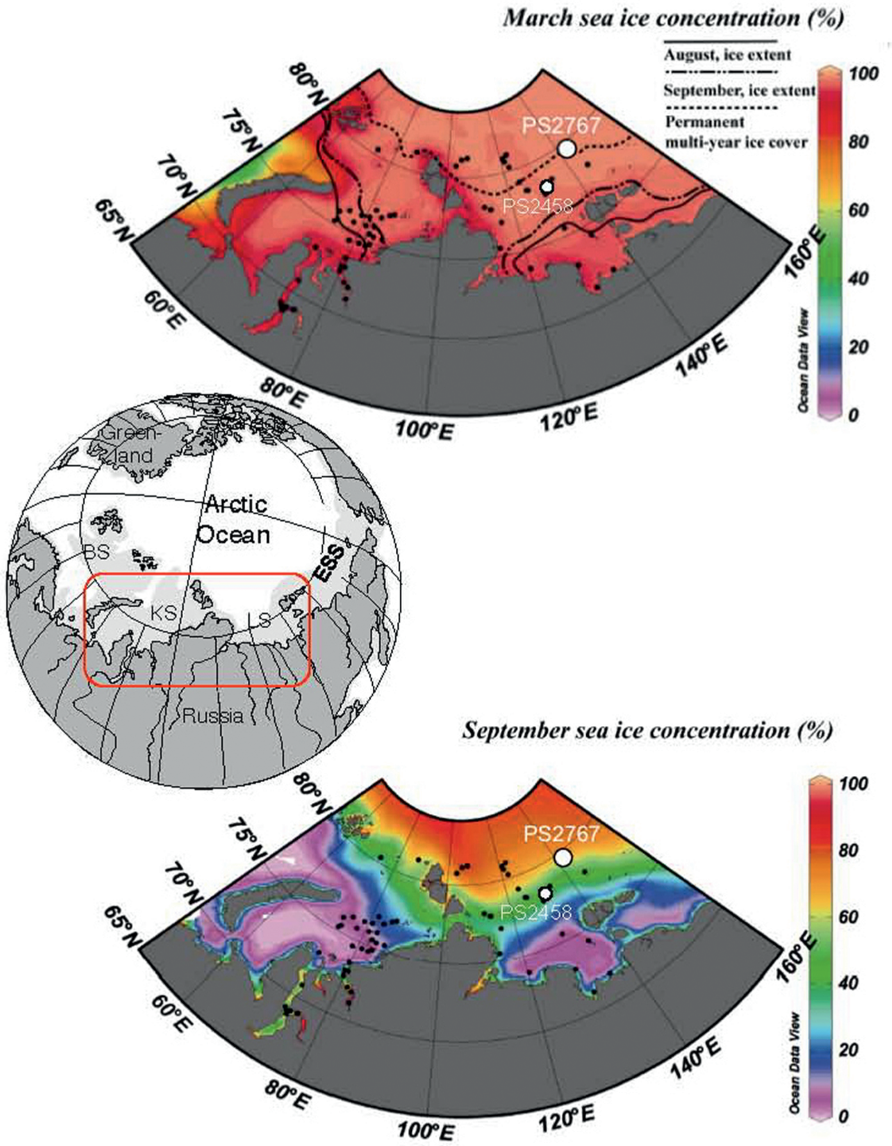

Fig. 1: Averaged sea-ice concentration in (A) March and (B) September from 1978-2007 (http://nsidc.org). Dashed line indicates southern boundary of permanent sea-ice cover (>60 % through the year). August and September boundaries of sea-ice cover represent the 30 % isoline for the specific months. Locations of core PS2767-4 and core PS2458-4 are indicated.

Abb. 1: Durchschnittliche Meereiskonzentration für März (A) und September (B) für das Zeitintervall 1978-2007 (http://nsidc.org). Die gestrichelte Linie zeigt die südliche Grenze der permanenten Meereisbedeckung (>60 % Eisbedeckung das ganze Jahr über). Zusätzlich sind für die Monate August und September die südlichen Grenzen für eine Meereisbedeckung von >30 % eingetragen. Die Lokationen der Kerne PS2767-4 und PS2458-4 sind angezeigt.

RESULTS AND DISCUSSION

With the biomarker records determined in the sediments from core PS2767-4 we yield some direct information about the development and variability of the sea-ice conditions in the High Arctic at the interception of the Lomonosov Ridge and the East Siberian Sea continental margin during the last about 60 ka. Although the data set produced within this study neither represents a high-resolution record nor has a precise age model needed for paleoenvironmental reconstruction with centennial- to millennial-scale resolution, it allows some statements related to general trends in sea ice and climate conditions from MIS 3 to MIS 1.

Based on the biomarker data (Fig. 2), the records can be divided into three sections, coinciding approximately with MIS 3, MIS 2, and MIS 1. During MIS 3, i.e., between about 60 and 30 ka, variable concentrations of the phytoplankton biomarker brassicasterol and the sea-ice proxy IP_{25} were determined, suggesting variable seasonal sea-ice coverage and open-water periods typical for ice-edge situations (cf. Müller et al. 2011, Fahl & Stein 2012). These minimum and maximum values may reflect short-term climate changes (Fig. 2) although, of course, our low-resolution record does not allow to resolve such high-frequency climate variability.

For most of the interval between 30 and 15 ka (Late Weichselian glacial phase to early deglaciation), both brassicasterol and IP_{25} concentrations reached minimum values around zero (Fig. 2). Following Müller et al. (2009), the absence of both IP_{25} and brassicasterol is interpreted as a period of permanently closed sea-ice cover. Under such conditions, sea-ice diatom and phytoplankton growth is limited since the presence of thick pack ice inhibits light penetration and enhanced stratification reduces nutrient availability. These observations suggest that the spring to summer sea-ice margin significantly extended towards the south during most of MIS 2, coinciding with a minimum in summer insolation (Fig. 2). This situation is very similar to that described for the Fram Strait area based on the same set of biomarkers (Müller et al. 2009).

At the end of the glacial, both brassicasterol and IP_{25} concentrations increased which may suggest conditions favourable

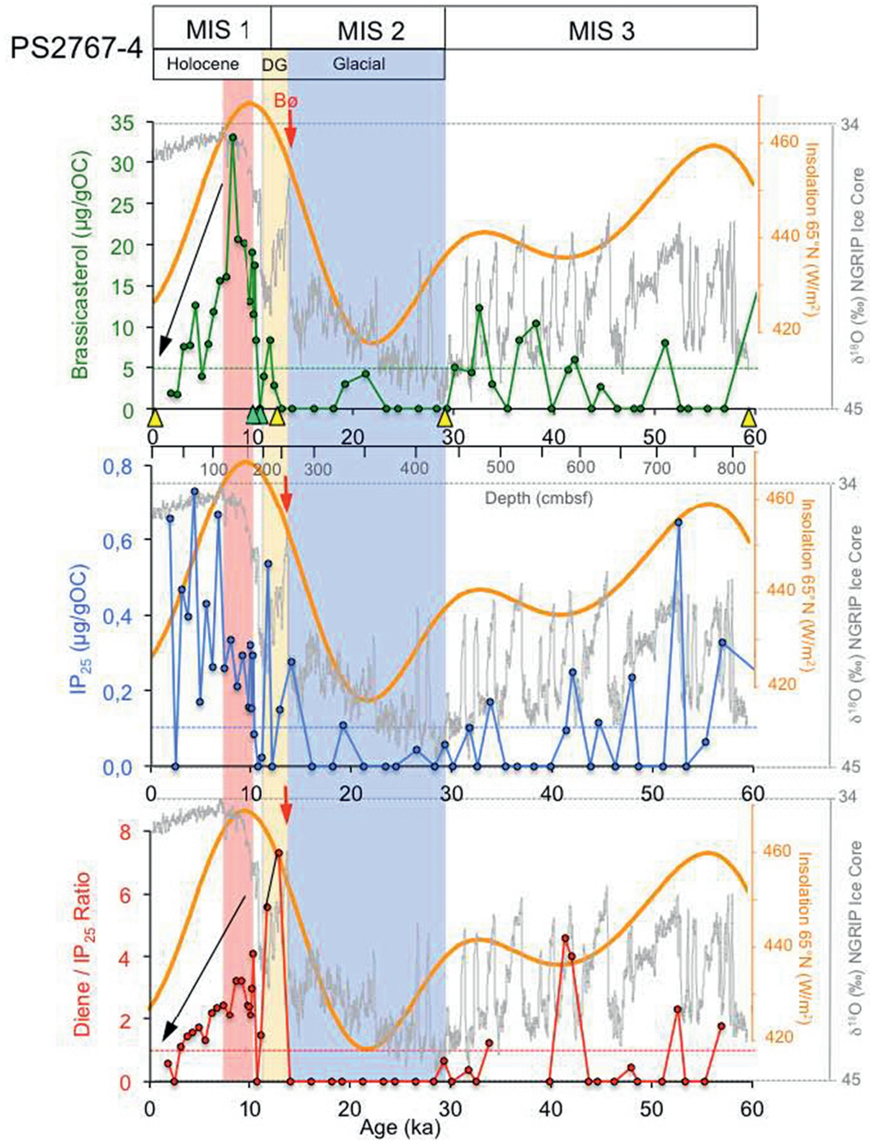

Fig. 2: Concentrations of brassicasterol (green curve) and IP_{25} (blue curve) (in μg/g OC) as well as HBI_{25} diene/IP_{25} ratios (red curve) determined in Core PS2767-4 and plotted versus age. Marine Isotope Stages (MIS) and age model according to STEIN et al. (2001); green triangles indicate depth of AMS^{14}C datings, yellow triangles top and base of MIS 1 to MIS 3. Glacial phase (blue bar), deglacial phase – DG (yellow bar) and Holocene with Holocene Climate Optimum (red bar) are highlighted. Red arrow indicates Bølling peak warm interval (Bø). As background information for the climatic evolution during the last 60 ka, the insolation record (orange curve; BERGER & LOUTRE 1999)) and the oxygene isotope record of the NGRIP Ice Core (light gray curve NGRIP MEMBERS 2004) are shown.

Abb. 2: Konzentrationen des Phytoplankton-Biomarkers Brassicasterol (grüne Kurve) und des Meereis-Biomarkers IP_{25} (blaue Kurve) und das Verhältnis der Biomarker HBI_{25}-Dien/IP_{25} (rote Kurve), ein möglicher Biomarker-Proxy für die Oberflächenwassertemperatur (cf. ROWLAND et al. 2001), geplottet gegen das Alter. Marine Isotopenstadien (MIS) und Altermodell nach STEIN et al. (2001): Grüne Dreiecke markieren Tiefen von AMS^{14}C-Altern, gelbe Dreiecke Top und Basis von MIS 1 bis 3. Glazialphase (blauer Balken), Abschmelzphase (gelber Balken) und das Holozän mit dem Holozänen Klimaoptimum (roter Balken) sind farblich hervorgehoben. Als Hintergrundinformation sind zusätzlich die Insolationskurve für 65° N (orange Kurve; BERGER & LOUTRE 1999) und die Sauerstoffisotopenkurve des NGRIP-Eiskerns (hellgraue Kurve; NGRIP MEMBERS 2004) dargestellt.

for production of phytoplankton and sea-ice algae as typical for an ice-edge situation (cf., MÜLLER et al. 2009, 2011, FAHL & STEIN 2012). During the Early Holocene, between about 10 and 7 ka, brassicasterol values reached a prominent maximum, followed by a steady decrease during the late Holocene. The IP_{25} values, on the other hand, display a high-amplitude variability with an opposite trend towards higher IP_{25} values during the Holocene. The brassicasterol maximum more or less coincided with the Early Holocene Climate Optimum (cf., KAUFMAN et al. 2004, CRONIN et al. 2010), interpreted as signal for increased phytoplankton productivity due to a reduced sea-ice cover. During the Holocene, sea-ice cover increased and phytoplankton productivity decreased, as reflected in the opposing trends of the two biomarker records (Fig. 2). This interpretation is in agreement with multi-proxy compilations based on calcareous microfossils, drift wood, bowhead whale and IP_{25} data from other Arctic sites as well as climate models indicating that early Holocene temperatures were higher than today and that the Arctic contained less ice, consistent with a high intensity of orbitally-controlled spring and summer insolation that peaked around 10–11 ka and gradually decreased thereafter (Fig. 2; e.g., CRUCIFIX et al. 2002, GOOSSE et al. 2007, JAKOBSSON et al. 2010 and further references therein).

In addition to IP_{25}, the C_{25}-HBI diene was determined in the sediment samples from core PS2767-4 as well. Both isomers, IP_{25} and the HBI diene, display a quite similar, mostly parallel variability in the available Arctic sedimentary records (VARE et al. 2009, FAHL & STEIN 2012). In addition to its use as sea-ice proxy, however, the combination of IP_{25} and the HBI diene might give additional information about the sea-surface temperature. This assumption is based on the study by ROWLAND et al. (2001) who found that the grade of unsaturation increases with diatom growth temperature (for further background information see also STEIN et al. 2012, this vol.). Such a relationship seems to be reflected in the HBI diene/IP_{25} ratio determined in close-by core PS2458-4 (see Fig. 1 for location), reaching maximum values during the Bølling-Allerød warm interval and decreasing parallel to the Holocene climate cooling trend (FAHL & STEIN 2012). The HBI diene/IP_{25} ratio determined in the sedimentary record of core PS2767-4 shows a very similar deglacial to Holocene trend as core PS2458-4 and seems to support the interpretation by FAHL & STEIN (2012). During the glacial cold interval, the HBI diene is totally absent whereas during the deglacial phase an absolute maximum of the HBI diene/IP_{25} ratio was determined, probably coinciding with the Bølling peak warm interval (Fig. 2). During the Holocene, the HBI diene/IP_{25} ratio decreases, parallel to the Holocene cooling trend. Unfortunately, the age model as well as the time-resolution of the core PS2767-4 record are not good enough to prove the hypothesis that the HBI diene/IP_{25} ratio might have the potential for becoming a new temperature proxy for low-SST environments. Here, certainly more data and ground-truth studies are needed.

CONCLUSIONS

Within this pilot study, the novel sea-ice proxy IP_{25} developed by BELT et al. (2007) was determined in a low-resolution record going back in time to about 60 ka. Concentrations of IP_{25}, in combination with the phytoplankton biomarker brassicasterol, give first information about changes in the sea-ice cover in the East Siberian Sea continental margin area during MIS 3 to MIS 1. The HBI diene/IP_{25} ratios seem to follow the deglacial to Holocene warming and cooling trends, suggesting a correlation with sea-surface temperature.

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