Variability of sea-ice conditions in the Fram Strait over the past 30,000 years

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Sea ice is a critical component of the climate system: variations in sea-ice cover affect the albedo of polar regions, and also the rate of deepwater formation[1,2]. Changes in the sea-ice cover of the North Atlantic Ocean are thought to have been related to abrupt climate changes throughout the last glacial termination[3], but reconstructions of sea-ice conditions are rare. Here we use the sedimentary abundance of the IP_{25} and brassicasterol biomarkers, produced by sea-ice-associated diatoms and open-water phytoplankton, respectively, to generate a record of sea-ice conditions in the northernmost Atlantic Ocean for the past 30,000 years. Our reconstruction shows that a stationary margin between sea-ice cover and the open ocean existed during the Last Glacial, although perennial sea-ice cover prevailed for most of the Last Glacial Maximum. An early warming about 14,000 years ago was associated with ice-free conditions; however, seasonal sea ice was present throughout the Holocene. We find temporal links between our record of sea ice and reconstructions of the amount of relatively warm Atlantic water advected into the Nordic Seas[4,5]. We therefore conclude that changes in sea-ice conditions are linked to regional and global climate anomalies and oceanographic circulation in the North Atlantic.

The distribution of sea ice in Fram Strait, the only deepwater connection (∼2,600 m mean water depth) between the Arctic and Atlantic oceans, is mainly controlled by the inflow of temperate water from the North Atlantic along the western continental margin of Spitsbergen through the Norwegian and West Spitsbergen currents[1]. In contrast, the East Greenland current carries cold water (and sea ice) southward through this gateway[1] (Fig. 1). The relative contributions of these currents strongly influence the thermohaline circulation, thus contributing to global climate[1].

Previously, it has been shown that, when detected in marine sediments, a C_{25} isoprenoid lipid (IP_{25}) biosynthesized by Arctic sea-ice diatoms acts as a proxy for previous spring sea-ice occurrence and subsequent melt[6,7], whereas the phytoplankton-derived sterol brassicasterol, reflects open-ocean conditions during summer[8]. In the current study, we present organic carbon[9] (global productivity and terrigenous organic carbon input) and fluxes of IP_{25} (sea ice) and brassicasterol (phytoplankton; ref. 9) for a sediment core (PS2837-5) from the western flank of the Yermak Plateau (81° 13.99′ N, 02° 22.85′ E, northwest of Spitsbergen, 1,042 m water depth; ref. 10) close to the present-day summer sea-ice margin in Fram Strait (Fig. 1). We use the previously reported age model of PS2837-5, which is based on 14 accelerator mass spectrometry ^{14}C ages of tests of the planktic foraminifer *Neogloboquadrina pachyderma* sin. and assumes a marine-reservoir correction of 400 years and linear interpolation between ^{14}C-dated horizons[11]. In the following, ages are given in calibrated calendar years before present.
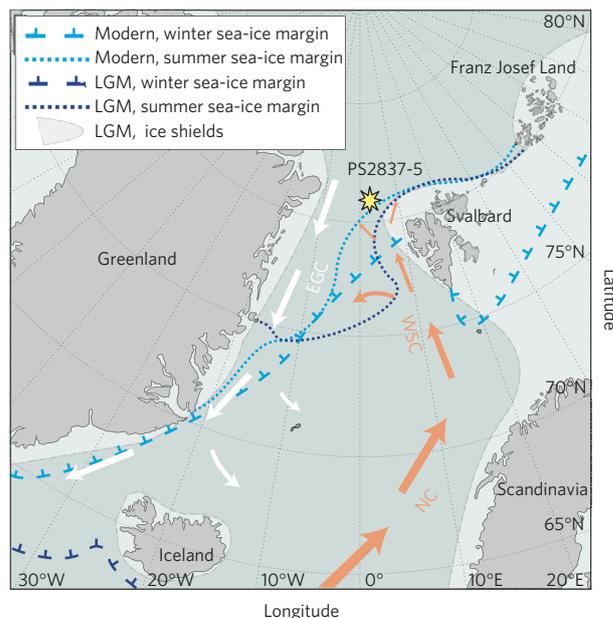
Figure 1 | Map showing the PS2837-5 core site in northern Fram Strait, major ocean currents and sea-ice margins[14]. White-shaded areas indicate the extent of the Greenland, Iceland and Scandinavian Ice Shields during the Last Glacial Maximum. Orange arrows refer to warm Atlantic water inflow through the Norwegian (NC) and West Spitsbergen (WSC) currents; white arrows indicate cold polar water transported by the East Greenland current (EGC; ref. 1).

For much of the interval between 30 and 17 kyr BP (Late Weichselian to early deglaciation; Fig. 2), IP_{25}, brassicasterol and organic carbon fluxes are amongst their lowest within the entire record. These near-zero fluxes for all three proxy records, especially during the Last Glacial Maximum (LGM) and the early deglaciation (23.5–17 kyr BP), are attributable to an almost permanent period of ice cover (Fig. 3a), possibly resulting from an extension of the Svalbard–Barents Sea ice sheet (SBIS) to the shelf edge during this time[12] and a distinct weakening of warm Atlantic water inflow into northern Fram Strait. Under such conditions, diatom and phytoplankton growth is limited because the presence of a thick ice sheet inhibits light penetration and enhanced stratification reduces nutrient availability. These observations demonstrate that the summer sea-ice margin during the LGM must have been located south of about 81° N (Fig. 1; refs 13, 14). Exceptionally, elevated IP_{25} fluxes at about 29.6 kyr BP (Fig. 2) probably indicate a short-term thinning of this near-perennial sea-ice cover allowing some sea-ice algal growth with subsequent release during a brief summer
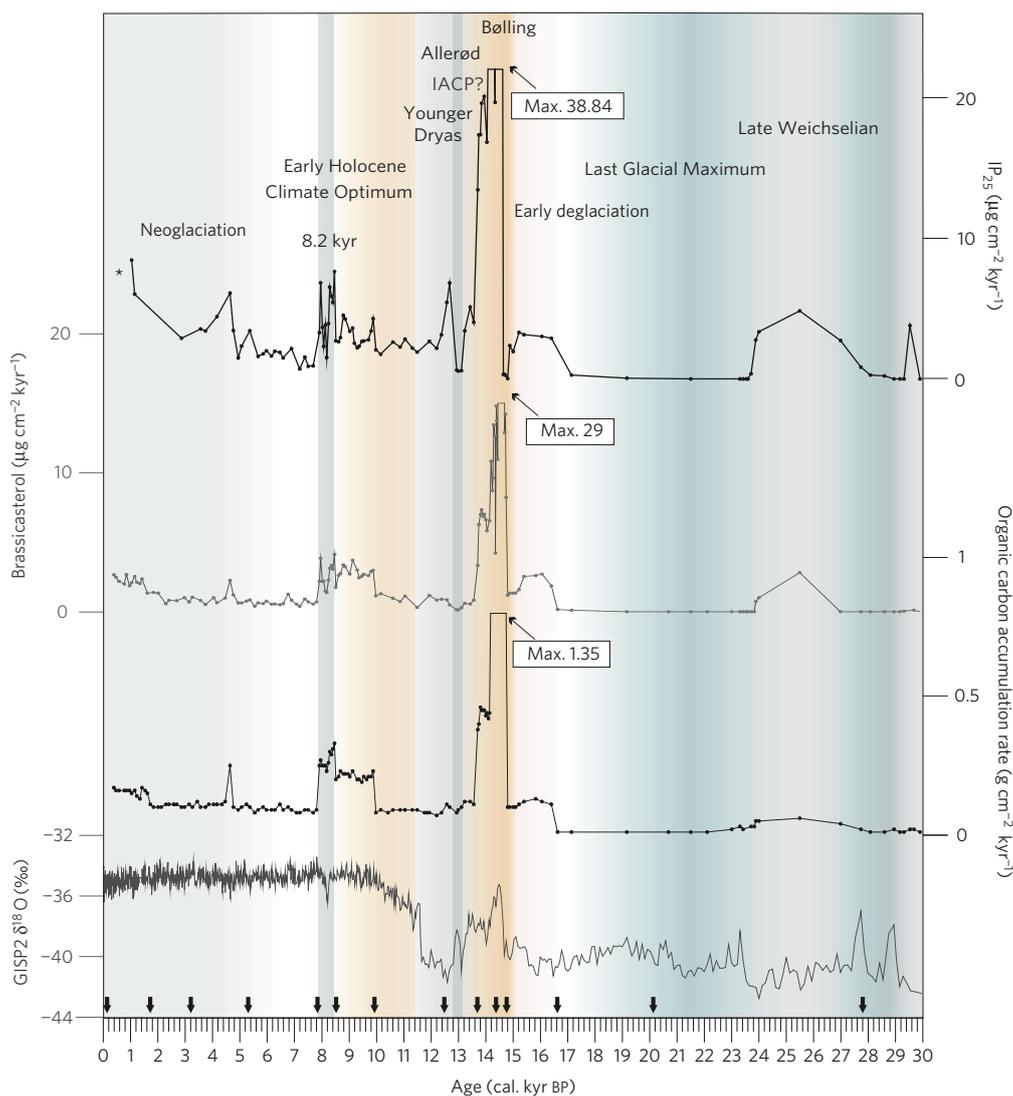
Figure 2 | Temporal evolution of organic carbon[9], brassicasterol[9] and IP$_{25}$ accumulation rates (fluxes), and δ^{18}O values from the GISP2 ice core[22]. The named geological epochs (for example, Late Weichselian) correspond to intervals for which discrete sea-ice conditions have been identified. Black arrows refer to ^{14}C accelerator mass spectrometry datings. * Interval for which IP$_{25}$ was not determined.

melt period (Fig. 3a). Between 27 and 24 kyr BP (Fig. 2), increased IP$_{25}$ and brassicasterol fluxes indicate favourable conditions for both sea-ice diatom and phytoplankton growth. Enhanced marine organic carbon accumulation has also been observed in other cores from Fram Strait and adjacent areas[15,16] in the vicinity of the SBIS. As primary production is enhanced at the ice edge[17], resulting in higher sedimentary concentrations of marine-derived biomarkers[18], these elevated fluxes of IP$_{25}$ and brassicasterol probably reveal the occurrence of a stationary ice margin (about 81° N; 2° E) during this otherwise perennially ice-covered interval (Fig. 3b). A coeval enhancement in ice-rafted detritus in PS2837-5 (ref. 11) provides evidence for the presence of drifting sea ice or icebergs at this time and, in turn, the occurrence of coastal polynyas. Such polynyas probably resulted from strengthened Atlantic water advection and/or katabatic winds as suggested previously[19], with parallel formation of an adjacent stationary ice margin.

Coincident with intensified Atlantic water advection[20] and the onset of the SBIS disintegration at about 17 kyr BP (refs 12, 16, 21), higher fluxes of IP$_{25}$ occurred, probably as a result of reduced ice thickness and thus better light penetration and nutrient availability suitable for sea-ice diatom growth (see 29.6 kyr BP event). An increase in brassicasterol and organic carbon fluxes

lagged those observed for IP$_{25}$ by about 400 yr (Fig. 2), consistent with a progressive retreat of the ice sheet and more frequent summer ice melt and open-water conditions. At the onset of the Bølling (about 15 kyr BP), a notable abrupt warm phase characterized by heavier GISP2 oxygen isotope (δ^{18}O) values[22], and exceptionally high sedimentation rates resulting from huge deglacial meltwater plumes carrying high amounts of terrigenous (Svalbard) material[9], led to extremely high OC and brassicasterol fluxes (Fig. 2). Coeval with this rapid warming, a sudden drop in IP$_{25}$ fluxes occurred for about 200 yr (14.8–14.6 kyr BP), reflecting significantly reduced sea-ice occurrence (Fig. 3c). At that time, the Yermak Plateau probably experienced only short-term advances of sea ice, barely sufficient for sea-ice diatoms to populate. On the other hand, open-water phytoplankton would have benefited dramatically from such essentially ice-free conditions.

The Early Bølling was followed by intervals of variable sea-ice cover (about 14.6–13.2 kyr BP), as reflected by the IP$_{25}$ fluxes. Massive sedimentary input continued during this interval, thus promoting an increased burial–preservation of organic matter (the 'ballast effect'; refs 9, 16) and peak fluxes of organic carbon, brassicasterol and IP$_{25}$. A prominent short-term decrease in δ^{18}O (GISP2), along with reduced IP$_{25}$, brassicasterol and organic carbon

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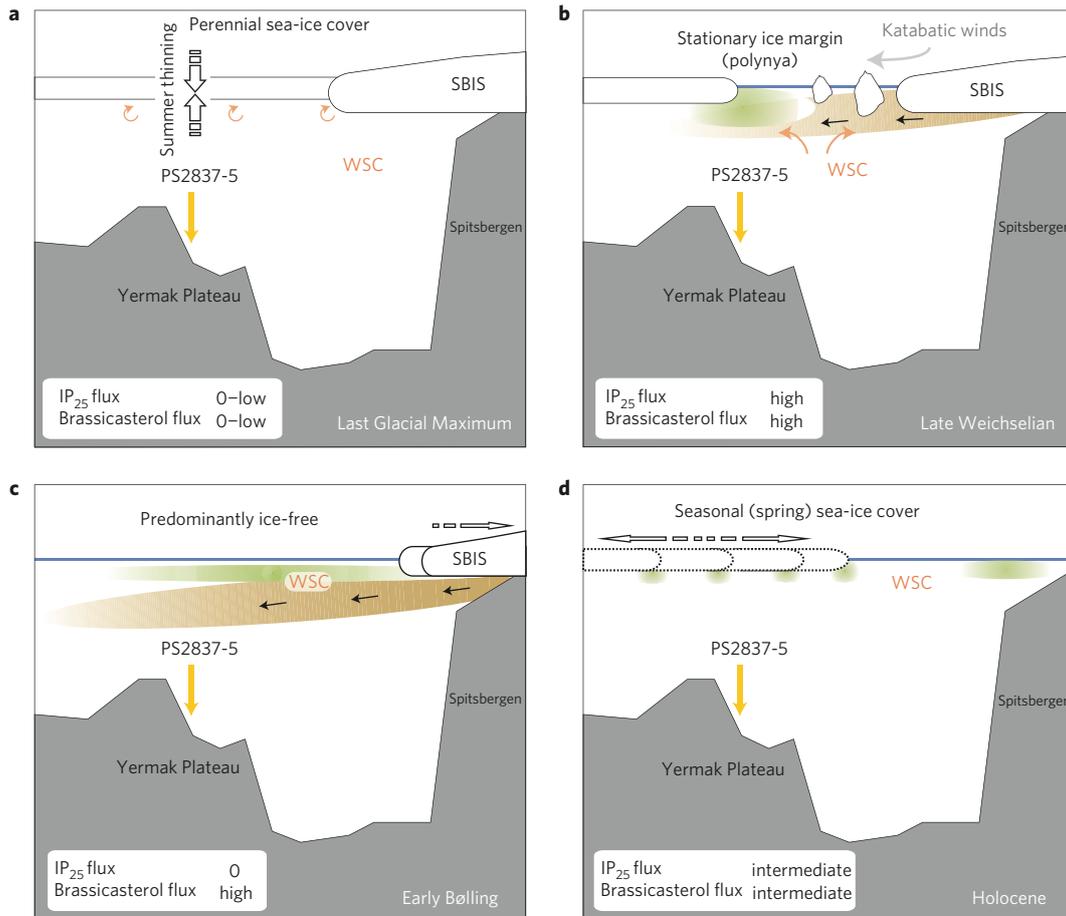
Figure 3 | Schematic illustrations of distinct sea-ice conditions at the PS2837-5 core site for selected time intervals. a–d, Green shadings refer to primary productivity whereas brown shadings indicate input of terrigenous matter. Overview IP_{25} and brassicasterol fluxes are indicated for each interval. WSC = West Spitsbergen current, SBIS = Svalbard–Barents sea-ice sheet.

fluxes, between 13.2 and 13 kyr BP, is consistent with a dramatic temperature decrease over Greenland, and generally unfavourable environmental conditions with extended (perennial) sea-ice cover and reduced primary production (Fig. 3a). These observations, together with an absence of benthic foraminifera in PS2837-5 (ref. 23), are associated with a deterioration of thermohaline processes and reduced bottom-current activity in Fram Strait[9], and demonstrate that this permanent sea-ice cover affected both primary production and higher trophic levels, resulting in a widespread ecological decline. In previous studies carried out on PS2837-5, this abrupt cooling event was tentatively assigned as the Intra-Allerød Cold Period (IACP; refs 9, 23). However, in the North Atlantic, higher ^{14}C reservoir ages have been determined specifically for this interval (500–600 yr; ref. 24). As these were not considered in the original age model for PS2837-5 (ref. 11), this abrupt cold spell may alternatively be assigned to the Early Younger Dryas (about 12.7 kyr BP), consistent with the common identification of the Younger Dryas as the major cold period in the northern hemisphere following the LGM (refs 25, 26). In further support of this assignment, IP_{25} and brassicasterol fluxes increased during the subsequent Mid–Late Younger Dryas intervals, as sea-ice diatom and phytoplankton activity improved owing to less severe sea-ice conditions (Fig. 2). Such conditions probably resulted from a weak but constant inflow of warm water from the Atlantic through the West Spitsbergen current, generating climate conditions also suitable for primary productivity, a conclusion consistent with diatom-valve assemblages from the Vøring Plateau in the Norwegian Sea[4].

An abrupt increase in GISP2 $\delta^{18}O$ values, together with numerous terrestrial and marine records, marks the beginning of the Holocene interglacial at around 11.5 kyr BP in northern latitudes[22]. Enhanced insolation and warm Atlantic water influx to the Nordic Seas[4,5] resulted in a northward retreat of the Polar Front, especially in the Early Holocene, as indicated from foraminiferal and diatom distributions[4,27]. This is further indicated here through the observation of significantly increased brassicasterol and organic carbon fluxes (Fig. 2). However, the co-occurrence of IP_{25} and the absence of ice-rafted detritus[11] demonstrates that seasonal sea ice, rather than the presence of polynyas with drifting icebergs and a stationary ice margin, must have prevailed in the northern Fram Strait throughout this period, with changes to the IP_{25} fluxes reflecting variability of spring sea-ice conditions (Figs 2, 3d). Around 8.4 kyr BP, a short-term increase followed by a rapid decrease at 8.2 kyr is observed in the brassicasterol and IP_{25} flux records. Subsequently, from about 8 to 5 kyr BP, IP_{25}, brassicasterol and organic carbon fluxes all remained low, similar to the Early Younger Dryas (or IACP) and the LGM when near-permanent sea-ice coverage severely restricted primary production. The '8.2 kyr event', a significant cold spell probably caused by the outburst of a giant glacial meltwater lake in North America[28], probably triggered an abrupt increase in sea-ice coverage at the western Yermak Plateau at the end of the Early Holocene Climate Optimum. Although the GISP2 $\delta^{18}O$ decline at 8.2 kyr BP describes a relatively short-term atmospheric cooling event in Greenland, the longer-term minimum fluxes of IP_{25} and brassicasterol in the northern Fram Strait suggest a more prolonged deterioration in the marine conditions,

with near-perennial sea-ice cover. This is reversed in the Late Holocene (since about 5 kyr BP), with slightly increasing organic carbon and brassicasterol fluxes indicative of an amelioration of the environmental conditions at the Yermak Plateau. Concurrent higher fluxes of IP$_{25}$ point to the re-establishment of seasonal sea-ice conditions in the northern Fram Strait. These observations are consistent with the widespread evidence for a neoglacial period in the northern North Atlantic during the Holocene[20,27].

This is the first application of the novel sea-ice biomarker IP$_{25}$ in determining Arctic sea-ice records before the Holocene. We also show how the variable occurrence of IP$_{25}$, when considered alongside other geochemical proxies such as brassicasterol from phytoplankton, can reveal more specific palaeo-sea-ice scenarios. The co-occurrence of the two biomarkers refers to either seasonal sea-ice cover (Early and Late Holocene) or a stationary ice margin (Late Weichselian) allowing spring sea-ice diatom and summer phytoplankton growth, with the latter scenario indicated further by the additional enhancement of sedimentary ice-rafted detritus[11]. In contrast, near-zero occurrences of both biomarkers (LGM and Early Younger Dryas/IACP) result from unfavourable environmental conditions for both organism classes during extreme cold periods with near-perennial sea-ice cover. Furthermore, the predominant occurrence of IP$_{25}$ (early deglaciation) or brassicasterol (Early Bølling) indicates the progressive thinning of the sea-ice cover, or sea-ice-free conditions, respectively. As such, the relationship between IP$_{25}$ and brassicasterol fluxes is strongly dependent on the specific sea-ice conditions, shown further by the variable correlation between these two biomarkers at different intervals across the record (Fig. 2).

As shown, our biomarker-based observations and interpretations align strongly with previous palaeoclimate records for the northern Fram Strait[9,12,19,23], but they also provide more specific palaeoceanographic information. First, during intervals of the Late Weichselian, our biomarker record indicates extended periods of near-perennial sea-ice cover (29–27.5 kyr BP and 23.5–17 kyr BP; Fig. 2), yet high fluxes of planktic and benthic foraminifera have been identified previously in PS2837-5, and these were attributed to a stronger though, significantly, subsurface input of warm Atlantic water[11,23] during so-called high-productive events[29]. We suggest that a temperate subsurface layer, causing thinning and short-term opening of the ice sheet during summer months (Fig. 3a), was sufficient for short-term blooms of phytoplankton-grazing foraminifera without significant deposition of marine surface-water or sea-ice-derived biomarkers (23.5–17 kyr BP). Second, significantly higher biomarker fluxes are observed during an interval (27–24 kyr BP) barren of planktic foraminifers[11], which may be ascribed to enhanced sedimentary carbonate dissolution[11,19,23,30] as a consequence of elevated sea-surface primary productivity at the ice edge during polynya conditions. These observations further reinforce the importance of evaluating the significance of individual proxies when carrying out integrated palaeoclimate reconstructions.

Methods

The analysis of the IP$_{25}$ biomarker was carried out on freeze-dried sediment material from individual horizons from the PS2837-5 core. Before extraction, an internal standard (7-hexylnonadecane) was added to about 1.5 g freeze-dried and ground sediment material to permit quantification. Sediments were then extracted using dichloromethane/methanol (3×3 ml; 2:1 vol/vol) and ultrasonication (3×10 min). The resulting extracts were fractionated to yield hydrocarbon fractions containing IP$_{25}$ using open-column chromatography (SiO$_2$, hexane), and these were analysed using gas chromatography–mass spectrometry (GC-MS). Gas chromatography–mass spectrometry measurements were carried out on a HP 5,890 gas chromatograph (30 m fused silica column; 0.25 mm inner diameter, 0.25 μm film thickness) coupled to an HP 5970 mass-selective detector. The GC oven temperature was programmed from 40 to 300 °C at 5 °C min^{-1} and held at the final temperature for 10 min. Mass spectrometry operating conditions were 280 °C (ion source) and 70 eV (ionization energy). Deviation for the repeatability of measurements was less than 10%. The identification of the IP$_{25}$ monoene was based on its GC retention time and comparison of its mass spectrum with that of an authentic standard published previously[6]. Sedimentary IP$_{25}$ concentrations were determined by calculating the relative gas chromatography–mass spectrometry responses of IP$_{25}$ and the internal standard and taking account of the mass of sediment extracted in each case. Temporal fluxes of IP$_{25}$ and brassicasterol were determined by combining sedimentary concentrations with sediment densities and sedimentation rates.

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Author contributions

All authors contributed equally to this work; S.T.B. and G.M. designed the analytical method; J.M. carried out experiments, analysed data and drafted the original manuscript; all authors interpreted the results and contributed to the final manuscript.

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