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Deglacial and Holocene sea–ice variability north of Iceland and response to ocean circulation changes

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ABSTRACT

Sea–ice conditions on the North Icelandic shelf constitute a key component for the study of the climatic gradients between the Arctic and the North Atlantic Oceans at the Polar Front between the cold East Icelandic Current delivering Polar surface water and the relatively warm Irminger Current derived from the North Atlantic Current. The variability of sea ice contributes to heat reduction (albedo) and gas exchange between the ocean and the atmosphere, and further affects the deep-water formation. However, lack of long-term and high-resolution sea–ice records in the region hinders the understanding of palaeoceanographic change mechanisms during the last glacial–interglacial cycle. Here, we present a sea–ice record back to 15 ka (cal. ka BP) based on the sea–ice biomarker IP_{25}, phytoplankton biomarker brassicasterol and terrestrial biomarker long-chain *n*-alkanols in piston core MD99-2272 from the North Icelandic shelf. During the Bølling/Allerød (14.7–12.9 ka), the North Icelandic shelf was characterized by extensive spring sea–ice cover linked to reduced flow of warm Atlantic Water and dominant Polar water influence, as well as strong meltwater input in the area. This pattern showed an anti-phase relationship with the ice-free/less ice conditions in marginal areas of the eastern Nordic Seas, where the Atlantic Water inflow was strong, and contributed to an enhanced deep-water formation. Prolonged sea–ice cover with occasional occurrence of seasonal sea ice prevailed during the Younger Dryas (12.9–11.7 ka) interrupted by a brief interval of enhanced Irminger Current and deposition of the Vedde Ash, as opposed to abruptly increased sea–ice conditions in the eastern Nordic Seas. The seasonal sea ice decreased gradually from the Younger Dryas to the onset of the Holocene corresponding to increasing insolation. Ice-free conditions and sea surface warming were observed for the Early Holocene, followed by expansion of sea ice during the Mid-Holocene.

1. Introduction

Sea–ice cover on the North Icelandic shelf, at the Polar Front separating the North Atlantic and the Arctic Oceans, is principally linked to the advective strength of the relatively warm Irminger Current and the cold East Icelandic Current, which dominate the surface waters of the region (Fig. 1; Rudels et al., 2005). The Irminger Current is a branch of the North Atlantic Current and its strength is associated with another branch of the North Atlantic Current, the Norwegian Current. The Norwegian Current flows into the eastern Nordic Seas and is linked to the rate of North Atlantic Deep Water (NADW) formation and the strength of the Atlantic Meridional Overturning Circulation (AMOC), substantially influencing the global climate system (cf. Rayner et al., 2011). Furthermore, the waxing and vaning of sea–ice extent in the Nordic Seas also significantly influence the NADW formation and AMOC process, as a result of brine formation and freshwater input, respectively (Thornalley et al., 2010).

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Previous palaeo-sea–ice reconstructions north of Iceland have mainly been deduced from microfossil, sedimentological and geochemic data, including ice-rafted debris (IRD), stable isotopes, foraminiferal assemblages and diatoms (e.g. Eiríksson et al., 2000; Knudsen et al., 2004; Ślubowska-Woldengen et al., 2008). Poor preservation of foraminifera and diatoms due to carbonate or silica dissolution has limited sea–ice distribution reconstructions in many regions of the Arctic and sub-Arctic (Schlüter and Sauter, 2000; Zamelczyk et al., 2014). A molecular proxy, IP_{25}, mono-unsaturated highly branched isoprenoid (HBI) alkene biosynthesized by sea–ice diatoms (Belt et al., 2007; Brown et al., 2014), has turned out to be well-preserved in Arctic and sub-Arctic marine sediments and has been determined in a sediment core from the central Arctic Ocean during the Miocene, beyond 5.3 Ma (Stein et al., 2016), thus enabling its application for sea–ice assessment even during the distant past. Although there is still a lack of knowledge about the vertical transport, degradation process and environmental controlling factors of this novel biomarker (for details see Belt and Müller, 2013), IP_{25} has been applied for palaeo-sea–ice reconstructions covering different areas of the Arctic Ocean and sub-Arctic region (cf. Stein et al., 2012; Belt and Müller, 2013 and references therein). However, there is an ambiguous interpretation of the absence of IP_{25}, since the lack of ice cover or, conversely permanent sea–ice cover inhibiting light penetration, can both limit the sea–ice algal growth. Therefore, phytoplankton biomarkers (e.g. brassicasterol or dinosterol), as open water indicators (Volkman, 2003), have been proposed to be used alongside IP_{25} to distinguish these ambiguous scenarios (Müller et al., 2009). Generally, the lack of both IP_{25} and phytoplankton biomarker reflects permanent sea–ice cover; the absence of IP_{25} with elevated phytoplankton biomarker indicates an open-water condition; while the occurrence of both biomarkers suggests stable sea–ice margin or seasonal sea–ice condition (Müller et al., 2009). Furthermore, the new PIP_{25} (Phytoplankton-IP_{25}) index, a combination of IP_{25} and phytoplankton biomarker, was initially developed (Müller et al., 2011) to reconstruct the intensity of spring and summer sea–ice cover semi-quantitatively. By combining new data from high-Arctic realm surface sediments with published data from Arctic marginal areas, Xiao et al. (2015) found a pronounced correlation between PIP_{25} index values and satellite sea–ice concentrations, providing strong support for a broad application of the PIP_{25} index.

IP_{25}-based sea–ice reconstructions have been conducted for sediment cores from the Icelandic shelf. IP_{25} was below detection limit in a sediment core from the southwest of Iceland (Axford et al., 2011) as sea ice did not reach this area over the past 2000 yr, while Andrews et al. (2009) reconstructed the sea–ice condition in a low-resolution sampling core on the Northwest Icelandic shelf during the past 2000 yr by means of multiple proxies including IP_{25}. High-resolution IP_{25} records, established by Massé et al. (2008) and Cabedo-Sanz et al. (2016) in sediment cores from the North Icelandic shelf, revealed significant sea–ice variability during the past 1200 yr and 8000 yr, respectively. High-resolution IP_{25} records beyond the Holocene from the Icelandic shelf, however, are required to further understand rapid sea–ice variations and their responses to oceanic changes in detail.

Here, we present high-resolution (20 and 26 yr) biomarker records in marine sediment core MD99-2272 from the North Icelandic shelf during the last deglaciation and relatively lower-resolution (mostly about 100 yr) records during the Early to Mid-Holocene to assess the sea–ice conditions under different oceanic environments. Core site MD99-2272 (Fig. 1) is located in the frontal area between the Irminger Current and the East Icelandic Current, close to fjords influenced by glacial rivers from the Vatnajökull ice cap in Iceland, ideally archiving changes in the oceanic circulation system of the North Atlantic. To evaluate the sea–ice changes and related sea surface conditions, we compare an IP_{25} record with the phytoplankton biomarker brassicasterol record (an open-water indicator) and the terrestrial biomarker long-chain *n*-alkanols record (a freshwater input indicator; derived from leaf waxes of land plants, Englinton and Englinton, 2008) from MD99-2272. We also compare the IP_{25} record of MD99-2272 with the same proxy records in sediment cores from the Fram Strait and eastern Nordic Seas to assess oceanographic processes at a larger scale of the northern North Atlantic during the critical period of the last deglaciation. In addition, we focus on high-resolution sea–ice variability during the last deglaciation and its linkage with insolation, current circulation and AMOC changes, which influence this critical region for the global thermohaline circulation.

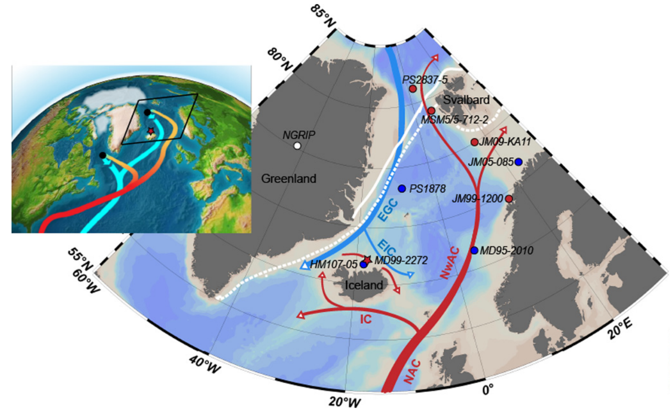

Fig. 1. Study area with the MD99-2272 core location (red star) used for our IP_{25} study on the North Icelandic shelf. Black dots in the left-hand map represent two areas of deep-water formation in the North Atlantic, and the black rhombus shows the extent of the Nordic Seas (modified from http://en.es-static.us). The modern average summer sea–ice extent (white line) and winter sea–ice extent (white dotted line) are indicated in the right-hand map. Red arrows show the surface circulation of warm Atlantic Water entering the Nordic Seas (NAC = North Atlantic Current, NwAC = Norwegian Atlantic Current, IC = Irminger Current), while blue arrows show the circulation patterns of the cold Polar water (EGC = East Greenland Current, EIC = East Icelandic Current). Red dots and blue dots refer to the core sites for IP_{25} records (Fig. 4) and isotope records (Fig. 5), respectively. White dot on Greenland is the location of the NGRIP ice core. The right-hand map was generated using Ocean Data View (Schlitzer, 2017). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Regional setting

Iceland is located in the northern North Atlantic (Fig. 1), an area which is sensitive to climate changes. Atmosphere–ocean interactions during abrupt climate shifts are therefore detectable in marine sediment cores from the area (cf. Jiang et al., 2015). Modeling experiments have shown that Iceland was extremely sensitive and vulnerable to temperature change, with just 3 °C of cooling being sufficient to create an ice sheet covering half the present land area (Hubbard et al., 2006). Today, the hydrography of this area is dominated by the cold East Greenland Current and East Icelandic Current from the Arctic Ocean, and the relatively warm and saline Irminger Current, a branch of the North Atlantic Current (Fig. 1; Rudels et al., 2005) which flows along the southern, western and northern shelf of Iceland. Furthermore, the northward flowing warm Atlantic Water becomes cold and dense in the Nordic Seas, northeast of Iceland. Here, cooled Atlantic Water sinks and forms the NADW which overflows the Iceland-Faeroe ridge towards south, associated with the AMOC (Fig. 1; Rayner et al., 2011).

At present, glaciers and ice caps cover ca. 10% of Iceland's area, locking up a considerable volume of freshwater (Ingólfsson et al., 2016), while during the glacial, Iceland and the surrounding