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Variability in drift ice export from the Arctic Ocean to the North Icelandic Shelf over the last 8000 years: A multi-proxy evaluation

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ABSTRACT

North Iceland represents a climatically sensitive region, in part, due to its location at the confluence of southward flowing and drift ice-laden polar waters from the Arctic Ocean delivered by the East Greenland Current, and the relatively warm and saline Irminger Current, a northerly flowing branch of the North Atlantic Current. Despite its pivotal location, there is a paucity of high resolution and long-term sea ice records for the region, with some disparities in certain previous investigations. Here, the identification of the biomarker IP_{25} as a reliable proxy for drift ice for North Iceland has been confirmed by measuring its abundance in surface sediments from the region and comparison of outcomes with documentary records of sea ice and other proxy data. By analysing IP_{25} in a well-dated marine sediment core from the North Icelandic Shelf (NIS) (MD99-2269), we also provide a high resolution (ca. 25 yr) record of drift sea ice for the region and complement this with a lower resolution record (ca. 100 yr) obtained from a second core site, located further east (JR51-GC35). Statistical treatment of equi-spaced time series reveals strong linear correlations between IP_{25} and a further drift ice proxy (quartz) in each core. Thus, linear regression analysis between both proxies gave correlation coefficients (R^2) of 0.74 and 0.66 for MD99-2269 (25 yr) and JR51-GC35 (100 yr), respectively. Further, the individual proxies were well correlated between the two cores, with $R = 0.91$ and 0.77 for IP_{25} and quartz, respectively. The IP_{25}-based sea ice record for MD99-2269, combined with other new biomarker and foraminifera data, and previously published proxy data for primary productivity and sea surface temperature, suggest that the paleoceanographic evolution for the NIS over the last 8 ka can be classified into three main intervals. The early mid Holocene (ca 8–6.2 cal ka BP) was characterized by relatively low or absent drift ice, low primary productivity and relatively high SSTs. During the mid-Holocene (ca 6.2–3.3 cal ka BP), drift ice increased concomitant with decreasing SSTs, although primary productivity was somewhat enhanced during this interval. IP_{25} first reached its mean value for the entire record at ca 5 cal ka BP, before increasing, continuously, ca 4.3 cal ka BP, broadly in line with the onset of Neoglaciation as seen in some other proxy records. Further increases in drift ice were evident during the late Holocene (ca 3.3 cal ka BP to present), culminating in maximum sea ice during the Little Ice Age. In addition, the IP_{25} record from MD99-2269 shows some positive regime shifts from the general trend, especially at ca 3.8, 2.7, 1.5, 0.7 and 0.4 cal ka BP, that have analogs in some other paleoceanographic reconstructions influenced by the East Greenland Current. The abrupt increases in IP_{25} at ca 1.5 and 0.7 cal ka BP are coincident with rapid cooling identified previously in an Icelandic lacustrine temperature record, suggesting significant coupling between the marine and terrestrial systems. The contribution of sea ice to the broader climate system is further evidenced through the identification of statistically significant periodicities (ca 1000 yr and ca 200–230 yr) in the drift ice proxy data that have counterparts in previous studies concerning atmospheric and oceanic variability and solar forcing mechanisms.

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1. Introduction

Sea ice plays a key role in determining the energy balance at high latitudes by influencing the exchange of heat, gases and moisture between the polar oceans and the atmosphere. By reflecting much of the incoming solar radiation, sea ice also insulates the cold polar atmosphere from the relatively warm ocean in winter. Changes in Arctic Ocean sea ice dimensions have received considerable attention in recent years, largely because of its recent and dramatic decline (e.g., Goosse et al., 2013; Schiermeier, 2012; Serreze et al., 2007). However, due to its strong positive feedback mechanism in controlling global climate, the role of sea ice through the geological record is also of considerable interest. For example, expanded sea ice has been suggested to play an important role in maintaining the unusual duration of mostly cold summers during the little ice age (LIA) (Lehner et al., 2013; Miller et al., 2012; Schleussner and Feulner, 2013), and greatly reduced sea ice is necessary to explain the warmth of the mid-Pliocene (Haywood and Valdes, 2004). However, since only a very few observational records of past sea ice exist (e.g. Bergthorsson, 1969; de la Mare, 1997; Divine and Dick, 2006; Ogilvie and Jónsdóttir, 2000), paleo sea ice reconstructions rely heavily on proxy-based methods, so the development and application of sea ice proxies have also received considerable attention in recent years (de Vernal et al., 2013a; Polyak et al., 2010). Some sea ice proxies have a biological origin and are typically based on species assemblages of diatoms, dinoflagellate cysts (dinocysts), ostracods and foraminifera (e.g., Justwan and Koç, 2008; Cronin et al., 2013; de Vernal et al., 2013b,c; Seidenkrantz, 2013) or the occurrence and distribution of marine mammal remains and driftwood from raised beaches (Dyke et al., 1996; Funder et al., 2011; Furze et al., 2014), while others rely on the identification of material entrained within the ice itself (i.e. ice-rafted debris (IRD)) and deposited in underlying marine sediments following ice melt (Andrews, 2009; Moros et al., 2006). Despite the range of sea ice proxies, however, there is as yet, no strong consensus on the changing dimensions of Arctic Ocean sea ice over the past 8 ka, although there is growing evidence for a strong regional dependence (de Vernal et al., 2013c).

In recent years, the analysis of the biomarker IP_{25} (Belt et al., 2007), a C_{25} highly branched isoprenoid (HBI) lipid made by certain Arctic sea ice diatoms (Brown et al., 2014), has been suggested to provide a more direct measure of past sea ice when detected in underlying sediments (a recent review is provided by Belt and Müller, 2013). Significantly, IP_{25} is stable in sediments for millions of years (Knies et al., 2014) and has a stable isotopic composition (δ^{13}C) that is highly characteristic of a sea ice origin (Belt et al., 2008). Sedimentary IP_{25} is generally interpreted as an indication of spring/early summer sea ice conditions due to its formation by sea ice diatoms during the spring bloom (Brown et al., 2011; Belt et al., 2013).

To date, the main applications of IP_{25} for Holocene sea ice reconstruction have been carried out for regions such as the Barents Sea (Belt et al., 2015; Berben et al., 2014; Vare et al., 2010), the Canadian Arctic Archipelago (Belt et al., 2010; Vare et al., 2009), Fram Strait (Müller et al., 2009, 2012) and the Laptev Sea (Fahl and Stein, 2012). On the other hand, relatively little attention has been given to the East Greenland shelf and North Iceland, although a low resolution study conducted for Foster Bugt on the central East Greenland shelf indicated relatively stable sea ice conditions for most of the Holocene apart from the last ca 1.4 cal ka BP (Müller et al., 2012; Perner et al., 2015). This paucity of research is somewhat surprising given that the East Greenland shelf is a very sensitive area to changes in sea ice and freshwater outflow from the Arctic Ocean (e.g. Jennings and Weiner, 1996), while the East Greenland Current (EGC), which flows adjacent to the East Greenland shelf, is one of the main sea ice and freshwater export pathways from the Arctic Ocean (Aagaard and Coachman, 1968) towards the Denmark Strait region (i.e. South-East Greenland and North Iceland) as evidenced by the Great Salinity Anomaly of 1969 (Belkin et al., 1998; Dickson et al., 1988). However, the first temporal IP_{25}-based sea ice reconstruction was carried out on a core from the North Icelandic Shelf (NIS) (Massé et al., 2008) and showed that IP_{25} concentrations were very well correlated with documented records of sea ice around Iceland over the last ca. 1 ka (Ogilvie and Jónsson, 2001). The outcomes from this initial study by Massé et al. (2008) were subsequently reinforced by analysis of three further cores from N, NW and SW Iceland (Andrews et al., 2009a; Axford et al., 2011; Sicre et al., 2013). Interestingly, the initial IP_{25} record from Massé et al. (2008) also closely matches the reconstructed expansion of the Langjökull ice cap, Iceland (Larsen et al., 2011), and a composite terrestrial record (Haukadalsvatn and Hvítárvatn, Iceland) (Geirsdóttir et al., 2013), suggesting a close link between terrestrial Icelandic summer temperatures and changes in sea ice cover in the adjacent ocean. However, each of these previous IP_{25}-based sea ice reconstructions for the East Greenland shelf and North Iceland were either of low resolution, temporally limited, or both. As such, there have been no high-resolution and long-term (e.g. Holocene) IP_{25}-based sea ice reconstructions for this climatically sensitive region.

In the current study, we quantified IP_{25} in surface sediments and two marine cores (MD99-2269 and JR51-GC35) from the NIS in order to both confirm the suitability of this biomarker as a drift ice proxy and also to gain further insights into the spatial and temporal sea ice evolution throughout the last 8 ka. In the first instance, therefore, we determined the distribution of IP_{25} in surface sediments from the region and compared outcomes with known modern sea ice conditions and a further drift ice proxy (i.e. quartz; Andrews, 2009). We then investigated the IP_{25} content in the giant Calypso core MD99-2269, an exceptionally well-dated high-resolution marine sediment record (Stoner et al., 2007) from ca 66° N on the NIS (Fig. 1a) and situated at the boundary between major oceanic and atmospheric circulation systems (Hopkins, 1991). In some recent IP_{25}-based Arctic sea ice reconstructions, combining IP_{25} concentrations with those of certain phytoplankton biomarkers (typically sterols) in the form of the so-called PIP_{25} index (Müller et al., 2011) has provided further insights into paleo sea ice conditions, most notably from a semi-quantitative perspective (e.g., Müller et al., 2011, 2012; Müller and Stein, 2014; Fahl and Stein, 2012; Xiao et al., 2015; Hörner et al., 2016; Smik et al., 2016). However, since the conceptual model that underpins the PIP_{25} index (viz. a stable winter ice margin with ice retreat during spring/summer) is not appropriate for the drift conditions pertinent to the NIS, we refrained from measuring PIP_{25} indices within the current study. We also note that, as yet, there has been no surface sediment-based calibration of the PIP_{25} index for North Iceland, although it has been suggested previously that such an approach may not be especially useful for regions of low sea ice cover (Navarro-Rodriguez et al., 2013), as is the case for the NIS.

Several other climate proxy datasets are, however, available from MD99-2269 at various resolutions that span the full 8 ka and beyond (e.g. Andersen et al., 2004b; de Vernal et al., 2013b; Giraudeau et al., 2004; Justwan et al., 2008; Kristjánsdóttir et al., 2007; Moros et al., 2006; Solignac et al., 2006) but it remains unclear which (if any) provide a secure record of changes in sea ice, especially as some show divergence in outcomes (de Vernal et al., 2013b; Moros et al., 2006; Solignac et al., 2006) and further conflicting evidence of Holocene climate evolution exists between some of the other proxy datasets, especially after 3 ka BP. For example, mineralogical-based sea ice (Moros et al., 2006) and microfossil-derived bottom water temperature proxies indicate