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Biomarker distributions in surface sediments from the Kara and Laptev seas (Arctic Ocean): indicators for organic-carbon sources and sea-ice coverage

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A B S T R A C T

Studies of spatial and temporal changes in modern and past sea-ice occurrence may help to understand the processes controlling the recent decrease in Arctic sea-ice cover. Here, we determined concentrations of IP_{25}, a novel biomarker proxy for sea ice developed in recent years, phytoplankton-derived biomarkers (brassicasterol and dinosterol) and terrigenous biomarkers (campesterol and β-sitosterol) in the surface sediments from the Kara and Laptev seas to estimate modern spatial (seasonal) sea-ice variability and organic-matter sources. C_{25}-HBI dienes and trienes were determined as additional palaeoenvironmental proxies in the study area. Furthermore, a combined phytoplankton-IP_{25} biomarker approach (PIP_{25} index) is used to reconstruct the modern sea-ice distribution more quantitatively. The terrigenous biomarkers reach maximum concentrations in the coastal zones and estuaries, reflecting the huge discharge by the major rivers Ob, Yenisei and Lena. Maxima in phytoplankton biomarkers indicating increased primary productivity were found in the seasonally ice-free central part of the Kara and Laptev seas. Neither IP_{25} nor PIP_{25}, however, shows a clear and simple correlation with satellite sea-ice distribution in our study area due to the complex environmental conditions in our study area and the transportation process of sea-ice diatom in the water column. Differences in the diene/IP_{25} and triene/IP_{25} ratios point to different sources of these HBIs and different environmental conditions. The diene/IP_{25} ratio seems to correlate positively with sea-surface temperature, while negatively with salinity distributions.

1. Introduction

The polar sea ice is a fundamental component of Earth's climate system, contributing to heat reduction (albedo), deep-water formation and gas exchange between the ocean and the atmosphere. The annual cycle of sea-ice formation and melting processes plays an important role in determining the global climate, furthermore it influences the primary productivity of surface water masses, the benthos in the abyss and the habitat for polar marine mammals and birds (Siegel et al., 1997; Stein, 2008; Dieckmann and Hellmer, 2010). In this context the rapid shrinking sea ice, especially in the Arctic Ocean, is of major interest for the entire community (Johannessen et al., 1995; Francis et al., 2005; Stroeve et al., 2005, 2007, 2008; Thomas and Dieckmann, 2010). In order to understand processes controlling the recent dramatic reduction in Arctic sea-ice cover, it is essential to determine spatial and temporal changes in sea-ice occurrence and its natural variability in the present and past.

The recent Arctic sea-ice conditions have been determined by microwave satellite remote sensing observation (Johannessen et al., 1995, 1999; Comiso and Parkinson, 2004; Stroeve et al., 2005, 2007, 2008) as well as from the data set based on cruise reports, aerial observation and digitization of the sea-ice charts for the early 20th century (Rothrock et al., 1999; Walsh and Chapman, 2001; Rayner et al., 2003), while the reconstruction of the palaeo-latitudinal extent of sea ice is mainly derived from geological data, including sedimentological, geochemical and micropalaeotological parameters of surface sediments and sediment cores (Cremer, 1999; Fahl and Stein, 1999, 2007; Knies et al., 2001; Polyakova and Stein, 2004; Armand and Leventer, 2010). However, the use of some of these parameters, e.g. siliceous frustules and calcareous microfossils as indicators of sea ice, has been limited due to the restricted preservation of diatoms and foraminifera in Arctic Ocean sediments (Wollenburg et al., 2001, 2004; Armand and Leventer, 2010). Therefore, stable and well-preserved biomarker proxies derived from sea ice, have been developed recently. The novel sea-ice

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biomarker IP$_{25}$, a mono-unsaturated highly branched isoprenoid (HBI) alkene with 25 carbon atoms biosynthesized specifically by sea-ice algae, has been used to reconstruct the sea-ice distribution (Belt et al., 2007). These authors also showed that this biomarker is stable in marine sediments due to its resistance to degradation in the water column and to other diagenetic processes in the sediment. IP$_{25}$ data were compared with historical sea-ice records and other proxy data (e.g. isotopic composition, foraminifera and particle size) in further studies (Massé et al., 2008; Vare et al., 2009), which provided evidence for the stable preservation of this new proxy in marine sediments. The occurrence of this monoene in sediment cores from the North Icelandic Shelf, the central Canadian Arctic Archipelago, the central Arctic Ocean and the northern Fram Strait, consistent with other palaeoclimatic parameters, has demonstrated that IP$_{25}$ is a reliable proxy to reconstruct past sea-ice distribution (Massé et al., 2008; Müller et al., 2009; Vare et al., 2009; Belt et al., 2010; Fahl and Stein, 2012; Stein et al., 2012). Stein and Fahl (2013) could show that IP$_{25}$ is even preserved in sediments as old as 2.2 Ma. The absence of IP$_{25}$ illustrates ice-free or permanent ice conditions, whereas the presence of IP$_{25}$ indicating spring sea-ice occurrence (Belt et al., 2007; Müller et al., 2009). Recently, the combination of brassicasterol derived from open-water phytoplankton with IP$_{25}$ enables the reconstruction of various sea-ice conditions (Müller et al., 2009, 2011). The absence of both biomarkers demonstrates a permanent ice cover, whereas the absence of IP$_{25}$ with elevated brassicasterol suggests ice-free conditions. On the other hand, the occurrence of both biomarkers reflects the seasonal ice margin. Müller et al. (2011) have reconstructed modern sea-ice distribution using a combined phytoplankton marker – IP$_{25}$ approach ("PIP$_{25}$ index"), which may provide a more quantitative evaluation of paleo sea-ice conditions to be incorporated into models for forecasting further climate change.

2. Study area

In this study, we analysed surface sediments from the Kara and Laptev seas, fringing the northeastern rim of the Eurasian continent and covering large part of the Siberian shelf area. Both seas are of essential importance for water-mass and sea-ice transport into the Arctic Ocean (Lisitsyn and Vinogradov, 1995). The hydrography of this area is influenced by the inflow of warm Atlantic water and supply of freshwater from major rivers (Jones, 2001; Peterson et al., 2002) (Fig. 1).

Relatively warm, dense water from the Atlantic Ocean enters the Arctic Ocean through Fram Strait between Greenland and Svalbard and through the Barents Sea. This water transport occurs through two branches, the Fram Strait Branch and the Barents Sea Branch (Fig. 1). The Barents Sea Branch crosses the Barents Sea and enters the Kara Sea via the St. Anna Trough. The Fram Strait Branch flows eastward along the continental slope north of the Barents Sea after entering the Eurasian Basin. Here, north of the Kara Sea, part of the Fram Strait Branch returns in the vicinity of the Nansen-Gakkel Ridge, and part joins the Barents Sea Branch to continue to cross the boundary of the Kara and Laptev seas (Schauer et al., 1997; Jones, 2001). The cold, freshwater from the Kara and Laptev seas joins the Transpolar Drift, flowing from the Siberian Coast towards the Fram Strait.

River inflow into the Kara and Laptev seas is dominantly contributed by three of the largest rivers on Earth: Yenisei, Ob and Lena, which drain about 60% of Eurasian Arctic landmass and transport myriads of organic matter into the Kara and Laptev seas (Peterson et al., 2002; Fahl et al., 2003; Stein et al., 2004; Stein and Fahl, 2004a,b). This supply of freshwater substantially affects the process of freezing, transport, and melting of sea ice (Aagaard and Carmack, 1989), and is particularly important for coastal fast ice processes (Divine et al., 2004; Bareiss and Görgen, 2005).

The ice realm of the Kara and Laptev seas is characterized by strong seasonal and interannual variability, comprising a variety of sea-ice conditions such as drift ice, fast ice, ice massifs and coastal polynyas (Parkinson et al., 1999; Bareiss and Görgen, 2005, Fig. 2A–C). Corresponding to the sea-ice conditions, the sea-surface temperature (SST) also shows a distinct seasonal variability in this area and increases gradually from north to south in summer (Fig. 2D). The sea-ice cover reaches its maximum in March and then starts to retreat northward (Fig. 2A). The sea-ice extent reaches its minimum in September with major parts becoming ice-free (Fig. 2B). With respect to sea-ice conditions, the Kara and Laptev seas present a complex system. First, the sea-ice cover of these areas is characterized by large zones of fast ice (motionless ice along the shore line) during winter (Pfirman et al., 1995; Polyakov et al., 2003; Divine et al., 2004; Bareiss and Görgen,

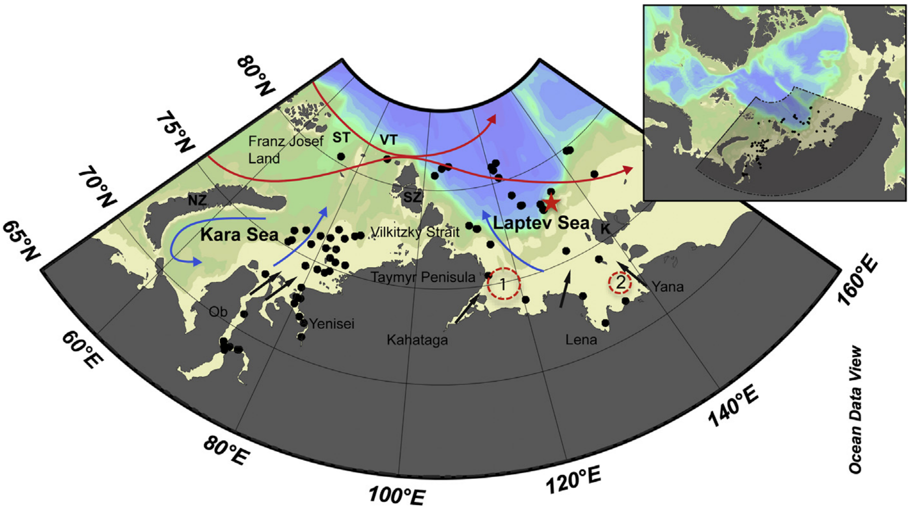

Fig. 1. Map of sampling location (black dots) and oceanographic setting (Jones, 2001). Red arrows show the flow of warm Atlantic water and the blue arrows represent the water entering the Arctic Ocean from Kara and Laptev seas. Straight arrows indicate river discharges (Peterson et al., 2002). SZ: Severnaya Zemlya; NZ: Novaya Zemlya; K: Kotelnyy; ST: St. Anna through; VT: Voronin through. The location of Core PS2458 is shown as red star. Dashed circles indicate (1) Taymyr ice massif and (2) Yana ice massif. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)