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Post-glacial variability of sea ice cover, river run-off and biological production in the western Laptev Sea (Arctic Ocean) – A high-resolution biomarker study

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ABSTRACT

Multi-proxy biomarker measurements were applied on two sediment cores (PS51/154, PS51/159) to reconstruct sea ice cover (IP_{25}), biological production (brassicasterol, dinosterol) and river run-off (campesterol, β-sitosterol) in the western Laptev Sea over the last ~17 ka with unprecedented temporal resolution. The absence of IP_{25} from 17.2 to 15.5 ka, in combination with minimum concentration of phytoplankton biomarkers, suggests that the western Laptev Sea shelf was mostly covered with permanent sea ice. Very minor river run-off and restricted biological production occurred during this cold interval. From ~16 ka until 7.5 ka, a long-term decrease of terrigenous (riverine) organic matter and a coeval increase of marine organic matter reflect the gradual establishment of fully marine conditions in the western Laptev Sea, caused by the onset of the post-glacial transgression. Intensified river run-off and reduced sea ice cover characterized the time interval between 15.2 and 12.9 ka, including the Bølling/Allerød warm period (14.7–12.9 ka). Prominent peaks of the DIP_{25} Index coinciding with maximum abundances of subpolar foraminifers, are interpreted as pulses of Atlantic water inflow on the western Laptev Sea shelf. After the warm period, a sudden return to severe sea ice conditions with strongest ice-coverage between 11.9 and 11 ka coincided with the Younger Dryas (12.9–11.6 ka). At the onset of the Younger Dryas, a distinct alteration of the ecosystem (reflected in a distinct drop in terrigenous and phytoplankton biomarkers) was detected. During the last 7 ka, the sea ice proxies reflect a cooling of the Laptev Sea spring/summer season. This cooling trend was superimposed by a short-term variability in sea ice coverage, probably representing Bond cycles (1500 ± 500 ka) that are related to solar activity changes. Hence, atmospheric circulation changes were apparently able to affect the sea ice conditions on the Laptev Sea shelf under modern sea level conditions.

1. Introduction

Positive feedback mechanisms occurring in the Arctic lead to amplified responses to environmental changes (Arctic amplification) (Lawrence et al., 2008; Serreze and Barry, 2010). The sensitivity of the Arctic climate system is strongly affected by the abundance of sea ice that chiefly affects the salinity balance of the Arctic Ocean and the heat and moisture transfer between ocean and atmosphere. Consequently, sea ice distribution influences the Atlantic Meridional Overturning Circulation (AMOC) (Dieckmann and Hellmer, 2008) and the atmospheric circulation pattern (Overland and Wang, 2010). Furthermore, sea ice contributes to the albedo feedback mechanism that amplifies a climatic forcing and affects the marine primary production (Loeb et al., 1997; Dieckmann and Hellmer, 2008; Stein, 2008). Over the last 30 years, a global temperature increase (Johannessen et al., 1995; Grotefendt et al., 1998; Dickson, 1999) and a significant reduction in Arctic summer sea ice have been observed (Johannessen et al., 2004; Francis et al., 2005; Serreze et al., 2007; Stroeve et al., 2007, 2012). Historical sea ice minima have been recorded for late summer of 2007 (Serreze et al., 2007; Comiso et al., 2008; Kwok and Rothrock, 2009; Miller et al., 2010) and 2012 (National Snow and Ice data center; http://nsidc.org), which are not expressed by climate models (Stroeve et al., 2007, 2012). Since the Arctic sea ice is diminishing at an alarming rate, it is fundamental to better

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understand its behavior under varying climatic conditions. In order to improve and validate models predicting the future development of the sea ice extent, a better knowledge about past changes in sea ice cover is essential.

Shelf areas like the Laptev Sea (Fig. 1) represent important locations for studying various environmental processes, such as sea ice production and export, primary production and the input of nutrients and terrigenous matter from land. For these reasons, the area is suggested to be an appropriate region for monitoring climate variability (Bauch and Kassens, 2005).

In this study, we provide the first continuous high-resolution sea ice reconstruction at two nearby sediment cores (PS51/154-11 and PS51/159-10, Fig. 1) from the western Laptev Sea over the last ~17 ka by means of IP_{25} (ice proxy with 25 carbon atoms, Belt et al., 2007). In addition, we reconstructed river run-off and biological production based on biomarker analyses. The multi-proxy approach enables us to address the linkage between sea ice distribution and riverine discharge (Antonov, 1978; Dean et al., 1994; Searcy et al., 1996; Bareiss et al., 1999) and primary production (Legendre et al., 1992) that are crucial processes for the Laptev Sea's environment and the entire Arctic Ocean.

IP_{25} has become a widely accepted proxy for paleo-sea ice reconstructions (Massé et al., 2008; Müller et al., 2009; Varé et al., 2010; Fahl and Stein, 2012; Stein et al., 2012; Belt and Müller, 2013; Cabedo-Sanz et al., 2013; Müller and Stein, 2014). However, IP_{25} has so far not been applied for sea ice reconstructions in the western Laptev Sea. One aim of the study is to obtain information about sea ice conditions (at a high temporal resolution), during intervals of intense ice-rafted debris (IRD) deposition on the western Laptev Sea shelf, during the last deglaciation and the Mid to Late Holocene (Taldenkova et al., 2010). IRD depositions were inferred to reflect phases of local ice-cap expansion on the Severnaya Zemlya Islands (Fig. 1). Fahl and Stein (2012) observed climatic-induced variations in the seasonal sea ice cover of the eastern Laptev Sea. Including their results allows a west - east comparison of the Laptev Sea's environment, since there might be regional differences due to the influences of the mostly eastwards flowing Lena River plume or the local ice sheets in the western part. Moreover, we are expecting to gain our knowledge about the environmental conditions during the Late Holocene in this region, since the reconstructions by Fahl and Stein (2012) are documented in low resolution during this period.

Investigating both sediment cores, PS51/154-11 and PS51/159-10, from the western Laptev Sea offer unprecedented, continuous high-resolution biomarker-reconstructions that provide insights into the development of the environment (e.g. sea level rise) on the shelf.

1.1. Significance of organic biomarkers for environmental reconstructions

For our environmental reconstruction, i.e. sea ice cover, river run-off and biological production, specific biomarkers were used.

1.1.1. Indicators for sea ice

The presence of sea ice can be reconstructed by means of the direct proxy IP_{25} (Belt et al., 2007). IP_{25} is a highly branched isoprenoid (HBI) molecule (a monoene with 25 carbon atoms) synthesized only by specific sea ice diatoms (Brown et al., 2014). When using IP_{25} one has to consider, that the absence of IP_{25} may be the result of two different scenarios, i.e., either ice-free conditions or permanent ice cover (Müller et al., 2009). To distinguish between these two scenarios, IP_{25} can be combined with phytoplankton biomarkers (e.g., brassicasterol and dinosterol) to determine the phytoplankton marker-IP_{25} index (PIP_{25} index) (cf., Müller et al., 2011; EQ 1). The PIP_{25} Index approved to be an appropriate proxy for sea ice coverage, as demonstrated by correlations with satellite observations (Müller et al., 2011). As phytoplankton marker

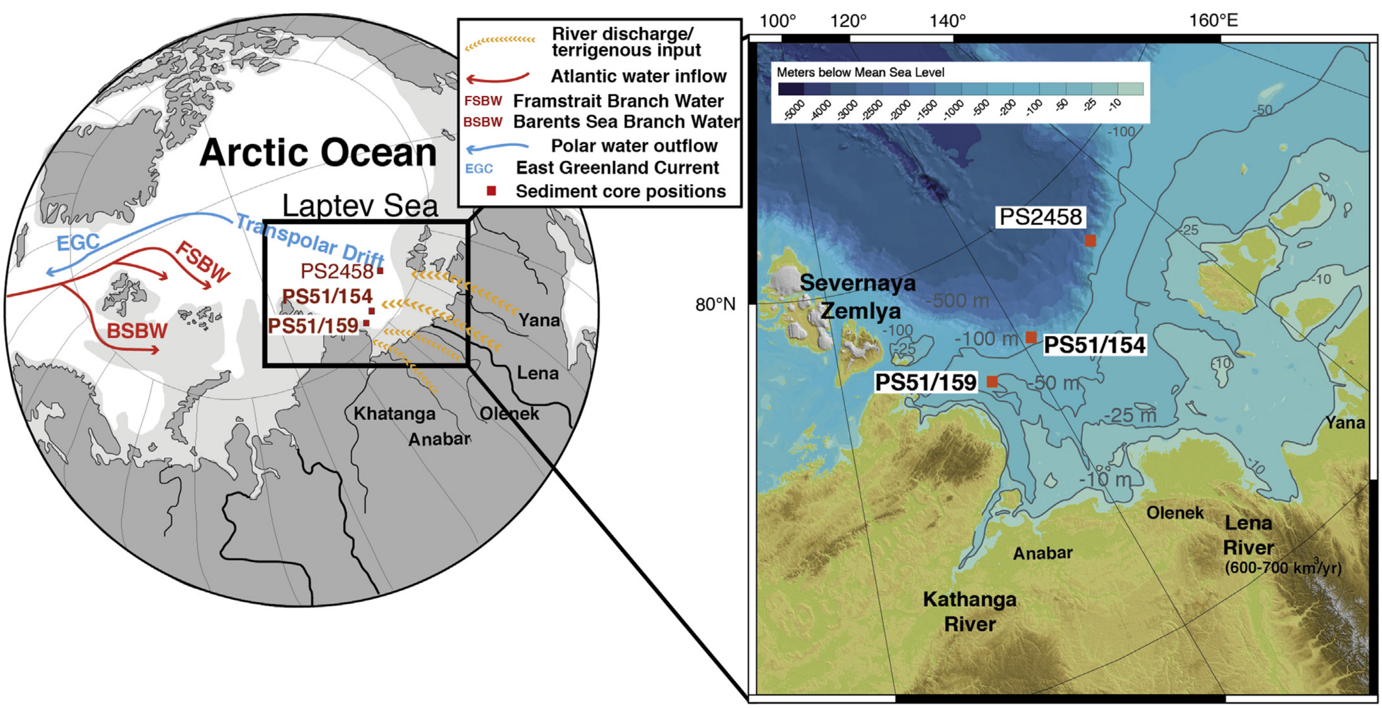

Fig. 1. An overview map showing the Arctic environment (on the left) with the major ocean currents according to Rudels et al. (2005) and the sites of the sediment cores PS51/154, PS51/159 and PS2458 located in the Laptev Sea. A more detailed (bathymetry) map of the Laptev Sea is displayed on the right (*The International Bathymetric Chart of the Arctic Ocean (IBCAO)*, http://www.ibcao.org).