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# Seasonal sea ice cover during the warm Pliocene: Evidence from the Iceland Sea (ODP Site 907)

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A B S T R A C T

Sea ice is a critical component in the Arctic and global climate system, yet little is known about its extent and variability during past warm intervals, such as the Pliocene (5.33–2.58 Ma). Here, we present the first multi-proxy ($IP_{25}$, sterols, alkenones, palynology) sea ice reconstructions for the Late Pliocene Iceland Sea (ODP Site 907). Our interpretation of a seasonal sea ice cover with occasional ice-free intervals between 3.50–3.00 Ma is supported by reconstructed alkenone-based summer sea surface temperatures. As evidenced from brassicasterol and dinosterol, primary productivity was low between 3.50 and 3.00 Ma and the site experienced generally oligotrophic conditions. The East Greenland Current (and East Icelandic Current) may have transported sea ice into the Iceland Sea and/or brought cooler and fresher waters favoring local sea ice formation.

Between 3.00 and 2.40 Ma, the Iceland Sea is mainly sea ice-free, but seasonal sea ice occurred between 2.81 and 2.74 Ma. Sea ice extending into the Iceland Sea at this time may have acted as a positive feedback for the build-up of the Greenland Ice Sheet (GIS), which underwent a major expansion ~2.75 Ma. Thereafter, most likely a stable sea ice edge developed close to Greenland, possibly changing together with the expansion and retreat of the GIS and affecting the productivity in the Iceland Sea.



## 1. Introduction

The modern sea ice cover is rapidly diminishing in the Arctic Ocean and seasonally ice-free conditions are projected for the middle of the 21st century (Wang and Overland, 2012). Satellite data document the Arctic sea ice evolution over the past decades, but its development throughout Earth's history is poorly known, even though sea ice is a very crucial and sensitive component in the climate system. Sea ice influences heat, moisture and gas exchange between ocean and atmosphere, Earth's albedo and primary production (e.g. de Vernal et al., 2013a). Also, brine rejection during sea ice formation affects ocean circulation and deep-ocean ventilation due to production of dense water masses (Aagaard and Carmack, 1989).

To understand sea ice variability in a globally warmer world, it is essential to document sea ice extent, and understand the underlying mechanisms that govern sea ice distribution during past warm climates. The Pliocene (5.33–2.58 Ma) is one period in Earth's history that experienced sustained intervals with global temperatures higher than preindustrial (Dowsett et al., 2013). The Pliocene is also characterized by a gradual transition from the relatively warm climates of the Early Pliocene towards cooler conditions in the Late Pliocene and early Quaternary. The Late Pliocene (3.60–2.58 Ma) had atmospheric $CO_2$ levels ranging between 250 and 450 ppm, global annual mean temperatures ~3 °C higher than today, higher sea level, and reduced continental ice sheets (e.g. Dolan et al., 2015; Haywood et al., 2016; Martínez-Botí et al., 2015). Late Pliocene sea surface temperatures (SSTs) in the Norwegian Sea (Ocean Drilling Program (ODP) Site 642; Bachem et al., 2016; Fig. 1) and in the Iceland Sea (Herbert et al., 2016) were generally 2–3 °C higher than today, but fluctuate between those and present day values. In the Labrador Sea, SSTs were also higher than today, but Sarnthein et al. (2009) identified a freshening and cooling of the East Greenland Current in the Late Pliocene. The emerging high-resolution datasets reveal that the Pliocene climate was dynamical and variable, especially in the Nordic Seas (Bachem et al., 2016; Herbert et al., 2016; Risebrobakken et al., 2016). Although not a perfect analogue for a future globally warm climate, the (mid) Late Pliocene remains a key interval to understand the processes and mechanisms contributing to a globally warmer world with most likely reduced Arctic sea ice (e.g. Dowsett et al., 2010; Haywood et al., 2011).

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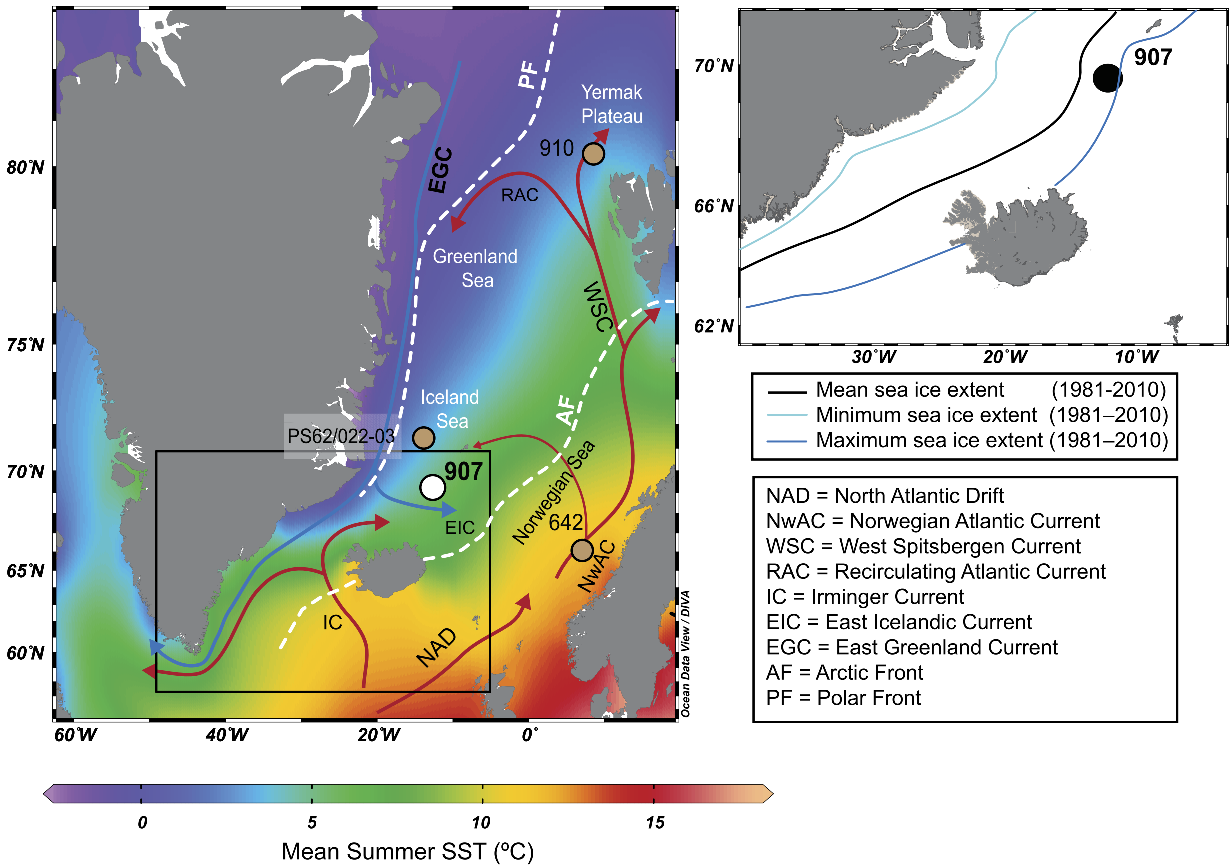


**Fig. 1.** Map of the Nordic Seas, with location of ODP Site 907. Other core locations discussed in the text (PS62/022-03, ODP 642, ODP 910) are also indicated. Left map shows modern averaged July–August–September SSTs from 1955–2012 from the World Ocean Atlas 2013 (Locarnini et al., 2013). Major warm (red arrows) and cool (blue arrows) surface currents in the Nordic Sea are shown. Right map shows a close-up of the study area with minimum, mean and maximum sea ice extent between 1981 and 2010 (http://nsidc.org). Maps were generated with Ocean Data View (http://odv.awi.de/). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Model studies show that mid-Pliocene Arctic terrestrial surface temperatures are strongly influenced by sea ice extent (Ballantyne et al., 2013; Howell et al., 2016b). Perennially sea ice-free conditions (Ballantyne et al., 2013), seasonal sea ice cover or even a perennial sea ice cover (Howell et al., 2016b) have all been proposed for the Pliocene Arctic based on comparing model simulations with available data. These comparisons are hampered by limitations of the sea ice proxies as well as lack of temporal and spatial coverage of data. Fragmentary evidence for Arctic sea ice during the Pliocene has been extracted using micropaleontology (dinocysts, foraminifera, diatoms), sedimentology and geochemistry. Dinoflagellate cysts and planktonic foraminifers occur in seasonal sea ice environments, but are generally indirect sea ice indicators (de Vernal et al., 2013a). Applying foraminifera and diatoms for reconstructing sea ice in the Pliocene Arctic is furthermore limited by a low diversity as well as carbonate and opal dissolution (e.g. Fronval and Jansen, 1996; Stabell and Koç, 1996). A compilation of the available evidence by the Pliocene Research, Interpretation and Synoptic Mapping (PRISM) Project suggested a sea ice-free summer and a winter sea ice cover equivalent to modern summer as the most plausible scenario for the mid-Pliocene (e.g. Dowsett, 2007 and refs therein). However, a different scenario emerges when considering the more recent sedimentological and geochemical evidence, which suggests that the Late Pliocene central Arctic Ocean was perennially sea ice covered (e.g. Darby, 2008), whereas the marginal Arctic Ocean (Yermak Plateau; Fig. 1) was seasonally sea ice covered (Knies et al., 2014). While the latter scenario corresponds to some model simulations, it is contradicted by others (e.g. Howell et al., 2016a, 2016b). To improve model-data comparison and/or compare model performances, it is thus essential that new Arctic sea ice records be generated (Howell et al., 2016a; Matthiessen et al., 2009).

Given the importance of the Nordic Seas and sea ice within the global climate system, here we aim to provide a better understanding about the Late Pliocene sea-surface conditions in the Iceland Sea, by (1) reconstructing the sea ice cover, (2) documenting the paleoproductivity and (3) determining the paleo sea surface temperature. To address these goals, we here present a new, relatively high-resolution (∼7–8 ka) time series of biomarkers ($IP_{25}$, sterols, alkenones) and a lower resolution marine palynomorph record from ODP Site 907 in the Iceland Sea between 3.50 and 2.40 Ma. The time interval we investigate includes (1) the mid-Pliocene (3.26–3.03 Ma), target interval of the PRISM project (Dowsett et al., 2010) and an often used analogue for the projected future climate; and (2) the intensification of the Northern Hemisphere glaciation (here 2.90–2.40 Ma), which marks a transitional period from the relative warm Pliocene climate towards the intense glacial/interglacial cycles of the Quaternary.

## 2. Oceanography

The Nordic Seas (Iceland Sea, Greenland Sea, Norwegian Sea) is the main link between the Arctic Ocean and the North Atlantic (Fig. 1; Blindheim and Østerhus, 2005). Today, the relatively warm (∼10 °C) and saline (∼35 psu) North Atlantic Drift (NAD) enters the Nordic Seas over the Greenland–Scotland Ridge (GSR; Blindheim and Østerhus, 2005) through the Faeroe–Shetland Channel. In the eastern Nordic Seas, the NAD continuous northward