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# Past glacial–interglacial changes in Arctic Ocean sea-ice conditions

Ruediger Stein[1,2,3], A. Kremer[3] and K. Fahl[3]

**Biomarker proxy records indicate that a permanent central Arctic Ocean sea-ice cover existed during the penultimate glacial (MIS 6) but was also still present during the Last Interglacial (MIS 5e), which was characterized by significantly warmer conditions than the present. However, extended seasonal open-water conditions occurred along the northern Svalbard–Barents Sea continental margin during MIS 5e.**

Over the past three to four decades, coincident with global warming and atmospheric $CO_2$ increase, Arctic sea ice has significantly decreased in its extent as well as in thickness (Kwok and Cunningham 2015; Notz and Stroeve 2016; 2018). The loss of sea ice results in a distinct decrease in albedo, causing further warming of ocean surface waters. When extrapolating this trend, the central Arctic Ocean might become ice-free during summers within about the next three to five decades, or even sooner (Masson-Delmotte et al. 2021). Based on a biomarker proxy reconstruction, such ice-free summers also occurred during the middle-late Miocene (12–6 million years before present (BP)), supported by climate modeling with simulated atmospheric $CO_2$ concentrations of 450 ppm (Stein et al. 2016), a value we might reach in the near future. However, although the sea-ice conditions might be similar, the rate of change was quite different between both situations. Whereas the recent change from a permanent to a seasonal central Arctic Ocean sea-ice cover (strongly driven by anthropogenic forcing; cf. Notz and Stroeve 2016) proceeds over a few decades, the corresponding past (natural or non-anthropogenic) change occurred over thousands to millions of years. Furthermore, the closure of the Bering Strait, a shallow-water connection between the Arctic and Pacific oceans, also has an effect on sea-ice formation in the Arctic Ocean (Hu et al. 2015) that has to be considered when comparing past and present conditions.

## Proxy-based reconstruction of past sea-ice conditions

One key aspect within the scientific and societal debate about present climate change is to distinguish and more precisely quantify natural and anthropogenic forcing of global climate change and related sea-ice decrease. In this context, it is fundamental to study paleoclimate records that document the natural climate, rates of change, and variability prior to anthropogenic influence.

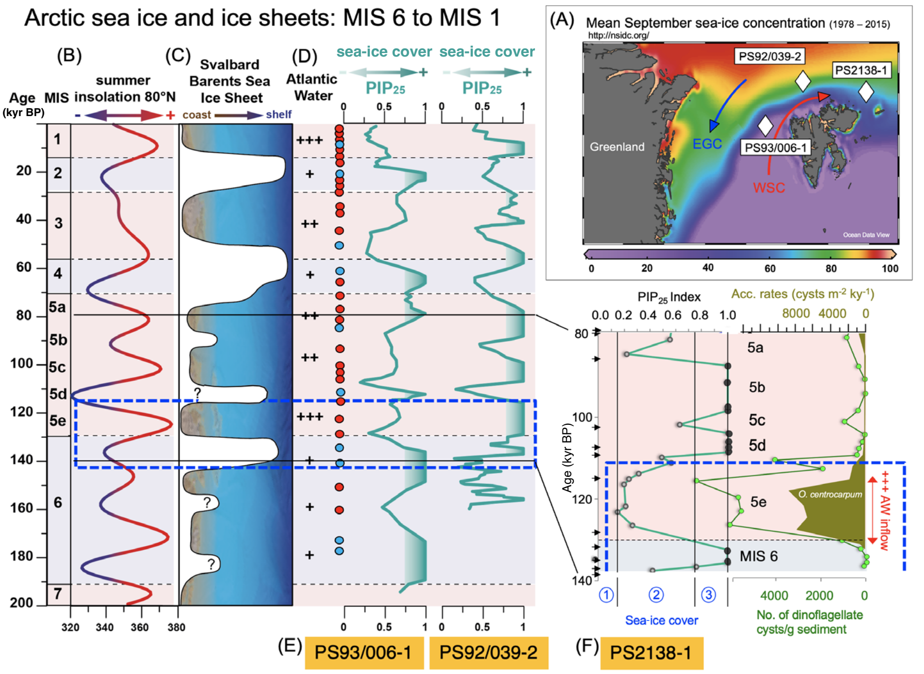


**Figure 1:** Changes in summer insolation, Arctic sea-ice cover and Svalbard-Barents Sea Ice Sheet extent during the last 200 kyr. **(A)** Modern mean September sea-ice concentration in the Fram Strait area and core locations; WSC (West Spitsbergen Current); EGC (East Greenland Current). **(B)** Summer insolation (Laskar et al. 2004). **(C)** Advance/retreat of Svalbard-Barents Sea Ice Sheet (Mangerud et al. 1998). **(D)** Strength of Atlantic water advection along the continental margin north of Svalbard (Wollenburg et al. 2001). **(E)** Biomarker proxy-based ("PIP25") reconstruction of sea-ice cover at cores PS92/039-2 and PS93/006-1; blue (red) circles indicate absence (presence) of alkenones at PS93/006-1 (Kremer et al. 2018). **(F)** PIP25 sea-ice record with (1) ice-free, (2) seasonal to ice-edge situation; and (3) extended to permanent sea-ice cover (Stein et al. 2017), and dinoflagellate records (i.e. number of cysts and accumulation rates of AW-indicator species *Operculodinium centrocarpum*) (Matthiessen and Knies 2001) at Core PS2138-1 representing the 140 to 80 kyr BP time interval. Marine Isotope Stages (MIS) are indicated with blueish (cold) and reddish background color.

Paleoclimate reconstructions allow us to assess the sensitivity of the Earth's climate system to changes of different forcing parameters (e.g. $CO_2$ and insolation; Fig. 1b) and boundary conditions (e.g. presence/absence of major ice sheets and opening/closure of ocean gateways), and to test the reliability of climate models by evaluating their simulations with boundary conditions very different from the modern climate. Of special interest are records representing past climatic conditions that were significantly warmer than the modern one, such as the early Eocene, mid-Miocene, and mid-Pliocene, as well as the Last Interglacial (LIG = Marine Isotope Stage (MIS) 5e), as these climate stages might represent analogs of our future climate, depending on the different IPCC scenarios and related future $CO_2$ emissions (Burke et al. 2018; Masson-Delmotte et al. 2021).

In order to test and approve climate models for simulation and prediction of Arctic climate and sea-ice cover, precise proxy records recording past sea-ice concentrations are needed. Such records may be obtained using a promising biomarker approach that is based on the determination of a highly branched isoprenoid (HBI) with 25 carbons (ice proxy "IP25"; see Belt 2018 for details). This biomarker is (1) only biosynthesized by specific diatoms living in the Arctic sea ice, i.e. the presence of IP25 in the sediments is direct proof of the presence of past Arctic sea ice; and (2) seems to be quite stable over millions of years, as it was found in sediments as old as the late Miocene, i.e. 10–7 million years BP. By combining the environmental information carried by the sea-ice proxy IP25, and specific open-water phytoplankton biomarkers (i.e. using the so-called "PIP25 Index"), even more semi-quantitative estimates of present and past sea-ice coverage, seasonal variability, and marginal ice-zone situations are possible (Fig. 1e, f; Müller et al. 2011; Stein et al. 2017). Meanwhile, this biomarker approach has been used successfully in many studies dealing with the reconstruction of the Arctic sea-ice history during the Last Glacial-to-Holocene time interval, i.e. the last ~30 kyr. For older glacial and interglacial intervals, e.g. MIS 6 and MIS 5, however, Arctic sea-ice biomarker records are still very limited (e.g. Stein et al. 2017; Kremer et al. 2018). Here, we present and discuss such records from cores from areas characterized by different sea-ice conditions today, ranging from perennial sea ice in the central Arctic Ocean to seasonal sea-ice cover along the Barents Sea continental margin (Fig. 2a, b).

 

## MIS 6–MIS 5 sea-ice conditions in the central Arctic Ocean

The absence of both open-water phytoplankton and sea-ice biomarkers in the studied sediment cores point to a more closed and thick ice cover that has prevented both phytoplankton as well as sea-ice algae production during the penultimate glacial MIS 6 but also during MIS 5, including the LIG (Fig. 2a, b; Stein et al. 2017), i.e. a period that was significantly warmer than the present (Holocene; CAPE 2006; NEEM community members 2013). In LIG samples, however, planktic foraminifers and carbonaceous algae were found at some sites in very similar abundances to those determined in Holocene sediments, suggesting similar sea-ice conditions during the LIG as during the latest Holocene (present). That means that the perennial sea-ice cover must have been interrupted by phases with some restricted open-water conditions during summer that allowed the planktic foraminifers and algae to reproduce.

## MIS 6–MIS 5 sea-ice conditions along the northern Svalbard continental margin

In comparison to the central Arctic Ocean, sea-ice conditions were much more variable and complex along the Svalbard/northern Barents Sea continental margin during glacial and interglacial periods (Fig. 1e). The biomarker records of Core PS93/006-1 reveal a prevalence of severe to perennial sea-ice conditions during glacial intervals at the western continental margin of Svalbard, coinciding with major advances of the Svalbard–Barents Sea Ice Sheet (SBIS) (Fig. 1c) and reduced, yet persistent, inflow of Atlantic water to the Arctic Ocean during MIS 6, 5d, 4 and 2 (Fig. 1d), and triggered by minimum summer insolation (Fig. 1b) (Kremer et al. 2018).

With the transition to interglacial conditions, moderate or low PIP25 values, and the constant presence of alkenones indicative of regular production of haptophyte algae at Core PS93/006-1 (Fig. 1e), imply improved conditions for sea-ice and open-water algae production. Hence, a reduced sea-ice cover with more frequent summer melt probably prevailed during interglacials at the western Svalbard slope at 79°N, triggered by high solar insolation (Fig. 1b). The most prominent sea-ice minimum occurred during the LIG (MIS 5e), as clearly reflected in the minimum PIP25 values of about 0.2 and less at Core PS2138-1 (Fig. 1f), i.e. values that may correspond to spring/summer sea-ice concentration of about 20% or even less (Müller et al. 2011; Stein et al. 2017). This sea-ice minimum was probably triggered by strong inflow of warm Atlantic water as indicated by biomarkers as well as micropaleontological proxy records (Fig. 1f).

Quite the opposite scenario can be observed when following the continental margin of the Svalbard Archipelago in a northeastern direction into the interior Arctic Ocean. At the eastern Yermak Plateau (Fig. 1a; PS92/039-2), simultaneous enhanced accumulation of IP25, open-water phytoplankton, and terrigenous biomarkers (Kremer et al. 2018) point to the presence of marginal sea-ice cover during intervals of an extended SBIS (Fig. 1c, e). A combination of katabatic winds from the protruded SBIS and upwelling of warm, subsurface Atlantic water along its shelf break triggered the formation of a coastal polynya along the northern Barents Sea margin with the parallel formation of a stationary ice margin on the eastern Yermak Plateau (Fig. 2d; cf. Knies and Stein 1998). Such polynya-type conditions have also been proposed from biomarker studies at Core PS2757 off an East Siberian Ice Sheet during MIS 6 (Stein et al. 2017).

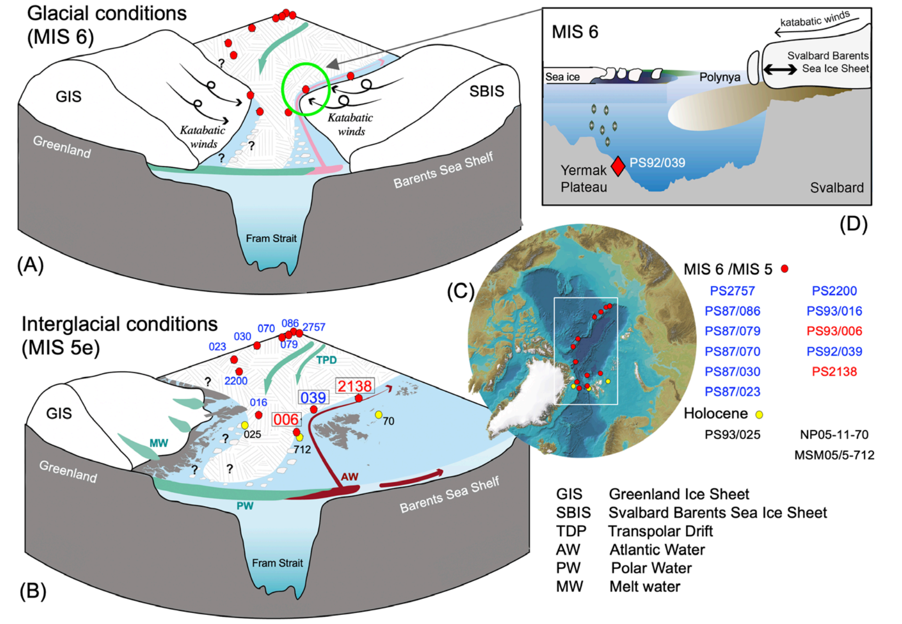


**Figure 2:** Schematic illustration of possible scenarios for the Arctic sea-ice cover under **(A)** glacial (late MIS6: 140–130 ky BP) and **(B)** interglacial (LIG/MIS 5e: 130–115 kyr BP) conditions (for database and further references, see Stein et al. 2017 and Kremer et al. 2018). Red (yellow) circles indicate locations of sediment cores representing the MIS 6 to MIS 5 (Holocene) time interval. Core numbers in blue (red) indicate sites with permanent (reduced/seasonal) sea ice during MIS 5e. The light red shading indicates the persistent, but decreased, northward advection of Atlantic water during glacials, while the dark red shading refers to the inflow of Atlantic water as a strong easterly boundary current during interglacials. The teal arrows indicate the outflow of polar water masses from the interior Arctic Ocean. Black arrows highlight katabatic winds blowing from the extended ice sheet seawards. **(C)** International Bathymetric Chart of the Arctic Ocean (IBCAO) with locations of cores. **(D)** Cartoon showing MIS 6 conditions north of Svalbard with an extended ice sheet and related polynya and sea-ice conditions (cf. Knies and Stein 1998).

## Outlook

The opposing sea-ice variations north (i.e. PS92/039-2) and west (i.e. PS93/006-1) of Svalbard highlight the diverse impact of ice-sheet activity in the region. While the expansion of the SBIS triggered the formation of perennial sea ice west of Svalbard, it led to the establishment of marginal polynya-type ice conditions north of Svalbard. Polynya-type conditions off the major ice sheets along the northern Barents and East Siberian continental margins contradict a giant MIS-6 ice shelf that covered the entire Arctic Ocean, as proposed by Jakobsson et al. (2016), based on new evidence of ice-shelf groundings on bathymetric highs in the central Arctic Ocean. These discrepancies might be explained by scenarios of a succession from an extended ice shelf to polynya/open-water conditions (cf. Stein et al. 2017). More well-dated high-resolution sea-ice proxy records along the circum-Arctic continental margin, representing the maximum MIS 6 glaciation, to the MIS 5e interglacial time interval are still needed to reconstruct the ice-sheet and sea-ice history with their different external forcings and related internal feedback mechanisms.

AFFILIATIONS

[1]Center for Marine Environmental Sciences (MARUM) and Faculty of Geosciences, University of Bremen, Germany

[2]Key Laboratory of Marine Chemistry Theory and Technology, Ocean University of China, Qingdao, China

[3]Alfred Wegener Institute (AWI) Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

CONTACT

Ruediger Stein: rstein@marum.de, ru_st@uni-bremen.de

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