Holocene Environmental Variability in the Arctic Gateway

Robert F. Spielhagen, Juliane Müller, Axel Wagner, Kirstin Werner, Gerrit Lohmann, Matthias Prange and Rüdiger Stein

Abstract Environmental changes in the region connecting the Arctic Ocean and the northern North Atlantic were studied for the last 9,000 years (9 ka) by a combination of proxy-based paleoceanographic reconstructions as well as transient and time-slice simulations with climate models. Today, the area is perennially ice-covered in the west and ice-free in the east. Results show that sea-ice conditions were highly variable on short timescales in the last 9 ka. However, sea-ice proxies reveal an overall eastward movement of the sea-ice margin, in line with a decreasing influence of warm Atlantic Water advected to the Arctic Ocean. These cooling trends were rapidly reversed 100 years ago and replaced by the general warming in the Arctic. Model results show a consistently high freshwater input to the Arctic Ocean during the last 7 ka. The signal is robust against the Holocene cooling trend, however sensitive towards the warming trend of the last century. These results may play a role in the observed Arctic changes.

Keywords Arctic Ocean · Holocene · Sea ice · Atlantic Water · River run-off · Global warming

R.F. Spielhagen (✉)
Academy of Science and Literature, Mainz, Germany
e-mail: rspielhagen@geomar.de

R.F. Spielhagen · K. Werner
GEOMAR, Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

J. Müller · A. Wagner · G. Lohmann · R. Stein
Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany

A. Wagner · M. Prange
University of Bremen, Bremen, Germany

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1 Introduction

The Arctic Ocean and sub-Arctic play a fundamental role in the global ocean-climate system. Siberian and North American rivers discharge enormous amounts of freshwater to the Arctic Ocean which, in combination with cold atmospheric temperatures, enables the formation and persistence of the Arctic sea-ice cover which is severely threatened today by global warming. The Fram Strait between Greenland and Svalbard is the main "Arctic Gateway" for water mass exchange between the Arctic Ocean and the northern North Atlantic (Fig. 1). In the east, relatively warm (2–7 °C) and saline ($S > 35$) Atlantic Water flows northward. In the west, cold, sea-ice covered low-saline Arctic surface waters are exported to the Nordic Seas. Given the strong E-W contrasts, saline Atlantic Water is preconditioned for convective overturning and deepwater renewal. The position of the sea-ice margin is strongly controlled by the intensity and temperature of advected Atlantic Water but little is known about the Holocene (last ~12 ka) variability of these parameters. To fill this knowledge gap and analyze the amplitudes of natural Arctic climate variations on (sub-)millennial timescales, expressed as, e.g., temporal and spatial variations of Atlantic Water temperature and sea-ice cover, high-resolution sedimentary records from the Arctic Gateway were investigated by micropaleontological and geochemical methods. Simulations with a coupled atmosphere-ocean circulation model were used to investigate the role of river discharge and to extend the spatial range of sea-ice reconstructions which are originally derived from (local) sediment core data series.

2 Materials and Methods

Sediment investigations were performed on selected long cores with multidecadal resolution from the continental margin of the eastern Fram Strait (78.9°N–81.2°N; Fig. 2) and the shelf off East Greenland (73.1°N). The cores were subsampled to reach a (sub-)centennial resolution. The stratigraphy is based on a series of radiocarbon datings. For sedimentological, micropaleontological and isotopic investigations, sediment preparations and analyses followed standard procedures described by Werner et al. (2011, 2013). To investigate the organic-geochemical content, sediments were analyzed for total organic carbon, carbonate and biomarker composition according to procedures described by Müller et al. (2011, 2012).

Model simulations were performed with the coupled atmosphere-ocean general circulation model ECHO-G using acceleration techniques for the Holocene and the regional North Atlantic/Arctic Ocean–Sea Ice Model (NAOSIM). Details of the model set-up are given by Müller et al. (2011) and Wagner et al. (2011). Forcing occurred solely by solar variations from orbital parameters between 7 ka and 1800 CE and additionally by anthropogenic greenhouse gases thereafter. The high-resolution NAOSIM simulations focus on the sea-ice distribution in the Greenland Sea and Fram Strait. Downscaling procedures were described by Müller et al. (2011) and Stärz et al. (2012).

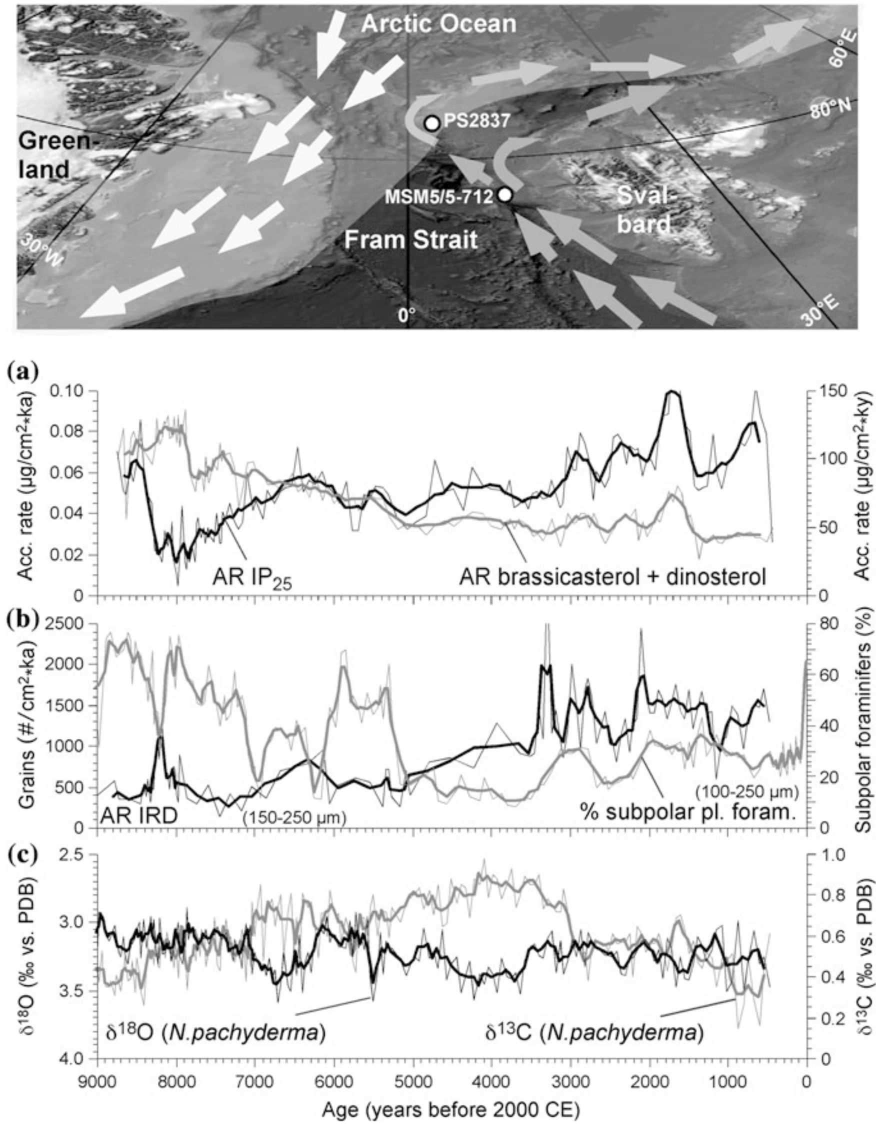

Fig. 1 Research area in the Fram Strait and proxy data sets from sediment core MSM5/5-712 for the last 9 ka. *Gray shading* denotes the modern average summer sea-ice cover. *White and gray arrows* in map indicate sea-ice drift and Atlantic Water advection, respectively. *Thick lines* in data series represent 3-point running means. **a** Accumulation rates (AR) of the sea-ice biomarker IP_{25} (*black*) vs. phytoplankton biomarkers (*gray*), **b** AR of terrigenous ice-rafted detritus (*black*) vs. relative abundance of subpolar planktic foraminifers (*gray*), **c** stable oxygen (*black*) and carbon isotopes (*gray*) of planktic foraminifers *Neogloboquadrina pachyderma* (125–250 µm fraction)

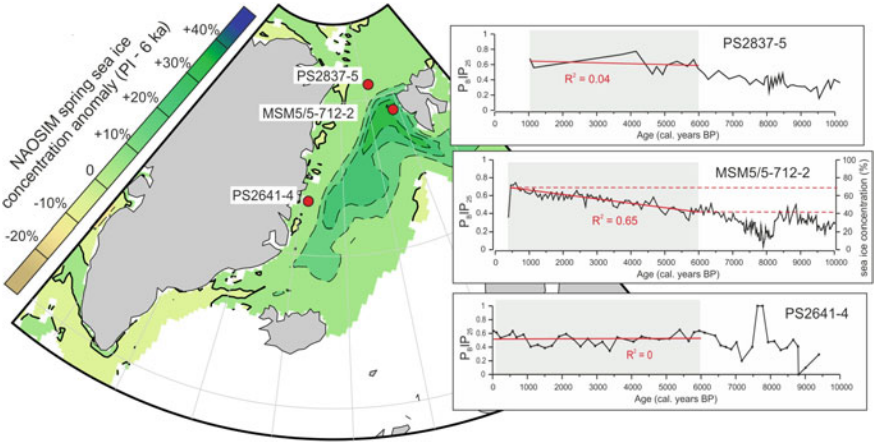

Fig. 2 NAOSIM-derived time-slice sea-ice anomaly for 6 ka to pre-industrial (PI) times in the Fram Strait area (map) and P_BIP_{25} (where B refers to the use of brassicasterol for calculating the PIP_{25} index) records of three sediment cores from the same area. *Gray shadings* and *red solid regression lines* highlight the individual P_BIP_{25} trends from 6 ka to PI times. Sea-ice concentration estimates for MSM5/5-712-2 are derived from the P_BIP_{25} vs. satellite sea-ice data correlation of Müller et al. (2011). Both proxy (P_BIP_{25}) and model results (*dark green* colours on the map) point to a 30 % sea-ice increase in the eastern Fram Strait between 6 ka and PI times (*red dashed lines* denote the increase in sea-ice concentrations from ca 40 % to 70 %). Only a minimum sea-ice increase is reconstructed (*solid red regression lines*)/modeled (*light green* colours on the map) for the northern and western Fram Strait core sites

3 Key Findings

The novel sea-ice proxy IP_{25}, a biomarker associated exclusively to diatoms living in sea ice, has opened new possibilities for reconstructions of past sea-ice coverage in the (sub-)Arctic. The method, originally based only on IP_{25} concentrations in sediments, has been further developed by combining data from IP_{25} and phytoplankton-derived biomarkers. This combination—resulting in the so-called PIP_{25} index—allows a (semi-)quantitative reconstruction of past sea-ice cover (Müller et al. 2009, 2011; Stein et al. 2012). This approach was first applied to core PS2837 from north of Svalbard (Fig. 1), close to the modern summer sea-ice margin (Müller et al. 2009). Variable contents of both biomarker types demonstrated that even the position of a seasonally fluctuating sea-ice margin can be reliably detected. A study on recent (surface) sediments in combination with numerical modeling results of the sea-ice distribution (Müller et al. 2011) showed that both methods successfully reproduce the degree and spatial distribution of the average ice coverage in the Fram Strait and Nordic Seas although in places local effects can distort the results.

Studies of biomarkers, microfossils, stable and radiogenic isotopes, as well as sedimentological proxies on core MSM5/5-712 (western Svalbard margin) allowed to reconstruct the variability of Atlantic Water advection (Fig. 1) to the Arctic and its effect on the regional ice coverage (Werner et al. 2011, 2013; Müller et al. 2012). IP_{25} accumulation rates are mostly low in late Early Holocene sediments and medium high at 7 to 3 ka, while phytoplankton biomarker contents decrease from 9 to 5 ka (Fig. 1). Proxy data and NAOSIM reconstructions (Fig. 2) suggest a general cooling trend and a successive southeastward shift of the sea-ice margin towards Svalbard since the Early Holocene (Müller et al. 2011, 2012), responding to the postglacial sea-level rise, a related onset of modern sea-ice production on the Siberian shelves (Werner et al. 2013), and to insolation-induced sea-ice and circulation changes. After 3 ka, biomarker accumulation rate peaks, highest contents of ice-rafted detritus, and a change in Nd isotope ratios of sediment leachates are evidence of a sea-ice margin rapidly advancing to and retreating from the core site (Müller et al. 2012; Werner et al. 2014). This interpretation is corroborated by microfossil and planktic isotope data. Generally high relative abundances of subpolar foraminifers until 5 ka indicate a strong influence of Atlantic Water as a near-surface water mass off western Svalbard, but low amounts thereafter demonstrate a drastic change to colder conditions (Werner et al. 2011, 2013). Low carbon and high oxygen isotope values of the polar planktic foraminifer species during the last 3 ka suggest a strengthened stratification due to a low-saline surface water layer. The drastic increase of subpolar species percentages in the last $\sim$100 years indicates an equally strong increase of Atlantic Water temperatures and advection to the Arctic. Modern temperatures are unprecedented for the last 5 ka, probably as a response to global warming, and pose a severe threat to the Arctic sea-ice cover (Spielhagen et al. 2011).

Transient simulations with ECHO-G were analyzed to investigate the history of circum-Arctic river run-off and elucidate its possible role in the environmental changes observed in the Fram Strait (Wagner et al. 2011). The discharges, as calculated by the model, are driven by the difference between precipitation and evaporation and show a strong variability on annual to multi-centennial timescales. Results reveal that the discharge from Eurasian rivers increased slightly (2.1 ± 0.6 %) between 7 ka and 1800 CE while that of North American rivers decreased by 4.6 ± 0.6 %. In the Holocene, the total discharge remained at a constant level, while atmospheric temperatures decreased. This may have supported a stable halocline, as indicated by proxy data, and favored sea-ice formation. The last 100 years have seen a strong run-off increase from both continents (7.6 % for the total Arctic Ocean), in line with 20th century observations, however, accompanied by a rapid warming of the Arctic. These findings, together with the results from high-resolution sediment cores, clearly reveal extremely strong and rapid environmental changes during the Industrial Period in the Arctic which are unprecedented for several millennia before.

References

Müller J, Massé G, Stein R, Belt ST (2009) Variability of sea-ice conditions in the Fram Strait over the past 30,000 years. Nat Geosci 2(11):772–776

Müller J, Wagner A, Fahl K, Stein R, Prange M, Lohmann G (2011) Towards quantitative sea ice reconstructions in the northern North Atlantic: a combined biomarker and numerical modelling approach. Earth Planet Sci Lett 306(3–4):137–148

Müller J, Werner K, Stein R, Fahl K, Moros M, Jansen E (2012) Holocene cooling culminates in Neoglacial sea ice oscillations in fram strait. Quat Sci Rev 47:1–14

Spielhagen RF, Werner K, Sørensen SA, Zamelczyk K, Kandiano E, Budeus G, Husum K, Marchitto TM, Hald M (2011) Enhanced modern heat transfer to the Arctic by warm Atlantic Water. Science 331(6016):450–453

Stärz M, Gong X, Stein R, Darby DA, Kauker F, Lohmann G (2012) Glacial shortcut of Arctic sea-ice transport. Earth Planet Sci Lett 357–358:257–267

Stein R, Fahl K, Müller J (2012) Proxy reconstruction of Arctic Ocean sea ice history: from IRD to IP_{25}. Polarforschung 82:37–71

Wagner A, Lohmann G, Prange M (2011) Arctic river discharge trends since 7 ka BP. Global Planet Change 79:48–60

Werner K, Spielhagen RF, Bauch D, Hass HC, Kandiano E, Zamelczyk K (2011) Atlantic Water advection to the eastern Fram Strait - Multiproxy evidence for late Holocene variability. Palaeogeogr Palaeoclimatol Palaeoecol 308(3–4):264–276

Werner K, Spielhagen RF, Bauch D, Hass HC, Kandiano E (2013) Atlantic Water advection versus sea-ice advances in the eastern Fram Strait during the last 9 ka: Multiproxy evidence for a two-phase Holocene. Paleoceanography 28(2):283–295

Werner K, Frank M, Teschner C, Müller J, Spielhagen RF (2014) Neoglacial change in deep water exchange and increase of sea-ice transport through eastern Fram Strait: Evidence from radiogenic isotopes. Quat Sci Rev 92:190–207