Evidence for ice-free summers in the late Miocene central Arctic Ocean

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Although the permanently to seasonally ice-covered Arctic Ocean is a unique and sensitive component in the Earth’s climate system, the knowledge of its long-term climate history remains very limited due to the restricted number of pre-Quaternary sedimentary records. During Polarstern Expedition PS87/2014, we discovered multiple submarine landslides along Lomonosov Ridge. Removal of younger sediments from steep headwalls has led to exhumation of Miocene sediments close to the seafloor. Here we document the presence of IP25 as a proxy for spring sea-ice cover and alkenone-based summer sea-surface temperatures >4 °C that support a seasonal sea-ice cover with an ice-free summer season being predominant during the late Miocene in the central Arctic Ocean. A comparison of our proxy data with Miocene climate simulations seems to favour either relatively high late Miocene atmospheric CO2 concentrations and/or a weak sensitivity of the model to simulate the magnitude of high-latitude warming in a warmer than modern climate.
There is a general consensus that the polar regions—and in particular the Arctic Ocean and surrounding areas—are at present, and were over historic and geologic time scales, subject to rapid and dramatic environmental changes. Owing to complex feedback processes, collectively known as ‘polar amplification’, the Arctic is both a contributor to climate change and a region that will be most affected by global warming\textsuperscript{1–3}. Despite the importance of the Arctic Ocean in the global climate...
system, this permanently to seasonally ice-covered region (Fig. 1) is one of the last major physiographic provinces on Earth, whose climate history and its transition from early Cenozoic Greenhouse to late Cenozoic Icehouse conditions remain still poorly known. Only one drill site recovered from the central Arctic Ocean during the Arctic Coring Expedition (ACEX)—the Integrated Ocean Drilling Program (IODP) Expedition 302 in 2004—gives some insight into the early Cenozoic climate1–6.

Concerning recent climate change, the most prominent example is the dramatic decrease of the extent and thickness of the Arctic sea–ice cover the last decades, a decrease that seems to be far more rapid than predicted by climate models1–3. The scientific community recognized this drastic change with major concern as the Arctic sea ice is a critical component in the global climate system, which contributes to changes in the Earth’s albedo, primary productivity and deep-water formation, a driving mechanism for global thermohaline circulation2. The causes of these recent changes, that is, natural versus anthropogenic forcings, and their relevance within the global climate system, however, are subject of intense scientific and societal debate. Thus, understanding the processes controlling Arctic sea-ice variability is of overall interest and significance2,8. In this context, records of past climate and sea–ice conditions going beyond instrumental records and representing times of different boundary conditions are of major value: such records can be used to assess the sensitivity of the Earth’s climate system to changes of different forcing parameters, for example, level of CO2, and to test the reliability of climate models by evaluating their simulations for conditions very different from the modern climate. This type of records giving detailed information about past Arctic sea–ice conditions are still very rare, especially due to the lack of precise proxies for sea-ice reconstructions (see review in ref. 9).

The ability to (semi-)quantitatively reconstruct paleo–sea–ice distributions has been significantly improved by a biomarker approach based on the determination of a highly branched isoprenoid (HBI) with 25 carbons (C25 HBI monoene = IP25)10. This biomarker is only biosynthesized by specific diatoms living in the Arctic ice11 and appears to be a specific, sensitive and stable proxy for Arctic sea ice in sedimentary sections representing Pliocene to Pleistocene times12,13. When using this proxy, one has to consider that IP25 is absent under a permanent sea-ice cover limiting light penetration and, in consequence, sea-ice algal growth (that is, IP25 = 0). The same consequence applies to totally ice-free conditions (Fig. 1). Müller et al.14,15 overcame this difficulty in interpreting IP25 data by the additional use of phytoplankton-derived open-water biomarkers such as brassicasterol or dinosterol (Fig. 1). Furthermore, Müller et al.14 combined the environmental information carried by IP25 and phytoplankton biomarkers in a phytoplankton-IP25 index, the so-called ‘PIP25 index’ (for calculation of PIP25, see ‘Methods’). In general, the PIP25 values determined in Arctic Ocean surface sediments correlate reasonably well with the modern sea–ice distribution based on satellite data, although regional differences in the correlation patterns seem to be obvious14,16. In the modern central Arctic Ocean characterized by a mostly perennial sea–ice cover, the PIP25 values of most of the surface sediments are between 0.65 and 1 (ref. 16). These data suggest that the PIP25 index seems to be a promising proxy for more semi-quantitative estimates of the present and past sea–ice extent, although certainly further groundtruth data are needed (see Methods for some more details)8,16.

Here we apply the new sea–ice biomarker approach together with alkenone-based sea–surface temperatures (SSTs) to sediment cores most recently recovered during Polarstern Expedition PS87 (ref. 17), to reconstruct upper Miocene Arctic Ocean sea–ice and SST conditions. The proxy data are combined with climate model simulations using a coupled atmosphere-ocean general circulation model (AOOGCM; see Methods) with focus on seasonal changes in the high northern latitudes. Based on our new proxy records, we demonstrate that only a seasonal sea–ice cover has been predominant in the central Arctic Ocean during (most of) the Late Miocene time interval. Furthermore, our combined data/modelling approach seems to indicate either relatively high atmospheric CO2 concentrations and/or an overly weak sensitivity of the model to simulate the magnitude of warm polar temperatures in the late Miocene. These new findings from the Arctic region provide new benchmarks for groundtruthing global climate reconstructions and modelling.

Results

Large submarine slide scars along Lomonosov Ridge. Polarstern Expedition PS87 was scheduled for August–September 2014 to explore the Lomonosov Ridge area (Fig. 2) with the objective of collecting seismic data and sediment cores to reconstruct the short- and long-term climate history and the tectonic evolution of the central Arctic Ocean17. More than 3,000 km of high-quality multi-channel seismic (MCS) profiles and ~10,000 km of high-quality multibeam bathymetry and sub-bottom sediment-echosounding (PARASOUND) profiles were acquired along the ship’s track and numerous sediment cores were recovered (Fig. 2). One major finding of the expedition was the discovery of numerous submarine slide scars that occurred on both sides of the crest of Lomonosov Ridge over a distance of ca. 350 km between 81°07’N and 84°14’N in water depths from ~800 to 1,500 m (Fig. 3a). Single scars are up to several kilometres wide and long, and their head walls are 100–500 m high. Swath-bathymetry data indicate that different processes probably triggered slope failures, that various processes of sediment evacuation took place, and that failures occurred at various times. Slide scars were earlier described from a restricted area on Lomonosov Ridge near 88°N18. However, the wide lateral distribution of mass wasting as presented here is a new discovery.

On top of the southern Lomonosov Ridge in areas between the slide scars, we discovered SE–NW oriented, streamlined landforms over distances of >100 km at water depths between 800 and 1,000 m (Fig. 3a). These features are interpreted to be glacial lineations that formed beneath grounded ice19,20. Similar unidirectional bed forms have also been identified further east on the East Siberian continental margin where they were related to large and coherent ice masses (East Siberian Chuetsk Ice Sheet—ES CIS)21. The lineations identified in this study are similar to those on the East Siberian continental margin with respect to their orthogonal orientations to the proposed centre of the former ESCIS. At the present state of knowledge, the most plausible glacial scenario is a larger than originally proposed ESCIS including an ice shelf extending into the Arctic Ocean, which formed an ice rise on the Southern Lomonosov Ridge over areas presently shallower than 1,000 m. The load and erosional behaviour of this ice rise that probably occurred during extended Quaternary glaciations, for example, during marine Isotope Stage 6 (MIS 6), may have caused physical conditions that triggered the landslides on this part of Lomonosov Ridge. A MIS 6 age of this erosional event is in line with the proposed age of a major glaciation with extended ice sheets/shelves in Eurasia and East Siberia19–21.

Exhumation of Miocene to lower Quaternary sediments. Sediment removal from the steep slopes of the escarpments exposed older, normally more deeply buried deposits at/near the present seafloor, allowing retrieval of older sediments by gravity
Figure 2 | Cruise track and multibeam bathymetric survey of Polarstern Expedition PS87. (a) PS87 cruise track (blue line)\(^7\). AB, Amundsen Basin; AR, Alpha Ridge; GR, Gakkel Ridge; LR, Lomonosov Ridge; MB, Makarov Basin; MR, Mendeleev Ridge; NB, Nansen Basin. Orange circles indicate coring stations, the red asterisk indicates the location of the ACEX Site and the green circle indicates the North Pole (Polarstern reached on 26 August 2014 at 10:23 UTC). (b) Track lines of multibeam bathymetric survey. Colour bar indicates water depth in metres (m WD). LR-01A, LR-02A and LORI-05B indicate locations of proposed IODP drill sites\(^51\) (cf., IODP Proposal 708; http://www.iodp.org/expeditions). Areas of Fig. 3a,b are indicated.

Figure 3 | Bathymetric and acoustic/seismic profiling records from southern Lomonosov Ridge. (a) Three-dimensional (3D) image of the swath bathymetry of southern Lomonosov Ridge, showing major slide scars and escarpments, streamlined SE–NW oriented glacial lineations formed beneath grounded ice sheets/streams and transects 1 and 2 with locations of sediment cores (cf., Supplementary Table 1). (b) PARASOUND profile across Transect 1 with locations of coring stations. (c) Processed multi-channel seismic profile AWI-20140311 across Transect 1, showing prominent reflectors and age assignments based on correlation between regional seismic lines and well data\(^22,23\).
coring from Polarstern, rather than expensive drilling. The PARASOUND and MCS profiles suggest that these sedimentary sections are composed of Eocene, Oligocene, Miocene, Pliocene and Quaternary strata (Fig. 3b,c). After evaluation of the multibeam bathymetry and PARASOUND data, we selected two transects across the steep western slope of Lomonosov Ridge for an extensive sediment coring programme (Fig. 3a, Transect 1 and Transect 2). In total, 16 sediment cores were recovered from water depths between 900 m (top of Lomonosov Ridge) and 1,500 m (foot of Lomonosov Ridge) (Fig. 3a,b and Supplementary Table 1).

Whereas most of the sediment cores of Transect 1 are composed of predominantly upper Quaternary (post slide) deposits, some contain prominent unconformities with lower/pre-Quaternary sediments underneath (see Methods and Supplementary Figs 1 and 2). At these unconformities, a 50- to 80-m-thick overburden has been removed, as demonstrated in compaction experiments (see ‘Sediment load and compaction experiments’). Unfortunately, the microfossil assemblages (that is, palynomorphs and agglutinated benthic foraminifers) do not allow a precise age determination of the sediments underlying the Quaternary near-surface deposits in most of these cores (Supplementary Table 1). The predominance of Quaternary sediments in the cores of Transect 1, however, seems to be supported by the biomarker composition determined in selected cores. Close to zero concentrations or the absence of specific biomarkers indicative for phytoplankton and sea-ice algae productivity point to surface-water conditions similar to those of the central Arctic Ocean during late Quaternary times, characterized by a thick perennial sea-ice cover and SSTs ≤0°C (Supplementary Table 2 and Fig. 1).

The only core providing a clear indication that old sediments are cropping out near the seafloor is Core PS87/106. In this core...
Late Miocene SST and sea-ice records. The biomarker data of Core PS87/106 suggest significantly different late Miocene paleoenvironmental conditions in comparison with those predominant during Quaternary times (Fig. 4 and Supplementary Table 2). In the upper Miocene sediments, elevated concentrations of alkenones and alkenone-derived SST between 4 and 7°C (or even 6–9°C in case other calibrations are used; cf. Supplementary Table 2) indicate relatively warm, open-water and productive paleoenvironmental conditions in the central Arctic Ocean during the summer season. This is also supported by SST values of >0°C determined in some samples from the ACEX Site (Supplementary Tables 2 and 3). Our results reveal for the first time the occurrence of the biomarker sea-ice proxy IP25 in sediments as old as late Miocene. This proxy was developed by Belt et al.10 and was before our study only found in Quaternary and Pliocene sediments12,13. The presence of IP25 in the PS87/106 sediments is indicative for the presence of (spring) sea ice in the late Miocene central Arctic Ocean (Fig. 1). In comparison with IP25 values from the Arctic Ocean surface sediments16 and sediment trap data28, the absolute IP25 concentrations ranging between 0.05 and 0.15 μg gOC−1 (Fig. 4 and Supplementary Table 2) are more than one order of magnitude lower. These differences are caused by an early degradation of biomarkers that already starts in the water column and reaches its maximum in the uppermost centimetres of the sediments28,29. On the other hand, both IP25 and phytoplankton biomarker concentrations determined in Core PS87/106 are in the same range than those determined in early-mid Holocene Arctic sediments8,30.

Using the ‘PIP25 Index’ as a more semi-quantitative proxy of paleo-sea-ice cover (see Fig. 1 and Methods), our data from Core PS87/106 point to a variable spring sea-ice coverage of ~20–70% in the lower part and ~100% in the upper part of the sequence.

Figure 5 | Schematic illustrations of the seasonal sea-ice cycle during the late Miocene. The seasonal sea-ice cycle and related principal processes controlling productivity and carbon flux at location of central Arctic Ocean Core PS87/106 during the late Miocene are shown for two different scenarios. (a) Scenario 2 (‘warmer/transitional situation’) = extended period of spring sea-ice algae productivity and increased IP25 and phytoplankton biomarker fluxes. (b) Scenario 1 (‘cold situation’) = restricted period of late spring sea-ice algae productivity and very reduced fluxes (almost to zero) of IP25 and spring phytoplankton biomarkers; cf. Fig. 1). MIZ, Marginal Ice Zone, that is, ice-edge situation. The dark period, height of the sun and changing thickness of snow and ice over the year, as well as phytoplankton, zooplankton and sea-ice productivity are shown. IP25 values for the different seasons are indicated (after ref. 72, supplemented).
The combination of IP25 and SST data indicates that the central Arctic Ocean must have been relatively warm and ice-free during summer throughout the time interval recovered in the sedimentary section of Core PS87/106 and variable sea ice must have existed during spring when daylight conditions allowed sea-ice algae production (Figs 1 and 5, and Supplementary Table 2). Furthermore, this implies the presence of an extended sea-ice cover during the dark, cold winter season. These new data clearly support that periods with only a seasonal sea-ice coverage must have occurred in the central Arctic Ocean during most of the late Miocene (Fig. 5; see further discussion below).

Simulations of late Miocene Arctic Ocean climate. Model simulations of global climate conditions reconstructing a warm late Miocene climate apply atmospheric CO2 concentrations in the range of 280–700 p.p.m.31–34. Different reconstructions of late Miocene CO2 levels have narrowed the uncertainties, with atmospheric CO2 values likely to be below the present day concentrations35,36. Nevertheless, the associated uncertainties in the late Miocene CO2 levels are at least 200 p.p.m.34,37,38. Therefore, we have re-analysed Miocene climate simulations32,39 with CO2 concentrations of 278 and 450 p.p.m. using a coupled AOGCM. The investigation focus is on seasonal changes in the central Arctic Ocean as simulated with the AOGCM32,39 (for details and background, see Methods).

Our simulated mean August SST and mean sea-ice concentrations for March, June and September for high (450 p.p.m.) and low (278 p.p.m.) CO2 levels (Fig. 6 and Supplementary Table 4) indicate the following: (1) a winter season with a closed sea-ice cover in the central Arctic Ocean decreasing towards the marginal seas for 450 p.p.m. CO2 (Fig. 6a) and a closed sea-ice cover in the entire Arctic Ocean including the marginal seas for 278 p.p.m. CO2 (Fig. 6d); (2) spring season sea-ice concentrations of 20–60% for 450 p.p.m. CO2 (Fig. 6b) and even 80–90% for 278 p.p.m. CO2 (Fig. 6e); and (3) a summer season with ice-free conditions and SSTs > 0°C for 450 p.p.m. CO2 (Fig. 6c,g) and a reduced but still present sea-ice cover of 10–50% and SSTs < −1°C for 278 p.p.m. CO2 (Fig. 6f,h).

In combination with our new SST and sea-ice proxy data, these results suggest that either late Miocene CO2 levels have been relatively high or, alternatively, the applied model has an overly weak sensitivity especially in the northern high latitudes, as in the

Figure 6 | Late Miocene Arctic Ocean climate simulations for high and low pCO2 levels using a coupled atmosphere–ocean general circulation model. (a–c,d–f) Sea-ice concentrations for March, June and September at 450 and 278 p.p.m. CO2 levels, respectively32. (g,h) Late Miocene August SST at 450 and 278 p.p.m. CO2 levels, respectively.
simulation with a relatively low CO₂ level of 278 p.p.m. summer SSTs are too low to explain our sedimentary SST proxy indicative of 4–7 °C. (Fig. 4 and Supplementary Tables 3 and 4). The latter reflects a characteristic challenge of current model approaches to simulate warm climates in the geological past. Hence, the new findings from the Arctic region provide an enhanced basis for groundtruthing global climate reconstruction and modelling.

**Discussion**

Late Miocene climatic conditions significantly warmer than today have been reconstructed from marine and terrestrial proxy records from different localities around the globe. However, quantitative SST proxy data from the High Arctic are exclusively restricted to a few terrestrial records. With our study, we show for the first time that the late Miocene central Arctic Ocean was relatively warm with SSTs of ~5 °C (Figs 4 and 8) and ice-free during summer, whereas sea ice occurred during spring and autumn/winter. During the late Miocene a general cooling trend is obvious as recorded in the SST record of the sub-Arctic ODP Site 907 (Fig. 8 and Supplementary Table 5). Such a cooling trend seems to be supported by the limited number of SST values available from the ACEX site (Fig. 8). Comparing this general cooling trend with the SST values from Core PS87/106, the sedimentary section of Core PS87/106 below the hiatus probably represents a time span within the upper Tortonian to lower Messinian as supported by palynomorph stratigraphy (Fig. 8). Furthermore, the new Arctic SST data fit in very well with the grander long-term Cenozoic cooling pattern (see Supplementary Fig. 4 and references in the figure legend).

Although on a first view this short sedimentary section of Core PS87/106 only represents a short snapshot of late Miocene Arctic climate, more detailed information about the late Miocene Arctic climate on a regional to even global scale can be obtained from our record. Based on the biomarker data, the 1.3-m-thick late Miocene section of Core PS87/106 probably represents almost one cycle with extended and reduced spring sea-ice conditions (Fig. 4). The (almost) absence of phytoplankton biomarkers and IP25 (PIP25 = ‘1’; see Fig. 1) and low concentrations of terrigenous biomarkers may be explained by an extended to closed sea-ice cover and a very restricted spring season (Scenario 1 in Figs 4 and 5). Scenario 2, on the other hand, represents a transitional phase with a stable ice edge during an extended and productive spring season, characterized by maximum input of phytoplankton biomarkers and IP25 (resulting in PIP25 values of 0.4–0.7), as well as maximum input of terrigenous biomarkers (and ice-rafted debris (IRD)) (Scenario 2 in Figs 4 and 5). The interval between scenarios 1 and 2 is characterized by very low to zero IP25 concentrations and increased concentrations of phytoplankton biomarkers, resulting in a distinct PIP25 minimum (Fig. 4). This interval is interpreted as a period of minimum spring sea-ice extent. Furthermore, maximum values of alkenones may reflect increased productivity of haptophyte algae during the summer season.

Using mean sedimentation rates of ~3.2 cm ky⁻¹ as calculated independently from close-by gravity cores and seismic data, the duration of this cycle is about 40 ky, that is, very similar to the 41 ky obliquity cycle (Fig. 4 and also see ref. 52 and references therein). Hence, our record may represent just one obliquity cycle with ice-free conditions during summers in both the cold (‘glacial’) and the warm (‘interglacial’) phase of this climate cycle (Figs 4 and 5). As Core PS87/106 probably is of upper Tortonian to lower Messinian age (see above),
ice-free summer conditions should have occurred in the central Arctic Ocean during the warmer Middle Miocene to early Late Miocene time interval a fortiori (Fig. 8). In contrast to several previous studies, we therefore propose that a seasonal sea-ice cover was predominant in the central Arctic Ocean during (most of) the late Miocene time interval (see discussion below).

Our new semi-quantitative sea-ice and SST records are an important contribution to the ongoing and controversial debate about the reconstruction of the early (pre-Quaternary) Arctic Ocean sea-ice cover. Within this debate, the distinction between seasonal and perennial sea ice is critical, because year-round sea ice in the central Arctic implies very different climate feedback mechanisms, that is, Earth’s albedo and heat exchange conditions, than an environment with ice-free conditions during summer. As outlined above, our new proxy data and modelling data clearly indicate a late Miocene seasonal sea-ice cover. Similar or even warmer climatic conditions also occurred in the Middle Miocene Arctic Ocean when looking at the alkenone-based summer SSTs of 10-13 °C reconstructed from ACEX sediments (Supplementary Fig. 4 and also see ref. 53). Abundant marine palynomorphs and foraminifers found in Miocene and early Pleistocene sediments of the ACEX section also point to at least periods with seasonally ice-free conditions24,25. These data are in contrast to an Arctic Ocean perennial sea-ice cover from middle Miocene onwards, as proposed by Darby55 and Krylov et al.56 based on their provenance studies of IRD in ACEX sediments. Taking the IRD with a North American or East Siberian origin found in the ACEX sediments and using modern sea-ice drift trajectories and velocities, these authors concluded that more than 1 year was needed to transport the sediments entrained in the sea ice to the ACEX site. Hence, the sea ice must have survived the summer melting season to reach the ACEX site.

Our proxy and model reconstruction of late Miocene Arctic climate is certainly a substantial step forward to improve the understanding of the pre-Quaternary Arctic Ocean sea-ice and SST history. However, to decipher the pre-Quaternary climate history of this unique and sensitive but still not well-known region on Earth in more detail, long continuous sedimentary records to be obtained only by scientific drilling are needed. These records are planned to be recovered within a new IODP drilling campaign scheduled for 2018 (IODP Proposal 708; http://

Figure 8 | Global climate (benthic δ¹⁸O) stack and (sub-) Arctic SST records for the Late Miocene time interval. (a) Global benthic δ¹⁸O stack from ref. 43. (b) Late Miocene (Messinian/Tortonian) alkenone-based U³⁷-SST of Site 907 (yellow circles)27 and this study (red circles; Supplementary Table 5), TEX⁸⁶-SST values of Site 910 (orange circles)12 and alkenone-based U³⁷-SST of the ACEX Site (blue circles; this study/Supplementary Table 2). The ages of the five ACEX samples are based on ¹⁰Be stratigraphy73. General cooling trends in the 907 SST record (stippled red line), the ACEX SST record (stippled blue line, assuming a parallel SST trend to Site 907 with an offset of about 5 °C) and the benthic δ¹⁸O record (stippled black line) are indicated. The alkenone-based U³⁷-SST of Core PS87/106 are plotted versus depth (centimetres below seafloor) (cf., Supplementary Table 2). The stratigraphic range of the acritarch Decahedrella martinheadii in the sub-Arctic/Arctic realm is indicated24,25. As the central Arctic Ocean ACEX and the PS87/106 SST values should be similar, the PS87/106 record probably represents a time span within the upper Tortonian to lower Messinian (light blue box). Pl, Pliocene; MM, Middle Miocene.
www.iodp.org/expeditions). Based on the new PS87 seismic data, ~200 m of Plio–Pleistocene, > 600 m of Miocene and > 300 m of Oligocene–Eocene may be recovered at the proposed drill sites31,32 (see Fig. 2 for locations). The outcome of such a new programme will certainly help to improve our understanding of the complex ocean–atmosphere–ice system in the polar high northern latitudes and its role in the past, modern and future global climate.

Methods
Shipboard surveys and measurements. The methods used on board Póls律师on during Expedition PS87 are shortly outlined in the following. For a more detailed information about the use and interpretation of the proxy data we refer to the different chapters of the Cruise Report17.

The bathymetric survey was performed using the hull-mounted ATLAS Hydrographic HYDROSWEEP DS3, a deep-sea multi-beam swath sonar system with a resolution of up to 320 receive beams per ping, a swath width of 4–5 times the water depth and a vertical resolution of ~0.5% of the water depth. It was operated in the chirp mode with a frequency of 14–16 kHz. The mean sound velocity of the water column was calculated from conductivity-temperature-density (CTD), expandable CTD (XCTD) and Valeport Sound Velocity Profiler data. Sub-bottom profiling data were acquired using the parametric hull-mounted system ATLAS PARASOUND, a passive acoustic profiling system PS87/060 DS. Primary operating frequencies were 18.75 and 22.95 kHz with a secondary sediment-penetrating frequency of 4.2 kHz, a beam angle of 4° and a pulse length of 2. The vertical resolution is ~0.2 m. As a result of the narrow beam angle, reflections from strata dipping by > 4° cannot be received by the vessel. This explains why the thin veneer of post-slide sediments covering the slump scar is not resolved as it is above and below the headwall (Fig. 3b). The headwall has an inclination > 4°. In contrast, the older (pre-Quaternary) sediments exhibit nearly horizontal bedding (Fig. 3), which are thus acoustically resolved along the headwall to their near-seafloor location. PARASOUND data visualization and processing was performed using ATLAS PARASOUND software. The vertical scale on profiles has been converted from travel time to metres using a constant sound velocity of 1.5 km s−1, which explains minor differences in water depth between PARASOUND and swath-sonar data. For the MCS data acquisition, a 3,000-m-long streamer (240 active channels, group interval of 12.5 m) and an air gun array of four G-Guns (total volume of 321, fired from 200 bars of air flow) were used. Dong repeated included sorting, that is, common depth point sorting with 25 m spacing, frequency filtering (20–180 Hz) velocity analysis, multiple suppression and stacking. Whole-core measurements included non-destructive, continuous determinations of core geometry (diameter), WBD, P-wave velocity (Vp) and loop-sensor MS at 10 mm intervals, using a standard Multi-Sensor Core Logger (GEOTEK Ltd., UK). The principle of logging cores is described in more detail in the GEOTEK manual ‘Multi-Sensor Core Logging’, which can be downloaded from the web (http://www.geotek.co.uk).

Line-scan images (Supplementary Figs 1 and 2) were acquired with a Lai CV L107 camera with RGB (red-green-blue) channels at 630, 535 and 450 nm, respectively, mounted to an Avacade XRF core scanner. The camera contains three charge-coupled device sensors and a beam splitter to separate the RGB signal. Images were acquired with a down-core resolution of ~70 μm.

Stratigraphic framework and marine palynology process. The general lithostratigraphic framework and age model of the upper Quaternary sedimentary sections recovered during Expedition PS87 are robust and based on lithostratigraphic descriptions of the cores. In Core PS87/106, the consistent occurrence of D. martinheadii and N. labritius from 8.2 Ma onwards suggests a minimum age for 8.2 Ma which after it only occurs sporadically up to its highest occurrence at 4.5 Ma56–57. Therefore, the co-occurrence of D. martinheadii and N. labritius in combination with the absence of B. microspillata complex may allow to place the analysed interval of Core PS87/106 into the upper Tortonian to lower Messinian. However, we note that the highest occurrence derived from ODP Site 907 may represent a minimum age for this bioevent in the Central Arctic Ocean, as successive Neogene cooling may lead to an earlier disappearance of species in the higher latitudes.

D. martinheadii and N. labritius are both very delicate species that bear processes and trabeculae (ribbon-like bars), which tend to crumple easily. All specimens encountered during palynological analyses, however, are well preserved indicating in situ deposition.

Biomarker analyses. Extraction of ~5–10 g of freeze-dried sediments was carried out using an accelerated solvent extractor (DIONEX, ASE200; 100 °C, 3 min, 1 bar) with dichloromethane:methanol (2:1, v/v) and quantification using standard internal standards, 7-hexynoladecane (7-HND, 0.076 μg per sample for IP25 quantification), squalane (2.4 μg per sample) and cholesterol-d6 (cholest-5-en-3-ol-d6, 10 μg per sample for sterol quantification) were added before analytical treatment. Separation of the hydrocarbon and sterol fractions was carried out via open column chromatography (hydrocarbon fraction with 5 cm x 1 cm, the sterol fraction with 6 ml n-hexane:ethylacetate (5:1, v/v)). The latter fraction was silylated with 500 μl BSTFA (bis-trimethylsilyl-trifluoroacetamide) (60 °C, 2 h). IP25 and sterols were analysed by gas chromatography (GC)/mass spectrometry. Component assignment was based on comparison of GC retention times with those of reference compounds and published mass spectra (Supplementary Figs 5 and 6). The Kovats Index calculated for IP25 has been calibrated to 10.5 Ma in ODP Hole 907A. R. microspillata complex dominates the assemblage until ca. 8.2 Ma after which it only occurs sporadically up to its highest occurrence at 4.5 Ma56–57. Therefore, the co-occurrence of D. martinheadii and N. labritius in combination with the absence of B. microspillata complex may allow to place the analysed interval of Core PS87/106 into the upper Tortonian to lower Messinian. However, we note that the highest occurrence derived from ODP Site 907 may represent a minimum age for this bioevent in the Central Arctic Ocean, as successive Neogene cooling may lead to an earlier disappearance of species in the higher latitudes.

D. martinheadii and N. labritius are both very delicate species that bear processes and trabeculae (ribbon-like bars), which tend to crumple easily. All specimens encountered during palynological analyses, however, are well preserved indicating in situ deposition.

The detection limit for quantification of IP25 (Agilent 7890B GC, Agilent 5977A Extractor MSD with Performance Turbo Pump) is 0.005 ng μl−1 in SIM (selected ion monitoring) mode. To obtain mass spectra in TIC (total ion current) the limit is 0.05 ng μl−1. The retention indices for brassicasterol (as 24-methylcholesta-5,22-dien-3β-O-Si(CH3)3), campeststerol (as 24-methylenecholest-5-en-3β-O-Si(CH3)3) and β-sitosterol (as 24-ethylcholesterol-5-en-3β-O-Si(CH3)3) were calculated to 1.018, 1.042 and 1.077 (normalized to cholesterol-5-en-3β-O-Si(CH3)3 set to 1.000), respectively. For the quantification of IP25, its molecular ion (m/z 350) in relation to the abundant fragment ion m/z 266 of the internal standard (7-HND) was used for quantification.

Age model of the late Miocene section of core PS87/106. Based on microfossil data (that is, palynomorphs and agglutinated benthic foraminifers), the core catcher samples from the sediment cores were barren or give a Pleistocene age (Supplementary Table 1). The only core providing any clear indication that the palynomorphs are cropping out is the shallower core PS87/110. Well-preserved specimens of organic-walled palynomorphs (dinoflagellate cysts and acritarchs) have been recorded in successive samples from the base of the core (including core catcher) up to 420 cmbsf (that is, 50 cm below the hiatus; Supplementary Table 1). Of the encountered species, the acritarch D. martinheadii was the most abundant. So far, the core is composed of sediments of Late Miocene age. This species is endemic to the high northern latitudes and its stratigraphic range has been discussed previously based on comprehensive reviews of its occurrence at several DSDP, ODP and IODP sites from the Central Arctic Ocean, Norwegian-Greenland Sea, Labrador Sea, Baffin Bay and Irminger Sea24–26. It is also restricted to the late Miocene Arctic and subarctic realm, and based on the pristine paleomagnetic record of Iceland Sea ODP Site 907, its stratigraphic range is independently calibrated against the astronomically tuned Neogene Timescale, thus providing absolute age control (Supplementary Fig. 3). A near-synchronous highest occurrence at ca. 6.3–6.2 Ma has been defined from several northern high latitudes sites, suggesting this species to be an excellent marker across the subpolar/polar North Atlantic and Arctic Ocean. In Core PS87/106, the consistent occurrence of D. martinheadii is accompanied by low numbers of the dinoflagellate cyst N. labritius. Such co-occurrence has also been observed in the upper part of its stratigraphic range in ODP Hole M2A24 and ODP Hole 907H (refs 25,27). Furthermore, the lowest occurrence is not very well constrained at other sites but certainly younger than 11 Ma across the northwesternmost North Atlantic and Arctic Ocean.

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Our reconstruction of SST is based on long-chain C37 alkenones synthesized by haphtophyte algae8. The C37- and C38-alkenes were present in all samples, whereas the C36-alkene was not found. For alkenone (C37- and C38-) analysis, extraction and identification of freeze-dried sediment was carried out using the ASE method under same conditions as described above but with dichloromethane as the solvent. The separation of compounds was carried out by open column chromatography using 5 ml n-hexane, followed by 5 ml n-hexanedicloromethane (1:1, v/v) and 3 ml dichloromethane for elution of the alkenones. As internal standard, we added before any analytical treatment the alkenones were analysed by GC. Individual alkenone (C37- and C38-) identification is based on retention time and the comparison with an external standard (Supplementary Fig. 7). To exclude a possible coelution of the alkenones with other compounds, the extracts were measured first as total extract, second after additional column chromatography with dichloromethane and third after saponification9. The instrument stability has been continuously controlled by re-runs of an external alkenone standard (extracted from cultures of Emiliania huxleyi with known growth temperature) during the analytical sequences. The range of the total analytical error calculated by replicate analyses is <0.4°C. For calculation of SST, we used the simplified U^c_{37}^c37 index63:

\[ U^c_{37} = \frac{C_{37}}{C_{38} + C_{37}} \]  

(2)

U^c_{37} was converted to SST according to the World Ocean core top versus annual temperature calibration (U^c_{37} = 0.0337t + 0.044) (ref. 64), the calibration most often used in the literature. Resulting SST’s vary between 4.2 and 6.7°C (SST-1; Fig. 4 and Supplementary Table 2). For the central Arctic Ocean, these samples certainly have to be interpreted as summer SSTS (instead of annual mean) due to the darkness during late autumn to winter (cf., Fig. 5). In addition, we also have used the Müller et al.44 calibration versus summer SST (STT-2), the Sikès et al.53 calibration versus summer SST obtained from the polar Southern Ocean (SST-3) and the recently published new IP25 calibration (STT-4). Whereas the STT-4 values are more or less the same as the STT-1 values, the SST-2 and SST-3 values (calculated as ‘summer SST’) are higher and vary between 6 and 9°C (Supplementary Table 2). Based on these results, we interpret our late Miocene summer SST’s of ~4–7°C (mean of 5.3°C) more as minimum values. For the Müller et al.44 calibration, the standard error is reported as ±0.050 U^c_{37} units or ±1.5°C for the entire temperature range from 0 to 27°C. In the lower temperature range <10°C, however, the scatter of the U^c_{37} values is significantly higher than the mean. Thus, one should not overinterpret the SST variability between 4 and 7°C. In any case and independently of the calibration approach, summr SST’s were significantly higher than zero, preventing sea-ice formation during summer.

The results of the biomarker analyses (that is, alkenones, selected sterols, SSTs, IP25 and PIP25) carried out on samples from various PS87 sediment cores, are listed in Supplementary Table 2. All biomarker data (expressed in μg GOOC^-1 and μg wet sample^-1) are available online at http://dx.doi.org/10.1594/PANGAEA.855509.

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Author contributions

R.S. and W.J. proposed the main research goals of the PS87 Expedition. R.S. was chief scientist of the PS87 Expedition and leader of the geology group, developed the lithostratigraphic framework of the PS87 sediment cores, and wrote the first draft of the manuscript. K.F. conducted all biomarker analyses, evaluation and quality control. M.S. and M.K. identified the assemblages of palynomorphs and benthic agglutinated foraminifers, respectively, used for biostratigraphy and age control. G.K. and G.L. developed the model and experimental design. G.K. carried out the experiments. F.N. compiled the physical property and PARASOUND data. L.J. acquired and processed multibeam bathymetry data. M.F. was responsible for XRF scanning and line-scan imaging of the sediment cores. J.M. led the offshore geological activities on deck and in the laboratories. W.J. led the offshore geophysical activities and data acquisition. C.G. processed the multi-channel seismic data. A.K. carried out the sediment load and compaction experiments. All authors contributed to the data interpretation and writing of the final version of the manuscript.

Additional information

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