Central Arctic Ocean paleoceanography from \( \sim 50 \) ka to present, on the basis of ostracode faunal assemblages from the SWERUS 2014 expedition

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Abstract. Late Quaternary paleoceanographic changes at the Lomonosov Ridge, central Arctic Ocean, were reconstructed from a multicore and gravity core recovered during the 2014 SWERUS-C3 Expedition. Ostracode assemblages dated by accelerator mass spectrometry (AMS) indicate changing sea-ice conditions and warm Atlantic Water (AW) inflow to the Arctic Ocean from \( \sim 50 \) ka to present. Key taxa used as environmental indicators include Acetabulastoma arcticum (perennial sea ice), Polycop spp. (variable sea-ice margins, high surface productivity), Krithe hunti (Arctic Ocean deep water), and Rabilimis mirabilis (water mass change/AW inflow). Results indicate periodic seasonally sea-ice-free conditions during Marine Isotope Stage (MIS) 3 (\( \sim 57–29 \) ka), rapid deglacial changes in water mass conditions (15–11 ka), seasonally sea-ice-free conditions during the early Holocene (\( \sim 10–7 \) ka) and perennial sea ice during the late Holocene. Comparisons with faunal records from other cores from the Mendeleev and Lomonosov ridges suggest generally similar patterns, although sea-ice cover during the Last Glacial Maximum may have been less extensive at the new Lomonosov Ridge core site (\( \sim 85.15^\circ \) N, 152° E) than farther north and towards Greenland. The new data provide evidence for abrupt, large-scale shifts in ostracode species depth and geographical distributions during rapid climatic transitions.

1 Introduction

Environmental conditions are changing rapidly in the Arctic Ocean today, but a longer time perspective is necessary to assess and contextualize these changes and their contributing factors. These changing conditions include sea-ice extent and thickness (Stroeve et al., 2012, 2014; Laxon et al., 2013), as well as ocean temperature, stratification, circulation, chemistry, and ecology (Polyakov et al., 2017; Moore et al., 2015; Chierici and Fransson, 2009; Rabe et al., 2011; Grebmeier et al., 2006; Grebmeier, 2012; Wassmann et al., 2011). Sea-ice extent and thickness, in particular, are challenging parameters to reconstruct because most sea-ice proxies lack temporal and geographical resolution (Stein et al., 2012). Sea-ice extent and thickness, however, are very important variables because they influence albedo, near-surface salinity, light levels, surface-to-seafloor organic carbon flux, and other variables that are important to ecosystems. In fact, sea ice exerts a primary control on Arctic biological and geochemical cycles (Anderson et al., 2011), and sea-ice changes are in part responsible for fast-feedback climate changes during the geologic past (Polyak et al., 2010).

Before the last few decades, instrumental oceanographic records were relatively sparse, and sediment proxy records provided insight into past sea-ice conditions and ocean circu-
The Arctic Ocean is strongly stratified, with distinct water masses separated by vertical changes in salinity and temperature (Fig. 1b). The following summary of Arctic water masses and circulation is taken from Aagaard and Carmack (1989), Anderson et al. (1994), Jones (2001), Olsson and Anderson (1997) and Rudels et al. (2012, 2013). Arctic Ocean water masses include a fresh, cold Polar Surface Water layer (PSW; $T \approx 0$ to $-2\,^\circ C, S \approx 32$ to 34), found between $\sim 0$ and 50 m. The PSW is characterized by perennial ice in most regions and seasonal sea ice in the margins of the Arctic Ocean. Beneath the sea-ice cover, a strong halocline separates the PSW from the underlying warmer, denser water mass of North Atlantic origin (Atlantic Water, AW; $\sim 200$ to 1000 m, $T = >0\,^\circ C, S = \sim 34.6$ to 34.8). One branch of the AW flows into the Arctic Ocean from the Nordic seas along the eastern Fram Strait off the west coast of Spitsbergen and another branch flows through the Barents Sea. An intermediate-depth water mass below the AW in the Eurasian Basin at $\sim 1000$–1500 m is called the Arctic Intermediate Water (AIW; $T = -0.5$ to $0\,^\circ C, S = \sim 34.6$ to 34.8). Below 2000 m, the deep Arctic basins are filled with Arctic Ocean Deep Water (AODW; $T = -1.0$ to $-0.6\,^\circ C, S = 34.9$; Somavilla et al., 2013). Bathymetry is a dominant factor governing circulation patterns for AW and AIW, and a sharp front over the Lomonosov Ridge near the SWERUS-C3 core site studied here partially isolates these waters in the Eurasian Basin from the Canadian Basin (Fig. 1b).

In addition to Arctic Ocean stratification, other factors influence sea-ice decay and growth over geologic time (i.e., Polyak et al., 2010). A recent study by Stein et al. (2017) notes the importance of large-scale atmospheric circulation patterns, such as the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO), and radiative forcing (i.e., solar activity) on Holocene sea-ice thickness, extent and duration. The NAO and AO influence changes of the relative position and strength of the two primary Arctic Ocean surface-current systems, the Beaufort Gyre in the Amerasian Basin and the Transpolar Drift in the Eurasian Basin (Fig. 1a; Rigor et al., 2002; Stroeve et al., 2014). Data resulting from the SWERUS expedition will help improve understanding of the spatial patterns of sea-ice and intermediate depth circulation, given the extreme variability in sea ice in this region recently evident from satellite records (Serreze and Stroeve, 2015; Stroeve et al., 2014), the importance of the Transpolar Drift in sea-ice export through Fram Strait (Polyak et al., 2010; Smedsrud et al., 2017) and new evidence for the influence of inflowing Atlantic Water on sea ice and “Atlantification” of the Eurasian Basin (Polyakov et al. 2017).
Figure 1. (a) International Bathymetric Chart of the Arctic Ocean showing the location of this study’s primary sediment cores on the Lomonosov Ridge (red star: 32-GC2 and 32-MC4), as well as other core sites discussed in this paper (black and white circles). (See Table 1 for supplemental core data.) White circles designate cores that contain *Rabilimis mirabilis* events. Red arrows show generalized circulation patterns of warm Atlantic Water in the Arctic Ocean. White arrows indicate the surface flow of the Transpolar Drift, which moves sea ice from the Siberian coast of Russia across the Arctic Basin, exiting into the North Atlantic off the east coast of Greenland. Transect line through the map from “1” in the Chukchi Sea to “2” in the Barents Sea shows direction of temperature profile in (b). (b) Cross section of modern Arctic Ocean temperature profile from showing major water masses. PSW: Polar Surface Water; AL: Atlantic layer; AIW: Arctic Intermediate Water; AODW: Arctic Ocean Deep Water. Ocean Data View source: Schlitzer, 2012. Ocean Data View: http://odv.awi.de.
3 Materials and methods

3.1 Core material and sample processing

Cores for this study were obtained during the September 2014 SWERUS-C3 (Leg 2) expedition to the eastern Arctic Ocean aboard Swedish Icebreaker Oden. Figure 1 shows the location of multicore SWERUS-L2-32-MC4 (85.14° N, 151.57° E; 837 m) and nearby gravity core SWERUS-L2-32-GC2 (85.15° N; 151.66° E, 828 m) on the Lomonosov Ridge. These cores are hereafter referred to as 32-MC and 32-GC, respectively. Both cores were stored at 4 °C and sampled at the U.S. Geological Survey (USGS) laboratory in Reston, Virginia. Sediment samples (1 cm thick, 30 g prior to processing) were taken every centimeter in 32-MC along its 32 cm length. Section 1 (117 cm) of 32-GC was sampled every 2–3 cm (2 cm thick). Processing of the samples involved washing the sediments independently (Pearce et al., 2017; Hanslik et al., 2010), and improved age models may be available in the future.

Patterns in ostracode assemblages in both cores were used to correlate cores 32-MC and 32-GC and produce a composite faunal record, which led to a 3 cm offset for core 32-GC. Planktic and benthic foraminifers were also present in abundance but not studied.

3.2 Chronology, reservoir corrections and sedimentation

Nine radiocarbon (14C) ages were obtained from core 32-MC using accelerator mass spectrometry (AMS) (Fig. 2, Table 2). Most dates were obtained on mollusks (Nuculidae and Arci-

dae spp.), except a few samples where mollusks and benthic foraminifera were combined. Two ages from 32-GC were obtained using a combination of mollusks, foraminifera and ostracode shells. The final age models representing the two cores combined are based on all the calibrated 14C ages listed in Table 2. Generally, ages > 40 ka should be considered with caution because of large uncertainties in the radiocarbon calibration curve and high sensitivity to even extremely small levels of contamination. Calibration into calendar years was carried out using Oxcal4.2 (Bronk Ramsey, 2009) and the Marine13 calibration curve (Reimer et al., 2013), using a local marine reservoir correction, ΔR, of 300 ± 100 years. Because ΔR values for the central Arctic Ocean were not constant during the last 50 kyr, it is difficult to date pre-Holocene sediments independently (Pearce et al., 2017; Hanslik et al., 2010), and improved age models may be available in the future.

Patterns in ostracode assemblages in both cores were used to correlate cores 32-MC and 32-GC and produce a composite faunal record, which led to a 3 cm offset for core 32-GC. After adding the 3 cm offset to sample depths of 32-GC, the 32-MC core chronology was applied down to 31.5 cm core depth (dated at 39.6 ka). The average sedimentation rate at the core site was ~ 1.5 cmkyr−1, which is typical of central Arctic Ocean ridges (Backman et al., 2004; Polyak et al., 2009).

Table 1. Expedition and core site data for cores presented in this study.

<table>
<thead>
<tr>
<th>Year</th>
<th>Expedition</th>
<th>Core name</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water depth (m)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>SWERUS-L2</td>
<td>SWERUS-L2-32-GC2</td>
<td>85.15</td>
<td>151.66</td>
<td>828</td>
<td>Lomonosov Ridge</td>
</tr>
<tr>
<td>2014</td>
<td>SWERUS-L2</td>
<td>SWERUS-L2-24-MC4</td>
<td>78.80</td>
<td>165.38</td>
<td>982</td>
<td>E. Siberian Sea Slope</td>
</tr>
<tr>
<td>2014</td>
<td>SWERUS-L2</td>
<td>SWERUS-L2-28-MC1</td>
<td>79.92</td>
<td>154.35</td>
<td>1145</td>
<td>E. Siberian Sea Slope</td>
</tr>
<tr>
<td>2014</td>
<td>SWERUS-L2</td>
<td>SWERUS-L2-33-TWC1</td>
<td>84.28</td>
<td>148.65</td>
<td>888</td>
<td>Lomonosov Ridge</td>
</tr>
<tr>
<td>2014</td>
<td>SWERUS-L2</td>
<td>SWERUS-L2-34-MC4</td>
<td>84.28</td>
<td>148.71</td>
<td>886</td>
<td>Lomonosov Ridge</td>
</tr>
<tr>
<td>1991</td>
<td>Arctic 91</td>
<td>PS 2179-3 MC</td>
<td>87.75</td>
<td>138.16</td>
<td>1228</td>
<td>Lomonosov Ridge</td>
</tr>
<tr>
<td>1991</td>
<td>Arctic 91</td>
<td>PS 2185-4 MC</td>
<td>87.53</td>
<td>144.48</td>
<td>1051</td>
<td>Lomonosov Ridge</td>
</tr>
<tr>
<td>2005</td>
<td>HOTRAX</td>
<td>HLY0503-6</td>
<td>78.29</td>
<td>−176.99</td>
<td>800</td>
<td>Mendelev Ridge</td>
</tr>
<tr>
<td>1992</td>
<td>USGS-Polar Star</td>
<td>P1-92-AR-P30</td>
<td>75.31</td>
<td>−158.05</td>
<td>765</td>
<td>Northwind Ridge</td>
</tr>
<tr>
<td>2007</td>
<td>LOMROG 07</td>
<td>LOMROG07-PC-04</td>
<td>86.70</td>
<td>−53.77</td>
<td>811</td>
<td>Lomonosov Ridge</td>
</tr>
<tr>
<td>1996</td>
<td>Oden 96</td>
<td>96-12-1PC</td>
<td>87.10</td>
<td>144.77</td>
<td>1003</td>
<td>Lomonosov Ridge</td>
</tr>
</tbody>
</table>
Table 2. Radiocarbon dates for SWERUS 32 cores, uncalibrated $^{14}$C age and calibrated $^{14}$C chronology. All ages as calibrated years BP. $\Delta R = 300 \pm 100$ years (Reimer and Reimer, 2001). Marine13 calibration curve (Reimer et al., 2013).

<table>
<thead>
<tr>
<th>Lab number</th>
<th>(14C date age, error)</th>
<th>Depth (cm)</th>
<th>Unmodeled 2$\sigma$ (2 SD)</th>
<th>Modeled 2$\sigma$ (2 SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From</td>
<td>To</td>
<td>Mean</td>
<td>Error</td>
</tr>
<tr>
<td>OS-124799</td>
<td>(3410, 25)</td>
<td>2.5</td>
<td>3168</td>
<td>2698</td>
</tr>
<tr>
<td>OS-124798</td>
<td>(6110, 20)</td>
<td>4.5</td>
<td>6435</td>
<td>5974</td>
</tr>
<tr>
<td>OS-124599</td>
<td>(7920, 35)</td>
<td>5.5</td>
<td>8313</td>
<td>7874</td>
</tr>
<tr>
<td>OS-124598</td>
<td>(8290, 30)</td>
<td>8.5</td>
<td>8715</td>
<td>8207</td>
</tr>
<tr>
<td>OS-124597</td>
<td>(11000, 35)</td>
<td>11.5</td>
<td>12525</td>
<td>11661</td>
</tr>
<tr>
<td>OS-124754</td>
<td>(11200, 40)</td>
<td>14.5</td>
<td>12635</td>
<td>12040</td>
</tr>
<tr>
<td>OS-125185</td>
<td>(18650, 80)</td>
<td>19.5</td>
<td>22116</td>
<td>21357</td>
</tr>
<tr>
<td>OS-125190</td>
<td>(29400, 280)</td>
<td>24.5</td>
<td>33567</td>
<td>31805</td>
</tr>
<tr>
<td>OS-125192</td>
<td>(35400, 560)</td>
<td>31.5</td>
<td>40705</td>
<td>38099</td>
</tr>
<tr>
<td>OS-127484</td>
<td>(40000, 1700)</td>
<td>33*</td>
<td>47589</td>
<td>40881</td>
</tr>
</tbody>
</table>

* Sample collected from 32-GC; original depth was 36 cm but corrected by 3 cm based on ostracode correlation with 32-MC.

** We used the modeled, mean, 2$\sigma$ age to plot species' relative frequencies.

The lower section of 32-GC, from 31.5 to 61 cm, is beyond the limit of radiocarbon dating. However, the lithostratigraphy of the gravity core can be readily correlated to other records from the central Lomonosov Ridge, where multiple dating techniques constrain the approximate positions of MIS 4 and 5 boundaries (Jakobsson et al., 2001; O’Regan, 2011). A correlation between SWERUS-C3 32-GC and AO96/12-1PC was previously presented in Jakobsson et al. (2016). The correlation is supported by the occurrences in 32-GC of the calcareous nannofossil *E. huxleyi* (Fig. 2). Based on this longer-term correlation, sediments between 31 and 61 cm are less than 50 ka. This age estimate is consistent with previous work on the Lomonosov Ridge, revealing a prominent transition from coarse-grained, microfossil-poor sediments (diamict) into bioturbated, finer-grained, microfossiliferous sediments that occurred during MIS 3 at approximately 50 ka (Spielhagen et al., 2004; Nørgaard-Pederson et al., 2007).

4 Results and discussion

4.1 Ostracode taxonomy and ecology

The SWERUS 32 cores contained a total of 13 767 ostracode specimens in 32-MC and a total of 5330 specimens in the uppermost 5–62 cm of 32-GC (the top few centimeters below the seafloor were not recovered in the gravity core). The lower 54 cm of 32-GC (section 1 from 63 to 117 cm) was barren of calcareous material. Twenty-eight ostracode species were identified in 32-MC and 21 species were identified in 32-GC. Supplement Tables S1 and S2 provide all species and genus census data for 32-MC and 32-GC, respectively. Data will also be accessible at NOAA’s National Centers for Environmental Information (NCEI, https://www.ncdc.noaa.gov/paleo-search/). The primary sources of taxonomy and ecology were papers by Cronin et al. (1994, 1995, 2010), Gemery et al. (2015), Joy and Clark (1977), Stepanova et al. (2003, 2007, 2010), Whatley et al. (1996, 1998), and Yasuhara et al. (2014).

Podocopid ostracodes were identified at the species level except the genera *Cytheropteron* and myodocopid *Polycypris*. Table 3 provides a list of species included in the genus-level groups, which was sufficient to reconstruct paleoenvironmental changes. There are several species of *Cytheropteron* in the deep Arctic Ocean, but they are not ideal indicator species given their widespread modern distributions. There are at least eight species of *Polycypris* in the Arctic Ocean, but juvenile molts of *Polycypris* species are difficult to distinguish from one another. Most specimens in 32-MC and 32-GC be-
Table 3. List of species included in genus-level groups.

<table>
<thead>
<tr>
<th>Group name</th>
<th>Species included in group</th>
</tr>
</thead>
</table>

Figure 2. Chronology and stratigraphy of SWERUS-32-GC and 32-MC. Bulk density and magnetic susceptibility profiles for 32GC were previously correlated to the well-dated 96-12-1PC core by Jakobsson et al. (2016). Bulk density primarily reflects changes in grain size, with coarser material having a higher density than finer-grained material. The overall position of MIS 5 is supported by the occurrence of *E. huxleyi*. The chronology for the upper 30–35 cm is based on radiocarbon dating in both 32-MC and 32-GC. Beyond the range of radiocarbon dating, an extrapolation to the inferred position of the MIS 3–4 boundary (57 ka at 105 cm) is applied.

From Table 3, it can be observed that the species included in the genus-level groups are typically found in environments with high surface productivity and organic matter flux to the bottom (Table 4; Karanovic and Brandão, 2012, 2016). The relative frequency (percent abundance) of individual dominant taxa is plotted in Fig. 3 and listed in Supplement.
Table 4. Summary of indicator species, pertinent aspects of their modern ecology and paleoenvironmental significance.

<table>
<thead>
<tr>
<th>Species</th>
<th>Modern ecology/paleoenvironmental significance</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Acetabulastoma arcticum</em> (Schornikov, 1970)</td>
<td>The stratigraphic distribution of <em>A. arcticum</em> is used as an indicator of periods when the Arctic Ocean experienced thicker sea-ice conditions but not fully glacial conditions when productivity would have halted. This pelagic ostracode is a parasite on <em>Gammarus</em> amphipods that live under sea ice in modern, perennially sea-ice-covered regions in the Arctic (Schornikov, 1970). Cronin et al. (2010) used <em>A. arcticum</em>’s presence in 49 late Quaternary Arctic sediment cores as a proxy to reconstruct the Arctic Ocean’s sea-ice history during the last ∼ 45 kyr.</td>
</tr>
<tr>
<td><em>Krithe</em> spp.</td>
<td>Species of the genus <em>Krithe</em> typically occur in low-nutrient habitats spanning across a range of cold, interstadial temperatures but are especially characteristic of AODW (Cronin et al., 1994, 1995, 2014). In SWERUS-32 cores, <em>K. hunti</em> was far more prevalent than <em>K. minima</em>. From a modern depth–distribution analysis using AOD, <em>K. hunti</em> appears in greatest abundance (50–80 % of the assemblage) at depths between 2000 to 4400 mwd; however, this taxon is also found in significant numbers (20–50 %) at depths between 400 to 2000 mwd. With a preference for deeper, cold, well-ventilated depths, <em>Krithe</em> spp. events are useful in identifying late Quaternary shifts in Arctic Ocean water masses and making biostratigraphic correlations (Cronin et al., 2014).</td>
</tr>
<tr>
<td><em>Polycope</em> spp.</td>
<td>Today, this Atlantic-derived, myodocopid genus is in highest abundance (40–60 % of assemblage) in cold intermediate-depth waters between 800 and 2300 mwd. It characterizes fine-grained, organic-rich sediment in well-oxygenated water. In fossil assemblages, <em>Polycope</em> is indicative of areas with high productivity that are seasonally ice-free or have variable or thin sea-ice cover (Cronin et al., 1995; Poirier et al., 2012).</td>
</tr>
<tr>
<td><em>Cytheropteron</em> spp.</td>
<td>The two dominant <em>Cytheropteron</em> species in 32-MC and 32-GC are <em>C. sedovi</em> and <em>C. scoresbyi</em>, along with lower but significant numbers of <em>C. parahamatum</em> (reaches 24 % of assemblage at 10 ka) and <em>C. higashikawai</em> (fluctuates in very low numbers between 0 and 3 % at any given time in downcore samples). These particular <em>Cytheropteron</em> species are broadly diagnostic of deeper, well-ventilated water masses (AIW and AODW).</td>
</tr>
<tr>
<td><em>Pseudocythere caudata</em> Sars, 1866</td>
<td>This species of North Atlantic origin rarely exceeds &gt; 15 % in modern Arctic Ocean assemblages. It characterizes lower AW and AIW at depths of 1000–2500 mwd. It usually co-occurs with <em>Polycope</em> spp. in fossil assemblages and may be associated with surface conditions (Cronin et al., 1994, 1995, 2014), but more work needs to be done on its ecological significance.</td>
</tr>
</tbody>
</table>

Table S3. Abundances were computed by dividing the number of individual species found in each sample by the total number of specimens found. For 32-MC, using the algorithm for a binomial probability distribution provided by Raup (1991), ranges of uncertainty (“error bars”) were calculated at the 95 % fractile for the relative frequency in each sample to the relative frequency of each species and the total specimen count of each sample at a given core depth (Supplement Table S4). Faunal densities were high enough to allow comparisons from sample to sample, and Supplement Table S4 lists the density of ostracode species per gram of dry sediment, which averaged > 125 shells per gram sediment. For this study of the SWERUS-C3 32 cores, the focus was on an epipelagic species (*Acetabulastoma arcticum*), a pelagic genus (*Polycope* spp.), three benthic species (*Krithe hunti, Pseudocythere caudata, Rabilimis mirabilis*) and a benthic genus (*Cytheropteron* spp.). Table 4 provides an overview of pertinent aspects of these species’ ecology that have paleoceanographic application.

4.2 Temporal patterns in ostracode indicator species from SWERUS-C3 32-MC/GC

The faunal patterns in cores from the SWERUS-C3 32-MC/GC sites confirm faunal patterns occurring over much of the central Arctic Ocean during the last 50 kyr, including the MIS 3–2 (∼ 50 to 15 ka), the last deglacial interval (∼ 15 to 11 ka), and the Holocene (∼ 11 ka to present). Similar patterns are seen in both the multicore and gravity core. Relative frequencies of indicator taxa in cores 32-MC and 32-GC (Fig. 3) show four distinct assemblages, which are referred to as informal faunal zones following previous studies (Cronin et al., 1995; Poirier et al., 2012). These zones are as follows: (1) *Krithe* zone (primary abundance up to 80 % during ∼ 45–42 ka and a secondary abundance of 5–10 % during ∼ 42–35 ka), (2) *Polycope* zone (with abundance of 50
to 75 % during ~40–12 ka, also containing a double peak in abundance of \( P. \) caudata, (3) Cythereopteron–Krithe zone (12–7 ka), and (4) Acetabulastoma arcticum zone (~7 ka–present). This paper briefly discusses the paleoceanographic significance of each period in the following Sects. 4.3–4.5 based on the comparison cores presented in Figs. 4 and 5. Figures 4 and 5 compare the new SWERUS-C3 results from 32-MC with published data from box and multicores from the Lomonosov and Mendeleev ridges, respectively, covering a range of water depths from 700 to 1990 m. Most records extend back to at least 45 ka, and the age model for each core site is based on calibrated radiocarbon ages from that site (i.e., Cronin et al., 2010, 2013; Poirier et al., 2012). In addition, Sect. 4.6 discusses a potential new indicator species, \( R. \) mirabilis, which exhibits distinct faunal migrations that coincide with Krithe zones in 32-MC/GC. \( R. \) mirabilis lives on today’s continental shelf but is found in limited intervals in sediment cores that are far outside its usual depth and geographic range. \( R. \) mirabilis migrations are documented not only in 32-MC/GC but also in cores 96-12-1PC, HLY0503-06JPC, P1-94-AR-PC10, P1-92-AR-PC40, LOMROG07-04 and P1-92-AR-PC30.

4.3 MIS 3–2 (~50–15 ka)

A strong peak in the abundance of Krithe hunti (Fig. 3) is seen in 32-GC sediments estimated to be ~45–42 ka in age. A similar peak of lower but still significant abundance also occurs in sediments dated between 42 and 35 ka, and this peak is consistent with other cores on the Mendeleev Ridge and particularly on the Lomonosov Ridge (Figs. 4, 5). Prior studies of Arctic ostracodes have shown that Krithe typically signifies cold well-ventilated deep water and perhaps low food supply (Poirier et al., 2012, and references therein). Krithe is also a dominant component (>30 %) of assemblages in North Atlantic Deep Water (NADW) in the subpolar North Atlantic Ocean. Its abundance varies during glacial–interglacial cycles, reaching maxima during interglacial and interstadial periods (Zarikian et al., 2009). Peaks in the abundance of Krithe in the Arctic Ocean probably signify faunal exchange between the North Atlantic Ocean and the Greenland–Norwegian seas through the Denmark Strait and Iceland–Faroe Ridge and the central Arctic through the Fram Strait. In other Arctic Ocean cores, the ostracode genus Henryhowella is often associated with Krithe sp. in sediments dated between ~50 and 29 ka (MIS 3), and its absence in the 32-MC/GC cores may reflect the relatively shallow depth at the coring site. While Henryhowella was absent in records from this site, \( R. \) mirabilis abruptly appears and spikes to an abundance of 60 % at 40 ka, which coincides with the Krithe zone.

\( A. \) arcticum is present in low abundance (~5 %) in sediment dated at ~42 to 32 ka in 32-MC/GC (Fig. 3), signifying intermittent perennial sea ice. A second increase in abundance of \( A. \) arcticum corresponds to a (modeled, mean, 2\( \sigma \)) radiocarbon date of 21.6 ka. This suggests the location of this core may not have been covered by thick ice during the LGM as long as other areas.

A Krithe to Polycope shift occurred at ~35–30 ka. This “K-P shift” is a well-documented, Arctic-wide transition (Cronin et al., 2014) that has paleoceanographic significance as well as biostratigraphic utility. Polycope is clearly the dominant genus group from sediment dated ~40–12 ka in 32-MC/GC and all sites on the Lomonosov and Mendeleev ridges (Figs. 4, 5), signifying high productivity likely due to an intermittent, rapidly oscillating sea-ice edge at the surface. \( P. \) caudata has varying percentages (3–14 %) in sediment dated ~40–12 ka, depending on the site. \( P. \) caudata is an indicator of AIW and Cronin et al. (2014) report that it appears to be ecologically linked to the surface conditions. Cythereopteron spp. is present in moderate abundance (20–30 %) in sediment dated ~35–15 ka.

Overall, the faunal characteristics from this time period imply relatively restricted and/or poorly ventilated intermediate waters near the 32-MC/GC site. The major exception to this corresponds with the pronounced peaks in Krithe and \( R. \) mirabilis. This significant shift in faunal composition implies changes in ice margins, AW inflow, deep-ocean ventilation and/or enhanced deep-water transfer between the central Arctic Ocean and the North Atlantic.

4.4 The last deglacial interval (~15 to 11 ka)

The major shift from Polycope-dominated to Cythereopteron-Krithe-dominated assemblages occurs in sediment dated 12 ka in 32-MC/GC and ~15–12 ka in other Lomonosov and Mendeleev Ridge cores. In 32-MC/GC, Krithe reappears in low (10 %) but significant abundance after 11 ka after being absent during MIS 2. Both Cythereopteron and Krithe are typical faunas in NADW. Although low sedimentation rates prevent precise dating of this shift, it almost certainly began ~14.5 ka at the Bolling–Allerød warming transition. Because the Bering Strait had not opened yet (Jakobsson et al., 2017), this faunal shift must have been related to one or several of the following changes: (1) atmospheric warming, (2) strong Atlantic Water inflow through the Barents Sea, and (3) strong Atlantic Water inflow through the eastern Fram Strait. \( A. \) arcticum is absent or rare (<2 % of the assemblage) in sediment dated ~15–12 ka, suggesting minimal perennial sea-ice cover and probably summer sea-ice-free conditions during late deglacial warming.

4.5 The Holocene (~11 to present)

Krithe and Cythereopteron remain abundant in sediment dated ~10–7 ka (early Holocene) across most of the central Arctic Basin, signifying continued influence of water derived from the North Atlantic Ocean (Figs. 4, 5). Also during this time, \( R. \) mirabilis reappears and spikes to an abundance of 55 % at ~8 ka. \( A. \) arcticum (which represents the \( A. \) arcticum
Figure 3. Relative frequencies (percent abundance) of dominant taxa in SWERUS-C3 32-MC and 32-GC. The y axis shows the modeled, mean age during a 2σ range of uncertainty.

zone) increases to >6–8% abundance beginning in sediment dated ∼7 ka, and increases to >10% abundance in sediment dated ∼3 ka. This increase in abundance is correlated with an increase in perennial sea ice, and is more prominent in cores from the Lomonosov Ridge than in cores from the Mendeleev Ridge (most likely due to more persistent perennial sea-ice cover over the Lomonosov Ridge sites). The inferred middle to late Holocene development of perennial sea ice is consistent with interpretations from other sea-ice proxies (Xiao et al., 2015) and with the transition from an early–middle Holocene “thermal maximum” (Kaufman et al., 2004, 2016) to cooler conditions during the last few thousand years.
Lomonosov Ridge

Acetabulastoma arcticum

Krithe spp.

Polycopote spp.

Cytheropteron spp.

Pseudocythere caudata

Figure 4. Relative frequencies (percent abundance) of dominant taxa in SWERUS 32-MC (dotted line) compared to other Lomonosov Ridge cores 2185, 2179 and AOS94 28 (Poirier et al., 2012). The chronology for core PS 2185-4 MC (1051 m) is described in Jakobsson et al. (2000), Nørgaard-Pederson et al. (2003), and Spielhagen et al. (2004), core PS 2179-3 MC (1228 m) in Nørgaard-Pederson et al. (2003) and Poirier et al. (2012), and core AOS94 28 (PI-94-AR-BC28, 1990 m) in Darby et al. (1997).

4.6 Rabilimis mirabilis: new faunal events signifying rapid oceanographic change

In addition to the standard ostracode zones discussed above, the cores from the SWERUS 2014 expedition provide evidence of uncharacteristic and brief yet significant events of faunal dominance of a taxon. Such events are indicative of rapid environmental change. For example, prior studies have documented range shifts in Arctic benthic foraminifera during the last deglacial and Holocene intervals from the eastern Arctic Ocean (Wollenburg et al., 2001), the Laptev Sea (Taldenkova et al., 2008, 2012), the Beaufort Sea and Amundsen Gulf (Scott et al., 2009) and in older sediments (Polyak et al., 1986, 2004; Ishman and Foley, 1996; Cronin et al., 2014). The SWERUS-32 data reveal two Rabilimis...
**Figure 5.** Relative frequencies (percent abundance) of dominant taxa in SWERUS 32-MC (dotted line) compared to other Mendeleev Ridge cores AOS94 8 (Poirier et al., 2012), AOS94 12, and HLY6. The chronology for core HLY6 (HLY0503-06JPC, 800 m) is described in Cronin et al. (2013); core AOS94 8 (PI-94-AR-BC8, 1031 m) in Cronin et al. (2010) and Poirier et al. (2012); and core AOS94 12A (PI-94-AR-BC12A, 1683 m) in Cronin et al. (2010).

**Table 5.** Although *R. mirabilis* (Brady, 1868) is known and named from Pleistocene sediments in England and Scotland (Brady et al., 1874), this list cites various workers since that have documented this species in Arctic deposits dating back to the late Pliocene, when summer bottom temperatures were inferred to be up to 4 °C warmer than today.

<table>
<thead>
<tr>
<th>Citation</th>
<th>Location/formation (age)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siddiqui (1988)</td>
<td>Eastern Beaufort Sea’s Iperk sequence (Plio-Pleistocene)</td>
</tr>
<tr>
<td>Repenning et al. (1987)</td>
<td>Alaska’s North Slope Gubik Formation (Pliocene)</td>
</tr>
<tr>
<td>Penney (1990)</td>
<td>Central North Sea deposits (early Pleistocene age, 1.0–0.73 Ma)</td>
</tr>
<tr>
<td>Feyling-Hassen (1990)</td>
<td>East Greenland’s Kap København Formation (late Pliocene)</td>
</tr>
<tr>
<td>Penney (1993)</td>
<td>East Greenland’s Lodin Elv Formation (late Pliocene)</td>
</tr>
</tbody>
</table>
**Figure 6.** (a) Occurrence map of *Rabilinis mirabilis* in the Arctic Ocean and surrounding seas based on 1340 modern surface samples in the Arctic Ostracode Database (AOD; Gemery et al., 2015). (b) Modern depth and (c) latitudinal distribution of *R. mirabilis* based on 1340 modern surface samples in the AOD (Gemery et al., 2015).
**Figure 7.** (a) Relative frequency (percent abundance) of *R. mirabilis* in SWERUS-32 cores and in central Arctic Ocean cores, 160 ka to present. (b) *R. mirabilis* in core LOMROG07-04 from 260 ka to present and in core P1-92-AR-PC30 from 340 ka to present.

*mirabilis* “events” – intervals containing high proportions of this shallow water ostracode species dated at ∼45–36 and 9–8 ka. The modern circum-Arctic distribution of *R. mirabilis* is confined to shallow (<200 m) water depths (Fig. 6a, b, and c; Hazel, 1970; Neale and Howe, 1975; Taldenkova et al., 2005; Stepanova, 2006; Gemery et al., 2015) and Table 5 lists historical occurrences. *R. mirabilis* can also tolerate a range of salinities, explaining its presence in regions near river mouths with reduced salinity (Fig. 6a). *R. mirabilis* also occurs in 2014 SWERUS-C3 multicore top samples on the eastern Siberian Sea slope (Supplement Table S5; cores 23-MC4 (4 %, 522 m), 18-MC4 (18 %, 349 m),
16-MC4 (11 %, 1023 m), 15-MC4 (41 %, 501 m) and 14-MC4 (70 %, 837 m). These locations correspond to the summer sea-ice edge that has receded during recent decades over the Lomonosov Ridge.

Figure 7a and b show the stratigraphic distribution of *R. mirabilis* at the new SWERUS site and other sites on the Lomonosov Ridge (96-12-1PC), the Mendeleev Ridge (P1-94-AR-PC10) and Northwind Ridge (P1-92-AR-PC40) and in longer cores on the Lomonosov and Northwind Ridge. These patterns suggest a depth range extension of *R. mirabilis* into deeper water (700 to 1673 m) during interstadial periods (MIS 5c, 5a, 3). The abundance of *R. mirabilis* reaches 40–50 % of the total assemblage at Lomonosov Ridge site 96-12-1PC at a water depth of 1003 m. Such anomalously high percentages of well-preserved adult and juvenile specimens of *R. mirabilis* indicate that they were not brought to the site through sediment transport from the shelf. Instead, the *R. mirabilis* events represent in situ populations. Although these *R. mirabilis* events are not synchronous, most occur in sediment dated ∼96–71 ka (late MIS 5) and at SWERUS-C3 sites of 32-MC and 32-GC in sediment dated 45–36 and ∼9–8 ka (early Holocene). Thus the *R. mirabilis* events correlate with interglacial/interstadial periods that experienced summer sea-ice-free and/or sea-ice edge environments or Atlantic Water inflow. However, additional study of cores from Arctic margins will be required to confirm the paleoceanographic significance of *R. mirabilis* migration events.

5 Conclusions

Changes in ostracode assemblages in new cores from the central Arctic Ocean signify major paleoceanographic shifts at orbital and suborbital scales during the last 50 kyr. Peaks in dominant ostracode taxa include (1) the *Krithe* zone (∼45–35 ka), (2) *Polycope* zone (∼40–12 ka), (3) *Cytheropteron-Krithe* zone (∼12–7 ka), and (4) *Acetabulastoma arcticum* zone (∼7 ka–present). Brief yet significant deep migrations of *R. mirabilis* corresponding with the *Krithe* zone and *Cytheropteron-Krithe* zone imply rapid paleoceanographic changes associated with influx of Atlantic Water and/or deep-ocean convection during suborbital events in MIS 3 and the late deglaciation to early Holocene. When ostracode assemblage patterns in 32-MC/GC cores are compared to similar records from the Northwind, central Lomonosov, Mendeleev and Gakkel ridges (Cronin et al., 1995, 2010; Poirier et al., 2012), these changes demonstrate pan-Arctic, nearly synchronous changes in benthic ecosystems in association with rapid sea ice, surface productivity, and oceanographic changes in the Atlantic Water and Arctic Intermediate Water during MIS 3–1 (the last 50 kyr). These results confirm the sensitivity of Arctic benthic fauna to large, sometimes abrupt, climate transitions.

Data availability. Additional 2014 SWERUS-C3 expedition data, such as sampling sites, cruise track lines and geophysical mapping profiles, are available through the Bolin Centre for Climate Research database: http://bolin.su.se/data/swerus/ (Bolin Centre for Climate Research, 2017).

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Bolin Centre for Climate Research: Bolin Centre Database, available at: https://bolin.su.se/data/, last access: November 2017.


